Roger Birkeland

Doctoral Thesis

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On the Use of Micro Satellites as Communication Nodes

in an Arctic Sensor Network

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Samandrag

Arktis og verdsrommet er to konsept som er kjelder til fascinasjon og undring for mange av oss. Begge stadane verkar fjerne og ugjestmilde, men samstundes er dei vakre og spanande. Saman utgjer dei ein del av verda som er full av utfordringar, samstundes som dei står for store moglegheiter for vitskap, rekreasjon, kunnskap, undring og inspirasjon.

Mange forskarar ynskjer meir og jamnleg oppdatert informasjon om miljøet i dei arktiske områda. I dag eksisterar det ikkje gode kommunikasjonssystem, heller ikkje satellittkommunikasjonssystem, som gjer det mogleg å enkelt hente ut sensordata utan å reise dit sjølv.

Gjennom dette arbeidet ynskjer eg å bygge ei bru mellom delar av Arktis til verdsrommet. Resultata frå denne systemstudia kan bringe Arktis nærare oss gjennom eit satellittkommunikasjonssystem, slik at sensorar i Arktis kan nåast av folk som held til i meir sentrale delar av verda.

Hovudmotivasjonen for oppgåva var å finne ut om eit kommunikasjonssystem basert på små satellittar kan vere eit brukbart alternativ for å tilby kommunikasjonsløysingar i Arktis. Hovudkonklusjonen viser at det ser ut til å vere mogleg. Småsatellittar har fleire utfordringar og avgrensingar, men ved å designe eit godt system kan dette ha ei yting samanliknbar med andre system, både når ein ser på nytte og på kostnad.

Eit av dei viktigaste bidraga i dette arbeidet er studiet av svermar av små satellittar, og korleis ein kan få til desse svermane. Med slike svermar kan ein oppnå god og hyppig dekning, utan å måtte nytte satellittar som har framdriftssystem. Ved å kutte ut framdriftssystemet, vert både kostnad, masse og volum redusert. Dette bidreg også til å redusere oppskytingskostnaden. Det å sende svermen av satellittar ut i bane, ser også mogleg ut, både frå ein teknisk ståstad og frå eit økonomisk perspektiv.

Ein av eigenskapane til satellittsvermar er at dekninga ein oppnår på bakken ikkje er konstant. På grunn av at satellittane endrar innbyrdes avstand heile tida, vil dei ved somme tidspunkt sjå ut til å overlappe, og ein mister difor litt kapasitet samanlikna med ein konstellasjon med like mange satellittar. I ein slik

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konstellasjon held satellittane deira innbyrdes avstand til kvarandre, men då er det naudsynt med eit framdriftssystem for å få dette til. Likevel, for dei fleste tenestene som er diskutert i dette arbeidet handlar det om å flytte informasjon som ikkje er tidskritisk. Difor er det at dekninga endrar seg mindre viktig. Når ein uansett ikkje treng dekning heile tida, spelar variasjon i dekning, samt kor lang tid det tek å flytte informasjonen frå sensor til sluttbrukar ei mindre rolle.

Eit anna bidrag frå dette arbeidet er ei systemanalyse om korleis ein heterogen kommunikasjonsarkitektur kan verte definert. Ulike nettverk kan koplast saman gjennom standard internettprotokollar tilpassa Internet of Things (IoT). Slik kan sensorar som står på aude stadar koplast saman med ein sluttbrukar, gjennom internett. Ved bruk av dei vanlege internettprotokollane, sikrar ein at ulike typar utstyr og ulike typar nettverk kan snakke saman. Desse nettverka kan vere lokale linkar i grupper av sensorar, det kan vere satellittlinkar mellom sensorar og ein satellitt, eller mellom satellitt og ein bakkestasjon. I tillegg kan andre bemanna eller ubemanna fartøy frakte data frå ein del av eit nettverk til ein annan del. Desse fartøya kan vere anten i lufta, på eller i sjøen, alt etter som kvar sensoren er plassert.

Når ein skal lage eit system for radiokommunikasjon er linkbudsjettet eit av dei viktigaste elementa som må studerast. Her har ein studert forskjellige fenomen som alle har ein innverknad på linkbudsjettet, og ei mogleg løysing er presentert. Likevel, ein må oppfylle fleire føresetnader for at linkbudsjettet skal vere nyttig. For å kunne lage eit system som har ei stor nok datarate til at det blir brukbart, må satellitten verte bygd for å kompensere for nokre av avgrensingane som vil finnast i ein typisk sensor i Arktis. Om ein ynskjer ei enno høgare datarate i systemet, treng også sensoren på bakken ei antenne med ei viss vinning. Dette er eit av fleire spennande tema som er føreslått som vidare arbeid.

Kostnaden ved å ta fram eit slikt system er også studert. Her er satellittsystemet samanlikna med eit system som bygger på bruk av ubemanna flygande fartøy, og eit system som nyttar eit fly til å samle inn data frå sensorane. Satellittsystemet vil kunne gi dekning mykje oftare, og vil vere i stand til å hente inn ei samanliknbar mengde data, til ein samanliknbar kostnad.

For å summere opp, så viser dette arbeidet at eit eige satellittsystem er ei god løysing på utfordringa det er å skaffe vitskaplege data frå sensorsystem i Arktis, og få dette levert til vitskapsfolk her heime. Arbeidet er basert på etablerte arbeidsmetodar for design og analyse av romprosjekt.

Abstract

The Arctic and space are concepts that fascinate us. Both places seem remote and hostile, but are at the same time beautiful and exciting. Together, they form a part of the world comprised of daring challenges, but also of endless possibilities for science, recreation, wonder, knowledge and inspiration.

Several scientists would like access to more and frequently updated information about the Arctic area. Today, no adequate communication systems allowing this exists. Due to this, access to sensor data is often limited to traveling to the sensor node and retrieve its data.

This thesis aims to bridge parts of the Arctic and space. The work in this system study may bring the Arctic nearer to us by proposing a space communication system that can connect assets in the Arctic with people residing in less remote areas.

The main research motivation was to investigate if a system of small satellites could be a viable solution to bridge the communication gap in the Arctic. An important use case is to enable access to sensor data from sensors deployed in remote locations without having to physically be at the node to download the data. The main findings show that this can be possible, by establishing a communication system with small satellites. The small satellites have their challenges and limits, but by careful design, a system can be made to compare with other solutions, both in utility and cost.

The main contribution from this work is the proposal on how to use a freely flying swarm of small satellites to provide good and frequent coverage, without having to use satellites with propulsion systems. This saves component cost, mass and volume, which in turn contribute to a reduced launch cost. The deployment of a satellite swarm seems feasible both from a technical point of view, as well as from an economical point of view.

The coverage property for a swarm is not constant, and on average it is not as good as coverage by a constellation consisting of the same number of satellites. However, for services that do not require to transmit time-critical sensor data, this is of less concern and variations in responsiveness can be accepted.

Another contribution is a system study on how a heterogeneous communication architecture can be designed, ensuring interoperability between satellites, sensor nodes and unmanned vehicles. Different networks may be interconnected and joined, providing connectivity between sensor systems and operators through the Internet. This interconnection can be made possible by the use of standard Internet-of-Things protocols. These networks can consist of local networks linking sensor nodes, satellite links between sensor nodes, satellites and gateway stations, as well as other types of unmanned or manned vehicles acting as data mules; ferrying data from one part of the network to another.

A central topic of investigation in any radio communication system is the link budget. By carefully evaluating the various contributing factors of the link budget, a feasible budget is presented. However, some assumptions are required. In order to design a system with a usable data rate, the satellite must be designed to compensate for some of the limitations of a typical sensor node. A system supporting an even higher data rate also requires the sensor node to be equipped with a high-gain antenna. This represents an interesting research topic for further study.

The cost of the space segment is also evaluated against the use of unmanned aerial vehicles and airplanes. From this analysis, it is shown that a satellite system will provide a more continuous coverage, being able to transmit a comparable amount of data, at a similar or lower cost. The satellites could be based on Cube-Sats.

To conclude, the outcome of this study shows that a dedicated satellite system, *your mission, your satellite(s)*, can be a viable solution to the challenge on how to relay sensor data from the Arctic to scientists at home. The work follows the early phases of established space mission analysis and design methods.

Preface

This thesis is submitted in partial fulfillment of the requirements of the PhD degree at the Norwegian University of Science and Technology (NTNU). The candidate has been employed at the Department of Electronic Systems (IES). Professor Vendela Paxal has been main supervisor. Professor emeritus Odd Gutteberg and Professor Yuming Jiang have been co-supervisors.

Contributions   The thesis is written as a monograph partially based on the papers included in Appendix A. The series of papers starts with presenting the communication gap in the Arctic, and the challenges for an Arctic communication system in Paper A (Section A.1) and Paper B (Section A.2). Then, swarms of small satellites, and how they can be designed to best provide coverage, are introduced in Paper C (Section A.3) and Paper D (Section A.4) respectively. A full communication architecture proposal encompassing satellites and other unmanned vehicles is presented in Paper E (Section A.5). Paper F (Section A.6) focuses on evaluation parts of the architecture introduced in Paper E, through simulation and emulation. Results on coverage and end-to-end delay for different swarm configurations, sensor node and gateway placements are presented. Finally, Paper G (Section A.7) presents a deeper analysis of how real IoT-protocols perform in this architecture. Suggestions on how to reduce delays by employing a forward-looking routing method are also presented.

In addition to these papers, the complete thesis presents a broad system design study of a satellite communication system suitable for providing a communication infrastructure for the Arctic area. The thesis covers central parts of a typical space mission design. The most weight is put on the feasibility study of a space mission architecture that can close the identified coverage gap.

Acknowledgments

The list of people who have made contributions to the progress of my work is long. Without either professional backing and support, or personal support and encouragement, this work would be impossible to carry out.

My supervisors Vendela Paxal, Odd Gutteberg and Yuming Jiang deserve huge thanks for their support and push throughout a period of almost five years.

Vendela, you have put so much effort behind your support, I am incredibly grateful for that. The feedback I have received for papers, and finally for this thesis, has been essential for me to be able to complete this work. I hope we can continue working together in years to come.

Odd, you have been a mentor for me for more than 12 years, through both my masters thesis, and now my pursuit of the PhD-degree. I am grateful for all our discussions, your insight and all the things I have learned from you.

Yuming, you brought me together with Artur and David, and gave us a place to meet until we gained our own momentum. You have been the catalyst enabling much of this work.

In addition to my formal supervisors, I have spent much time discussing with other people who have made considerable contributions to my progress.

Professor Torbjörn Ekman, you have been distracted from your work so many times during these years, and I'm very grateful for our discussions. I believe that my work perhaps did not take the focus you had hoped for, but even if I do not discuss the radio channel in great detail, you have always had time to talk. Perhaps, most of the time, I left your office with even more loose threads and thoughts than I initially had when I entered. This has been very inspiring, and your creativity and passion in all these projects is admirable.

I'm very glad that also Egil Eide has joined the staff at IES, and I value our discussions highly. We still lack the *"Eide and Birkeland"* publication though. That must be a goal for the near future.

Professor Tor Arne Johansen at the Department of Engineering Cybernetics has been a mentor for me during the last part of my fellowship. I have learned a lot from you, and greatly appreciate the inclusion in the emerging small satellite activities we now have established at NTNU. It has been demanding, but very rewarding work.

During the first half or so of my work, I often felt a bit out of context, and wondered how I could find better reason and application for the outcomes of my work. My fellow PhD-candidate Artur Zolich and Associate Professor David Palma have contributed to fill my work with more substance. You are valuable discussion partners, sounding boards, co-authors and friends.

During my stay at NTNU, I have also met a lot of new friends and colleagues abroad, mainly through my involvement in the Space Generation Advisory Council (SGAC). From the long list of people there, I would especially like to thank Andreas Hornig and Ozan Kara for pushing me, and including me, in projects and publications. Tale Sundlisæter deserves a thanks for introducing me to SGAC.

I also want to thank our continuously growing small-satellite team. I am very happy that we finally were able to start small satellite activities and research on this level. Mariusz, Gara, Evelyn, Milica, João, Sivert, Elizabeth, Alberto and Julian, thank you all for making my final months as PhD-candidate so much more hectic, interesting and rewarding. I am looking forward to the continuation!

My office roommate Amund Gjersvik deserves a huge thanks for being a very good friend for many years and also a discussion partner the recent years. I am grateful for the work you do with the continuation of the small satellite student project, and sharing the role as "space guru" at the department.

Terje Mathiesen has endured some extra coffee brakes when I invaded his office to release some steam and frustration during these years. I also want to thank the rest of the staff at the electronics lab and the mechanical workshop for being good colleagues for almost eight years now.

I have also met a lot of supportive people from various parts of the Norwegian space community, I'm grateful for everything you have taught me. One particular mention is deserved, Jøran Grande at NAROM has been a sparring partner and travel companion for many of the workshops and conferences I have attended.

Work is not only about work, the lunches together with fellow PhD candidates and other colleagues have been invaluable breaks. However, the team around the table in the library tends to change. Erlend, Magnus B. and Guro, you were the first to take me on board, and after you moved from Trondheim, the evenings with you in Oslo have been appreciated breaks from meetings and hotels. More recent and current people, Stein Arne, Ingrid, Dragan, Magnus M., Sam, Silje, Ine Mari, Jens, Ambjørn, Asgeir, Torstein, Einar, Harald, Hans Olaf, Ida, Kristoffer, Karolina, Fredrik and Nina; you have all provided your valuable insights in life,

#phdlife, fruit, coffee, travels and so much more! The lunch-room is an oasis in the university life. And we have had good company from more permanent residents, Erik, Astrid, Thomas, and Jostein.

Former and current members of the student satellite team; all of you deserve a thanks for contributing to more space activities! Especially Frida Vestnes, thanks a lot for our discussions, for your feedback and graphical skills.

To two of the students I have tried to help this year, Vilde and Petter, your sort of engagement, eagerness and persistence is not something I often see. I wish you the best of luck in pursuit of a space career!

So, to the most difficult part of this section. Una, I think you have endured a lot of me putting work first these years, especially during the final months when 95% of my focus has been on completing this thesis (and you have mastered your English-classes!). Your patience has been impressive! I am glad that both Håvard and Mats also have helped out making this possible by being two very kind and good boys. I love the three of you (and Mango) so much, and I look forward to being able to spend a bit more time with you now. I also would like to thank my friends and family whom I do not meet everyday, my parents, my brother and his family and Unas parents and family.

Finally, I would like to thank Dorothy Brown for proof-reading during the finalization of the thesis.

This thesis has given me the opportunity to combine two of my fascinations; the Arctic and space. Unfortunately (or luckily?), I have spent very little time either place. I did get to visit Svalbard for one week during a summer school. That was a very rewarding experience, and I am ready for more.

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Roger Birkeland
Trondheim, Norway
January 2019

Contents

Chapter 1

Introduction and Context

The Arctic is an area of growing interest, both amongst the Arctic nations as well as others. The European Union (EU), the Arctic nations through the Arctic Council, seek cooperation and aim to find common policies for managing resources, environmental concerns, and also security related issues. All this in a difficult and harsh environment where there also are some conflicting interests and agendas between stake holders [2, 3, 4, 5]. For most parties, it is important to protect the environment, limit military activities, and be able to handle the increasing activity that will follow when the Arctic ice diminishes. EU, the National Aeronautics and Space Administration (NASA) and the Arctic Council [6, 7, 8] foresee an increased utilization of resources, such as fishing, mining and shipping. In addition, activities for securing environmental situation awareness, both for governmental and military actors are increasing.

As the Arctic ice melts, more of the Arctic waters will be possible to navigate. Placed in the center between world powers like the US, Russia and the EU, the Arctic may become a hub for science, resource extraction and transport. The Arctic is becoming a strategic area, where presence and knowledge about resources and what activities other nations are doing is important. New sources of biomass as fish and new shipping routes can hold considerable values. Military aspects may also be important, less Arctic ice will considerably shorten the distance between East and West for a broader range of vessels.

For Norway's case, Svalbard plays an important role in Arctic policy. Since the mining activity is coming to a close, it is important for the nation to base the presence on Svalbard on other activities. Increased science and research activities are expected to be important. Regulation of new activities are important and acknowledged. For example, fisheries in the Arctic ocean has been unregulated [9], but just recently precautions to be able to handle an ice-free Arctic ocean has been taken, and an agreement to regulate fisheries is to be set in place [10].

Due to the lack of land-based infrastructure and satellite coverage, the communication infrastructure in the Arctic areas is generally scarce [11]. An ESA project called ArtiCOM [12] concluded in 2011 that there is a communication gap, and lists some projects which were mainly expected to cover parts of non-European Arctic. However, several of these projects are now canceled or delayed. It was further acknowledged by ArtiCOM that there were no planned systems for the European Arctic at the time the report was written.

More activity leads to an increased request for data, and then the communication infrastructure must be strengthened. This is important for several reasons, one is to provide better access to scientific sensor data. Another reason is that increased human activity will likely increase the frequency of accidents and incidents requiring Search-and-Rescue (SAR) operations. The Arctic nations share the responsibility for these operations, and Norway is allocated one of these sectors [13]. It is acknowledged that safety systems for the shipping industry may rely on satellite systems, which currently have no coverage in the Arctic regions [14]. SAR-operations would benefit of a better infrastructure than currently available.

A vast set of challenging topics can be investigated within this context. The scope of this thesis is to take a *system engineering* view and present measures to improve the situation for science and research. This thesis is a *system study* of a communication architecture comprising *small satellites*, proposed to use with *sensor networks* placed in the Arctic, as well as integration and cooperation with unmanned vehicles.

1.1   Communication Challenges in the Arctic

When Arthur C. Clarke in 1945 wrote his famous paper *EXTRA-TERRESTRIAL RELAYS - Can Rocket Stations Give World-wide Radio Coverage?* [15], he showed how the Earth can be covered by three satellites in Geostationary Orbit (GEO). That is; *nearly* covered by three satellites. Since the Earth is of the shape of a sphere (and not a flat disk), and a GEO orbit has a radius of about 42000 km, the Arctic areas above about 81° latitude are not covered by the geostationary satellites. This is shown in Figure 1.1.

The communication challenges in the Arctic are well known. There is little land-based infrastructure outside settlements on Svalbard, Greenland, Canada, Alaska and Russia. Satellite communication systems based on satellites in the GEO, such as the INMARSAT system [16], have virtually no coverage north of 75° latitude, and none at all above 81° latitude [17].

Furthermore, several communications systems based on Low Earth Orbit (LEO) satellites have orbits not covering the Arctic at all, such as Orbcomm [18] and Globalstar [19]. The ARGOS [20] system offers partial Arctic coverage, leaving
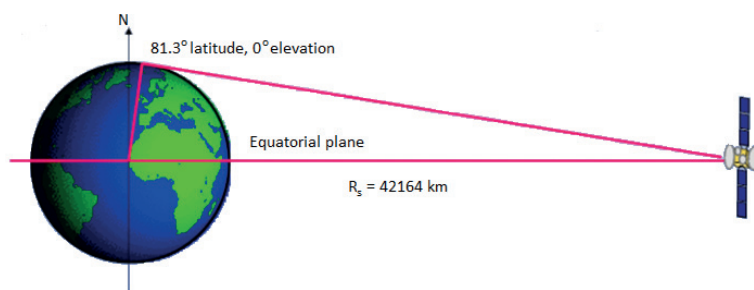
Figure 1.1: No GEO coverage north of 81° N. (Fig. is courtesy of Prof. O. Gutteberg)

Iridium [21] as the most used system providing continuous planet wide coverage. Some of the new proposed mega constellations such as OneWeb and Starlink will most likely provide coverage in the Arctic. Details of these systems will be discussed in Section 2.3.1.

Bridging this communication gap is the focus in this thesis. To cover the Arctic area, a system based on polar orbiting satellites is needed. Sensor nodes in the Arctic can potentially see every pass of a polar orbiting satellite. This simplifies design of constellations and swarms, which can be designed to have reasonable coverage by using satellites in only one orbital plane. For sensor nodes placed further south, more than one satellite plane must be employed in order to have the same re-visiting time.

In addition to the technical and physical communication challenges mentioned, the Arctic is a challenge in itself. The weather and climate conditions are harsh and unfriendly to both man and equipment [17]. Half of the year there is virtually no sunlight making energy harvesting from solar panels impossible. The equipment must therefore rely entirely on batteries. Temperatures are low and equipment floating in the sea will be subject to icing and potentially antenna drowning by waves during periods of roaring winds. Moreover, ionospheric and polar cap effects will influence the radio channel between the node on Earth and the satellite. These effects are frequency dependent and are further discussed in Section 6.2.

Even if the Arctic area is the foundation and motivation of this work, the Antarctica share many of the same challenges as mentioned above. A short discussion of this case is carried out in Section 2.2.6.

1.2 A Changed View on Space

In 2017 we saw launch of 35% of the total volume of CubeSats launched until then [22]. The first CubeSats, with the first launch in 2003, were tools used by universities to engage students in space activities. The situation has now changed, and commercial entities stand for the majority of launched and planned missions [22]. Several recent studies give overviews of the development of small satellites, their utility and applications [23], [24, Chapter 23].

Adding to the growth of small satellites, or even as a consequence of the growth, the available data volume from space is growing so fast that we are not able to make use of all data yet. This is not only thanks to the small satellites, but also due to large international programs such as EUs Copernicus program; a constellation of satellites for Earth Observation (EO).

Figure 1.2: The UN Sustainable Development Goals [25].

Small satellites have seen a rise in applications from many new actors, both commercial and governmental. In addition, data from space and infrastructure provided by space assets, such as communication systems and navigation systems, contribute to a plethora of new services that can improve life on Earth. It is possible to link space to several of the United Nations 17 Sustainable Development Goals (SDG). The goals are shown in Figure 1.2. The most visible link is that space in general is enabling better infrastructures for resource management. This can contribute to reach goals 1, 3, 6, 11, 12, 13, 14 and 15. Hopefully, the research activity carried out as part of this thesis, as well as in future works – within an Arctic context – may contribute to a better understanding of both the climate (13), and life in and under water (14).

In October 2016, the EU and European Space Agency (ESA) launched a joint vision and goals for Europe in space [26]. The goal of the strategy is to leverage technology development and cooperation all across Europe, to make a better living

and better understand both the Earth and the space around us. Public outreach was also identified as an important activity to address. It is important to educate the public on how space technology and services from space assets contribute to our daily life. Figure 1.3 shows two info-graphics where some of the challenges that can benefit from a better space infrastructure (right) and how space services are an integral part of the society around us (left).
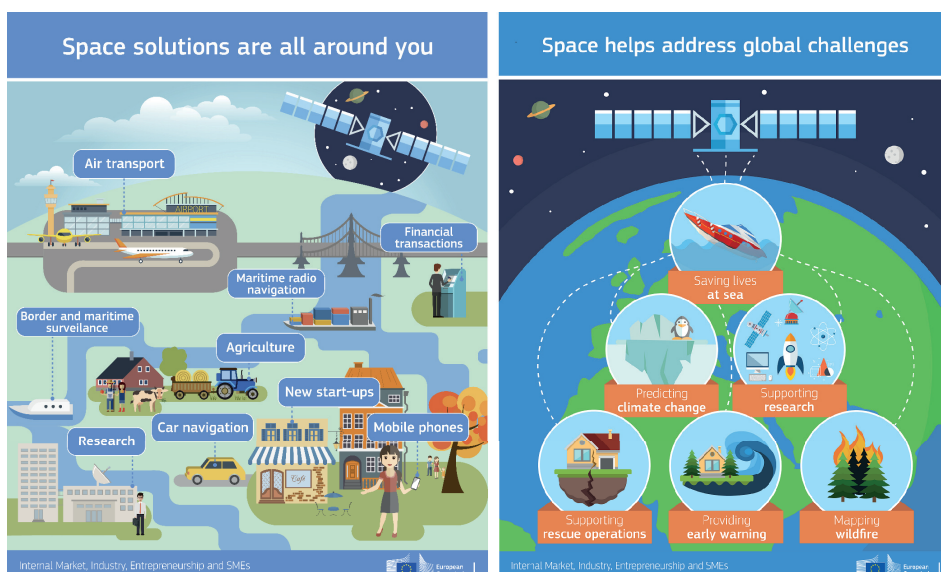
Figure 1.3: Space helps address global challenges. Info-graphic from the EU [26].

Without aiming too high, the work performed in this thesis could make its small contribution for a better world. Related to the topics depicted in Figure 1.3, supporting research and contributing to get better data to predict and understand climate change, are within the scope of this work.

1.3   Thesis Problem Statement

Building on the aforementioned background and motivation, the increased activity in the Arctic is acknowledged, as well as the current lack of suitable communication infrastructures. The work performed in this thesis will permit initiation of research and engineering activities that can lead to better support for environmental science missions to the Arctic, through improving the communication infrastructure.

This thesis will present a broad systems engineering view on this problem.

This broad view will cover many aspects; from satellite orbits, satellite communications, networking and interoperability between systems. Through this process a new solution which will cover a gap in current and proposed networks and communication systems will be presented.

The scope is sensor networks in the Arctic, and one on-going project, the Arctic ABC-project [27, 28], will be used as an example and baseline when defining mission and system requirements.

The Arctic ABC-project is one example of projects in need of better infrastructure than currently available. Their goal is to collect environmental and biological information from the Arctic ocean over a duration of several years. As this is a complicated logistical task, involving expensive manned expeditions, the wish is to make use of autonomous systems that do not require continuous human intervention. This goes for both operating the sensors and extracting the scientific data. Arctic ABC will employ several information collecting sensors with varying requirements, related to how much data the respective sensors generate every day. Accordingly, Arctic ABC will be used as an example when defining requirements for an Arctic communication system, including alternative satellite systems and payloads. The use case will be explored in greater detail in Section 2.2.3.

The duration of a project such as Arctic ABC is comparable for the lifetime of a dedicated *new space*[1] satellite mission, which typically spans 3 – 7 years. The deployed sensors will drift with the ice, from an area near the North pole, to around 75° North. This is reflected in the *Mission Statement*, and is the basis for the problem statement for this work, expressed by the research questions stated below.

Even though a specific example use case is used to help deriving mission requirements, the resulting architecture will be applicable to other use cases of similar nature.

1.3.1   Research Question Formulation

The main area of interest for the Coastal and Marine Operations and Surveillance (CAMOS) project [1], as it also is for Arctic ABC, is the polar area between the North Pole, Greenland and Svalbard, shown in Figure 1.4. However, the solutions proposed should be applicable to similar areas and situations in other places, for example, Antarctica. In its nature, the technical challenges of creating an architecture comprising sensor nodes, satellites and UVs, are general and can be applied to a vast set of problems and missions.

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[1]New space (or NewSpace) is a commonly used term representing the shift in the space industry from huge governmental funded programs and satellites to more commercial endeavors aiming to build better, cheaper and faster space systems.

Figure 1.4: The main area of interest. Defined to be between $74° - 90°$ North and $40°$ East to $20°$ West.

North of $75°$ latitude, there is little or no communication infrastructure readily available. Activities in this area must often rely on manned expeditions to survey equipment and extract scientific data from sensors placed far from settlements. These costly operations pose risks for the equipment and crew carrying out the operations. The main task through this work has been to investigate how this situation can be improved and how costs and risks can be reduced. This can be done by using heterogeneous networks employing satellites and other moving, autonomous or remotely operated, communication nodes. The following research questions are addressed, stemming from the problem defined, and the mission statement:

Research Question 1 *How can satellite communication payloads and sensor nodes be integrated with other (moving) network nodes into a resilient heterogeneous communication network?*

Research Question 2 *With the emerging possibilities from* new space *systems and satellite platforms, how can a small satellite mission be designed and used to aid operation in the Arctic area, or in any other remote location?*

Research Question 3 *Given the flexibility and simplicity of small satellites, how can swarms of small satellites be utilized to make up for a lack of capacity compared to larger satellites?*

RQ1 rises the issue on how to integrate satellites and other agents into one heterogeneous architecture. This is discussed in Chapters 3, 5, 4 and 7. *RQ2* addresses how a mission for satellite communication for remote areas can be defined. The concept *your mission, your satellite* while covering the objectives defined by the mission statement relates to this question. This is discussed in Chapters 2, 3, 6 and 7. Finally, *RQ3* discusses how the coverage can be increased by employing more satellites, and utilize the satellites in smarter, cost effective ways, as presented in Chapters 3, 4 and 7.

1.3.2 Satellite Mission Statement

The focus is to show that relaying of data directly from a sensor on sea or ice through a dedicated system based on small satellites is possible. The new space philosophy should enable the concept *your mission, your satellite(s)*. The satellite system will be part of a larger communication infrastructure, and data from sensor nodes may also be collected by other means, for example by recovering a node by ship or by uploading logged data from a node to Unmanned Aerial Vehicles (UAV).

A *Mission Statement* that stems from the research questions can be defined as follows:

> *In order to support new long-term scientific data collecting programs, enhanced satellite communication services are needed. This satellite communication system should be flexible and provide end users (scientists) easy access to their data, without having to retrieve data from the sensors manually. The communication system should have an overlapping life-time with the scientific missions it supports. In order to make the best use of the resources available (depending on the bit rate, power, link properties, timing and delay, and the amount of data), the payload should be re-configurable and adaptable in-flight.*

1.4 Thesis Outline

This first chapter briefly introduces the Arctic theme, new space and the new role space is expected to take in our future society. Further, Chapter 2 outlines the typical design methodology for space mission design, defines initial requirements for the space mission, and presents a literature study of relevant topics for the thesis. The following topics discuss the requirements in greater detail, and redefines requirements if needed.

Chapter 3 introduces a heterogeneous communication architecture, comprising satellites and UVs. Three different mission options for the network architecture are

discussed. In the next chapters, central topics of the architecture are more detailed. In Chapter 4 possible satellite orbits are discussed, and a selection is made and justified. The important part of the selected system architecture, the swarms of small satellites, is also discussed here. How to integrate all system components together into a common network is discussed in Chapter 5, where the selection of protocols for the network stack is presented. A reference scenario of the network is realized through simulations and emulations in order to investigate the system performance. The radio channel and link budget are discussed in Chapter 6. Implications following this discussion are fed back to a discussion about the system requirements. Chapter 7 walks through all components and parts needed to practically realize the satellite part of the defined architecture. Finally, Chapter 8 concludes the thesis, by addressing the proposed designs' compliance to system requirements, presenting contributions from the thesis and discussing its impact on further research.

Publications sourcing from this work are listed and included in Appendix A, while contributions in other papers (not included) are listed in Appendix B.

Chapter 2

System Design Process

This chapter first presents the system design methodology, and places the work into the system engineering context. Next, the process of deriving system requirements is presented, anchored in the context of the problem statement and research questions. Then the state-of art and similar solutions are investigated and analyzed in the context of the derived system requirements. Finally, the chapter concludes with identification of a service gap that requires new solutions.

2.1   Methodology

The work presented in this thesis is partially based on the method for space mission design, as described in the book "Space Mission Analysis and Design" [29, Chapter 1]. This process is iterative and works its way from a broad overview down to a more detailed level of specifications. However, this means that it most likely will be required to repeat some of the steps several times, even without completing all the steps first. When a mission concept is characterized the first time, the result and findings underway might lead to the need to revise mission objectives or re-define mission concepts before the process continues to a more detailed level.

Other mission design processes exist. One example, based on NASA design philosophy, can be found in a systems engineering PhD thesis by Asundi [30], where the described system engineering process is used for designing a CubeSat bus.

2.1.1   Mission Design Process and Life Cycle

There are several ways to illustrate the mission life cycle and the spacecraft or payload design cycle. In Figure 2.1, the project phases of a typical ESA space

project [29, 31] are shown. The work in this thesis could be considered most of phase 0 + parts of phases A and B.

| 0 Mission Analysis | A Feasibility | B Preliminary definition | C Detailed definition | D Production AIT | E Utilization | EOL Disposal |

Figure 2.1: ESA project phases

2.1.2   Steps in Mission Design

Figure 2.2 shows common steps in the design process, as adapted from [29, Chapter 1.1]. This thesis is not a complete design proposal and analysis for a space mission, so not all steps of the process are given the same weight and focus. The main work contributions fall within steps 1 and 2. The emphasis of this thesis is on the *use of small satellites as the space segment for an overall architecture for an integrated, heterogeneous network of networks*.

- Mission statement
- Mission requirements

1: Mission Objectives

- Mission concepts
- Mission architectures
System drivers

2: Mission Characterization

4: Define requirements

- System requirements
- Detailed design

3: Mission evaluation

Critical requirements
- Utility analysis
- Baseline concept
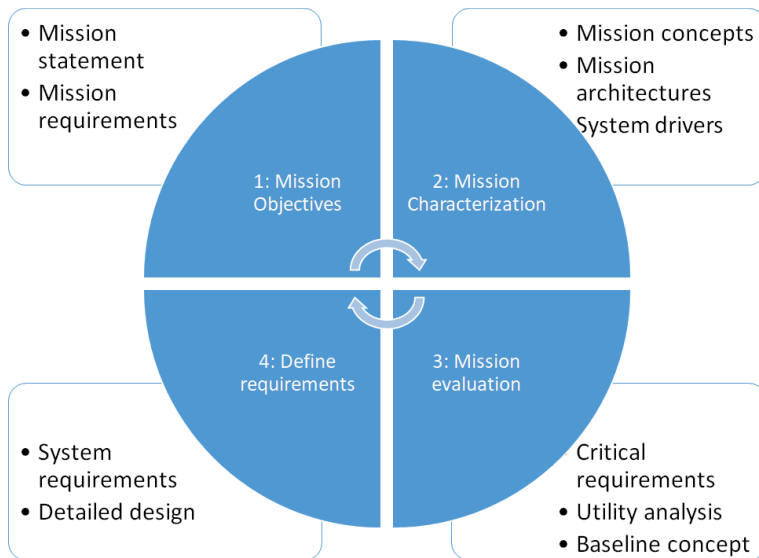
Figure 2.2: Space Mission Analysis and Design process. Adapted from Table 1-1 in [29, Chapter 1.1]

In this context, the word "mission" reflects the spacecraft mission, not to be confused with any scientific mission of the end user.

Following the methodology from [29], the first step is to *define the broad mission objectives and needs*. This is followed by *mission characterization*: Alternative mission concepts and architectures are defined, their respective system drivers

are identified and the concepts are characterized. The next step is to *evaluate the mission concepts* and evaluate the mission utility. This should lead to the *definition of mission requirements* that can serve as a baseline design. First, the system requirements are defined, then these requirements are allocated to the system elements.

By following this methodology, the user needs (Sections 2.2.1, 2.2.3) and requirements are broken down into technical requirements and specifications (Section 2.2.5) for the payload and the rest of the components in the mission architecture. This enables traceability as well as a focus on solving the problem, satisfying the user's needs.
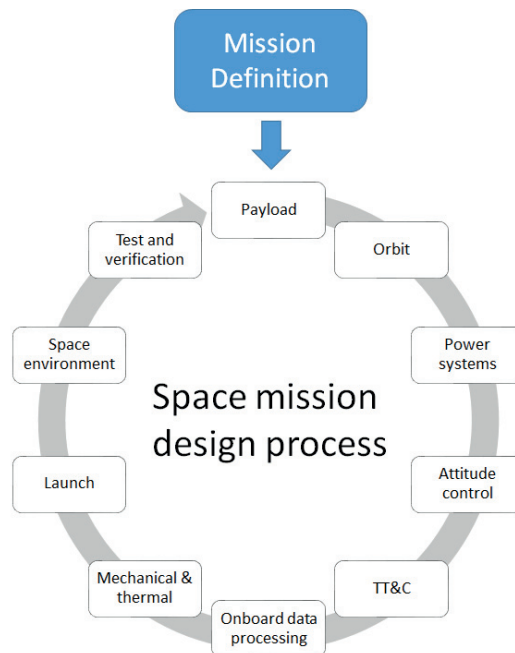
Figure 2.3: The circular, iterative design process for many of the mission elements and components.

The design process starts with an idea and a definition of a mission, which will require a *payload* to be flown on a spacecraft. The mission should be defined as detailed as possible, while keeping options open. Decisions and choices for one mission element or subsystem may cause other parts of the system to change. Several payloads and mission architectures can eventually fulfill the mission needs. All realistic alternatives should be explored, in order to reach the best possible solution. Knowledge acquired during the project steps will then be fed back into previous steps, and parts of the circle must be re-visited. Figure 2.3 illustrates

these interactions. The choices taken at any point in this process will influence the other steps, and continuous iteration is required.

2.1.3   Concepts and Definitions

This section introduces definitions and concepts used throughout the thesis, as listed in Table 2.1.

Table 2.1: Concepts and Definitions

Keyword	Description
Mission Objective	What the purpose of the mission is, and how it fulfills the user needs
Mission Concept	One way of designing the mission in order to fulfill the mission objective.
Mission Element	One of the components in a mission architecture. See definition in Table 2.2.
Mission Architecture	A combination of defined mission elements
Requirements	A set of definitions on what we want the mission to do, and how to do it. The mission requirements will then lead to system requirements. The system requirements then lead to requirements for each element of the mission architecture and will guide the detailed design and implementation processes.
Reviews	During various reviews of the mission design, or later in the process, the system design is presented and evaluated on how it fulfills the requirements.
Trade-off Study	The various mission concepts and options for each mission element must be evaluated against other concepts. Options often differ significantly in utility, cost and complexity. All of these values and variations must be taken into account when the final system design is proposed.

Each of the eight mission elements that will be part of any mission architecture are listed in Table 2.2, as defined in [29, Chapter 1.2], with references to corresponding sections where the topic is covered. All mission elements must be defined for each architecture. Design choices made for one element may cause the need for a design change in one or more of the other elements, as illustrated by Figure 2.3.

The final selection of, or design of, the elements presented in Table 2.2 will

Table 2.2: List of space mission elements

Element of Mission Architecture	Description	Section
Mission concept	The central element - what do we want to solve and achieve?	3.1
Subject	The elements on the ground that the space system interacts with. In our case, active subjects - the sensor nodes	2.2.3 7.2
Payload	The part of the space segment that interact with the subject. I.e, the communication payload in this case.	7.1.2
Spacecraft bus	The carrier of the payload	7.1.1
Launch system	How to put the spacecraft into orbit?	4.1.5
Orbit	Which orbit to use, how many orbital planes and how many satellites in each plane?	4.1.5
Ground system	How the spacecraft can downlink the aggregated sensor data from the nodes, and how this data is distributed to the end user	3.2
Mission operations	How the mission is controlled and performed	3.2

then follow from the set of defined mission (and later system-) requirements. These requirements stem from the mission objectives and enable the satisfaction and the achievement of the mission objectives. This will be presented in Table 8.2 in the Conclusions chapter.

2.2 Requirements Definition

Based on the problem statement, research questions and mission statement, the goal of this thesis is to define a realistic communication architecture, kept as general as possible. However, the Arctic ABC project will be used as an use case to define realistic requirements, stemming from realistic needs and challenges. A review of current and proposed communication systems, relevant for this use case, as well as other topics of related work is performed, and the identified gap will also be evaluated.

Thus, the flow to define the requirements goes from the *problem statement* ⇒ *research questions* and *mission objectives* ⇒ *mission requirements* and *constraints* ⇒ *system requirements* ⇒ *design proposal*.

This is a generic design methodology, based on [29]. The use case comes into play through the constraints it will set on the system design. Together with general mission requirements, the constraints will be used to derive system requirements. Figure 2.4 shows the process. A more detailed view of the requirements are listed in Table 2.4.
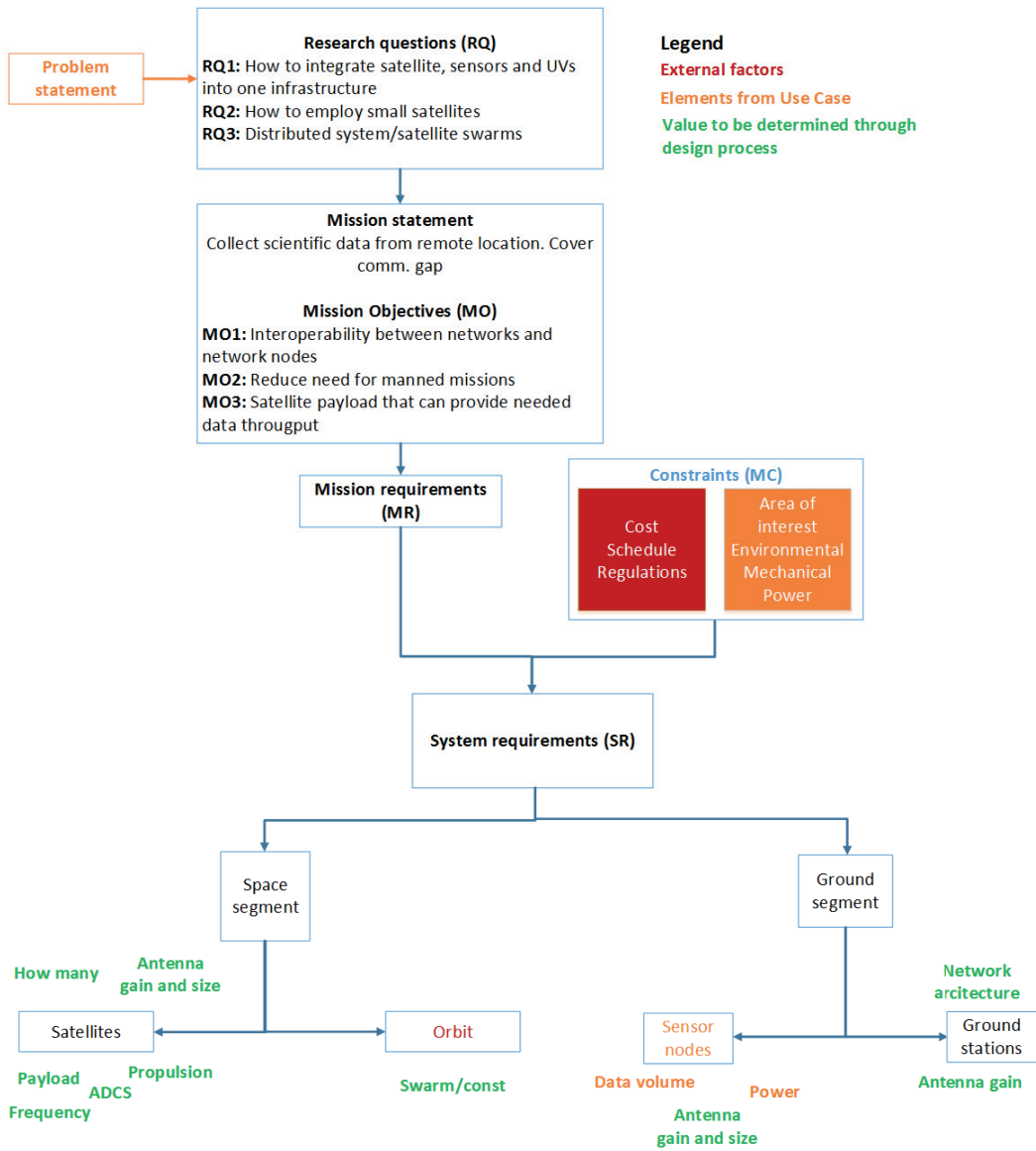
Figure 2.4: Workflow and requirement definition

2.2.1   Mission Objectives

From the *mission statement* defined in Section 1.3.2, we can identify the overall
objectives for the communication architecture required to meet the mission state-
ment, as listed in Table 2.3. These objectives are broad, and may be used to define
a multitude of missions. The mission objectives are stemming from, and linked to,
the research questions as indicated.

Table 2.3: Mission Objectives

ID	Mission Objective	Derived
MO-001	Set up a communication infrastructure that enables interoperability between various types of networks and network nodes in remote areas, for example, the Arctic.	RQ1
MO-002	Reduce or eliminate the need of manned expeditions, by enabling access to data from sensors in remote locations	RQ1 RQ2
MO-003	Define a satellite payload which provides the required data throughput in order to fulfill scientific mission needs	RQ2 RQ3

In addition to these objectives, other "secondary" objectives may also be part
of a satellite mission, or even the scientific mission. For university missions, the
educational aspect holds a value, as the mission and its outcome may contribute to
the education of master students or PhD-candidates. For a small satellite mission,
it can be an objective to prove new, more capable, and cheaper technology through
an in-orbit technology demonstration.

2.2.2   General System Requirements for the Space Mission

For some operations in remote areas, for example, in the Arctic or marine loca-
tions, the applications will require access to high data rate and near real-time data
transfer. However, many scientific applications do not have any low latency and
high bandwidth demands. In order to allow for a useful delivery of data, the data
rate, and allowed daily amount of data transmitted, are expected to be on the size
of several megabytes per sensor. Since the sensor nodes will be continuously log-
ging routine scientific data, we have no real-time demand. Therefore, continuous
coverage is not required. This can impact the number of satellites needed, as well
as the number of orbital planes needed. Even if real-time operation is not required,
it is beneficial that the round-trip delay between the sensor node and the end-user is
short; so Gateway (GW)s should be placed near the deployment area; preferably as
far north as possible. A tailored narrowband communications system can deliver
sensor and measurement data to the researchers in a much quicker and cheaper
manner compared to physically visiting one or more sensors to retrieve their data.

The network nodes may co-operate and communicate through radio links. This
can enable communication between sensor nodes in a cluster, between sensor

nodes and satellites, or between the sensor nodes and manned or unmanned vehicles. The system should then explore the use of open and standard protocols in order to integrate the various network members. In addition, the situation and network topology change over time; a vessel may enter or leave the area or a satellite will become visible, or descend past the horizon causing link loss. The network must always adapt itself and provide the best route to the data, depending on which links are available. In addition, the importance of the data must be considered. Alarms and disaster messages should be prioritized over other less critical sensor data. The less critical data should be transmitted when the network has capacity.

In order to fulfill requirements stemming from the scientific mission, the architecture must be interoperable, resilient, scalable, and adaptive. For the satellite mission, this leads to choices for the satellite orbit, frequency band and network stack. Some of the topics such as delay and throughput must be cared for within cost and energy constraints.

2.2.3   Requirements and Constraints from Use Case

To identify detailed and realistic requirements, a use case will be defined. The requirements form design constraints, as they define the framework of operation for the system.

The area of interest to cover for the satellite system will stem from the use case. There, the geographical area of interest is defined, together with which type of sensor nodes which are to be interfaced. The area of interest also impacts the available set of orbits that can be used.

Several research activities are motivated by the desire to know and learn more about the Arctic. To enable this, and extend scientific projects, the research is motivated by contributing to improving the infrastructure needed.

In addition to the ambitions of the CAMOS-initiative, Centre for Autonomous Marine Operations and Systems (AMOS) and the Arctic ABC-project have been used to derive use cases. The purpose of the resulting infrastructure is to provide a holistic communication infrastructure combining all available links and routes at a given time. This will relate to availability, network delay(s), available throughput and cost of employing the link. Several topics are investigated, such as the use of UAV and other Cyber-Physical Systems (CPS) [32, 33] as data mules, acoustic underwater communications and smart network management [34, 35]. The interaction between novel satellite systems and the other CPSs is instrumental to the use case.

Even if a satellite communication system and respective satellite payload can support different users by providing a two-way, narrowband, communication link, the selected use case is a sensor system that will be deployed in the Arctic area.

The purpose of the sensors is to enable long-term monitoring of environmental and biological parameters [27, 28, 36].

Generally, typical sensors such as floating or moored buoys and gliders[1], could be used for long-term environmental registrations. The sensors may monitor ice drift, biomass, weather, and polluting agents, for example, oil spills.

In addition to the requirements for the satellite communication system, environmental requirements for the terminals which are to be installed on the sensor nodes must be taken into consideration. Specifically, for a system to be deployed in the Arctic, the equipment must endure cold temperatures, there can be no moving or extruding parts. This is also related to wildlife; the polar bear is curious and there cannot be any edges or points for a bear to break or bite in order to prevent damage on equipment, and to prevent injuries to the animals.

Arctic ABC Sensor Nodes

The first phase of Arctic ABC plans to deploy two types of sensor nodes [36]. The nodes generate different amounts of data volume. Only a few bytes of data are generated every day by the first type of sensor. This is currently planned to be transmitted over Iridium SDB. The second type of sensor will generate 2 – 3 GB of data per year [36]. The next generation of this sensor node is expected to generate hundreds of GB per year. Figure 2.5 shows the concept of the second sensor node type, deployed on the ice. All antennas and equipment must be inside the sensor node housing.

The sensor nodes are expected to have a mass of several 10s' of kilogram and to be equipped with a battery pack of at least 2.5 kWh in the first configuration. The node design is flexible, and can be adapted to meet derived requirements from the proposed network architecture and communication system.

Sum-up of constraints from the use case:

- Cover Arctic area
- Yearly data volume: > 100 GB
- ABC sensor node mass: 10 – 200 kg
- ABC sensor node battery size: > 2.5 kWh
- The sensor node must be moveable by two persons
- Polar bear safe mechanical design
- No moving parts

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[1]Gliders are autonomous vehicles that are deployed in the deep oceans and follow waves and currents. A glider can monitor a multitude of parameters and usually sends data back to the end user through a satellite link.
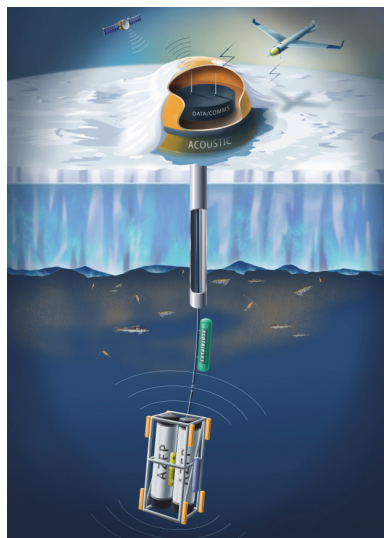
Figure 2.5: Illustration of a sensor node, deployed in the ice. Credits: AMOS/Bjarne Stenberg

2.2.4 Other Constraints

Both programmatic and other external factors enforce constraints on the system design process. Relevant examples here are that the cost of the system must be as low as possible, preferably allowing a scientific mission to set up its own infrastructure within its economical limits. This in turn impacts the schedule, as both the development, deployment and early operation of the architecture must be within the scope of the scientific project. Even further, constraints from regulatory bodies must be adhered to. Relevant in this case is frequency allocation and orbital life time.

2.2.5 Deriving Design System Requirements

Finally, the requirements and constraints discussed above are put together to form the mission- and system requirements for this particular system architecture. In further design phases, each subsystem will have to be assigned more detailed requirements. This is outside the scope of this thesis.

    The following requirements are derived through the flow presented in Figure 2.4. The mission requirements and constraints are listed in Table 2.4. The resulting initial assumptions for the system requirements are listed in Table 2.5. For both tables, the column "Section" list section(s) where a requirement is discussed. The column "Derived" links to parent requirements or topics.

Table 2.4: Overall mission requirements and constraints

ID	Requirement or Constraint	Impacts	Section	Derived
	Mission requirements (general)			
MR-001	The payload shall communicate with sensor nodes, collecting sensor data and transmitting commands from the SC&C to the sensor nodes	Architecture design Network stack	1.3	MO-001
MR-002	The payload shall aggregate the sensor data, store it onboard the satellite and transmit it to a gateway station which in turn forwards the sensor data to the end user at the SC&C	Payload design Data delivery	3.1.4	MO-002 MO-003
MR-003	The payload shall ensure that the sensor data from the nodes is received with the required BER at the SC&C.	Payload design Radio link design Data delivery, QoS	6.6 6.8	MO-003
MR-004	The payload shall assign communication resources to the sensor nodes, ensuring that all nodes are able to transfer their data.	Payload design Data delivery Multiple access	5.3	MO-003
MR-005	The payload shall prioritize which nodes are getting access to the communication resources, in case of special events. This includes expediting some aggregated messages with a higher priority than other messages.	Payload design Payload processing Data delivery, QoS	5.3 3.1.3	MO-003
MR-006	The communication system shall ensure interoperability between various agents, satellites, UVs and sensor nodes.	Network stack Payload design Payload processing	5.3	MO-001
MR-007	The communication architecture shall enable and allow dynamic networks, and dynamic allocation of network resources	Payload design Network stack	5.2 6.6	MO-001
	Constraints from usecase			
MC-001	The area of interest is the Arctic area (between Svalbard, north pole and Greenland)	Orbit	1.3 2.2.3	
MC-002	The system should support a data volume up to 200 GB/year	Number of satellites Bit rate	2.2.3	
MC-003	Sensor node battery pack is expected to be 2 – 4 kWh, < 1 kWh allocated to communication	Link budget Power budget	2.2.3	
MC-004	The sensor nodes shall be safe for wildlife (polar bears)	Antenna design	2.2.2	Env.
MC-005	The sensor node shall have no moving or extruding parts	Antenna design	2.2.3	MC-004 Env.
	Constraints from regulatory bodies			
MC-006	The satellite(s) shall de-orbit within 25 years after EOL	Orbital height	4.1.5 7.3.4	
MC-007	The satellite system should make use of the EESS frequencies	Frequencies	6.1	
	Programmatic constraints			
MC-008	The cost of the satellite system should be held low (less than $ 500 000 USD per satellite)	Payload design Satellite bus	1.3 7.4	
MC-009	Development, deployment and initial operation of the satellite system should be 3 – 7 years	Schedule	1.3	

Table 2.5: Initial System requirements

ID	Requirement or Constraint	Value	Impacts	Section	Derived
	System requirements				
SR-001	The communication system shall enable connectivity between various network nodes, under varying link conditions		Payload design Network stack	7.1.2 5.3	MR-001 MR-007
SR-002	Orbital type	Polar	Coverage	4.1.5	MC-001
SR-003	The ground terminal antenna shall not be moving		Antenna design	2.2.3 7.2	MC-005
SR-005	The satellite link shall have a adequate data rate to transmit the needed data volume	Up to 200 GB/year	Power budget Antenna design	6.8.3 7.3.2	MR-002 MC-002
SR-006	Responsiveness for a sensor node shall be less than	6 hours	Orbital planes Number of satellites	4.3.3 5.6	MC-001 SR-002
SR-007	The satellite bus shall be based on	CubeSat	Schedule Launch availability	7.1.1	MC-008 MC-009
	Requirements to be confirmed or revised during design iteration(s)				
SR-008	The satellite antenna gain shall be	1 – 10 dB		6.9	SR-005
SR-009	The sensor node antenna gain shall be	1 – 10 dB		6.9	SR-005 MC-005
SR-010	Number of satellites required	1 – 3		4.3.2 7.3.2	SR-006
SR-011	Satellite orbital height	450 – 800 km		4.1.5 7.3.4	MC-001 MC-006 SR-006
SR-012	Frequency band	UHF		6.1	MC-007
SR-013	The bitrate shall be	10 – 100 kbps		6.9 7.3.2	SR-005
SR-014	A suitable scheme for multiple access allowing nodes and satellites to register shall be defined			5.1	MR-002 MR-005 MR-007
SR-015	The network stack shall support interoperability with other agents	IoT protocols IP		5.1 5.3	MR-001 MR-004 MR-005 MR-006 MR-007 SR-001
SR-016	The BER should be less then	10^{-4}		6.8 6.6 6.7	MR-003 MR-005
SR-017	The payload shall adapt to changing link conditions	ACM/VCM		6.6	MR-007
SR-018	The satellite antenna shall point towards sensor nodes, within	10°	ADCS	6.8.3 7.1.3	SR-008 SR-013

The presented requirements are input to the first design iteration. Several of the system requirements (*SR-008 – SR-018*) will be defined or have to change due to findings in the first iteration of the design process. The final values of those requirements are presented in the conclusions in Chapter 8. Table 2.4 also maps to the section(s) where a given topic is discussed.

The fundamental task for the rest of the thesis is to define how the system will have to perform to meet the given requirements.

2.2.6   Alternative Use Cases

The scope of this thesis is motivated by providing support to ongoing and expected research and activities in the Arctic area. However, the results should be applicable for other uses as well. The Antarctica share some common features with the Arctic, the climate is cold and harsh, and infrastructure is generally lacking. Differences between Antarctica and the Arctic area are, for example, that Antarctica consists of an ice-covered continent, and that it extends much further north (to more than 70° Southern latitude) compared to parts of the Arctic area. This enables the use of GEO based communication systems for some applications.

By making use of the proposed satellite system in the Antarctic, it is possible to better make use of available resources. A reduction in the cost per Gigabyte of transmitted data will be expected (c.f Section 7.4).

The proposed satellite system will be able to provide temporal coverage at other parts of the globe too. However, as the system will be designed for polar operations, access to the system will be less frequent, unless more orbital planes are considered. Uses can be providing access to sensor systems and environmental monitoring in other remote areas, such as deserts, forests and mountain areas without coverage. Services for disaster management can also be envisioned.

If allowing more users to connect to the proposed system, the satellite power budgets (see Section 7.1.3) must be revised, to ensure that the satellites are operating within safe limits.

2.3   Related Work

The following sections discuss similar projects and findings from the literature and other available sources related to a selection of satellite communication systems, novel networking for small satellites, small-satellite constellations, and hybrid networks of satellites and UVs. First, a selection of existing and proposed satellite systems is discussed below. Projects with comparable scope; Arctic communication, comparable communication systems; communications for remote sensors,

and constellations and swarms of satellites are discussed. Most of the communication services are also presented in the included paper (Appendix A.1) [37], however, some updated information is added in this chapter.

2.3.1 Comparable Projects and Satellite Communication Solutions

Users of deployed equipment in remote areas outside of coverage from GEO-satellites can currently be grouped in three categories. The first is to let a sensor node be left alone for a period, and data is downloaded when the node is retrieved. The second, for transfer of small amounts of data and for two-way communication, Iridium dial-up service or Iridium Short Data Burst (SDB) (L-Band) can be used [21]. And the third, to track various objects or marine life ARGOS service can be used [20]. A tabulated overview with more details of the services discussed in this section can be found in Appendix C.

One-way Data Harvesting and Asset Tracking

Orbcomm and ARGOS are two examples of services for asset tracking. Satellite based reception of Automatic Identification System (AIS) and Automatic Dependent Surveillance – Broadcast (ADS-B) are other examples. AIS [38, 39] can be received in space in order to give global coverage for ship tracking. Experiments with spaceborne ADS-B for monitoring of air traffic have also been carried out with success [40]. These services (AIS, ADS-B) are originally designed to cover and operate within smaller geographical areas on or close to the Earth's surface. When the signals are received in space, they are therefore subject to system interference and packet collisions. In the AIS case, this means that probability of detection is very reduced in areas with dense traffic.

One example of using Iridium SDB for relaying wave spectrum data through a sensor buoy is described in [41]. Here, recorded and processed data is transmitted in near real-time to the end user. The amount of data transmitted is low, and the design life time of the buoy is limited to hours. The system under consideration in this thesis should support more data and a much longer operation.

Two-way Data Communication

The to-be-commissioned Iridium NeXT (the L-Band service) and VHF Data Exchange System (VDES) share some common features with what we want to accomplish. Iridium NeXT is to be put into service and VDES is currently under In-Orbit Demonstration (IOD) testing. Iridium NeXT is a general communication system offering a variety of services and data rates.

The current version of Iridium was tested through a series of measurement campaigns in the Arctic, and was found to experience quite long periods with loss of service [42]. These measurements may not be valid for Iridium NeXT, but indicate that outages should be expected.

VDES is mainly an aid for e-navigation services for shipping. However, there is an option in the standard to include messaging to and from users such as deployed sensors. The available resources to such services are not yet defined.

HumSAT [43, 44] is an educational initiative, also supported by European Space Agency (ESA), United Nations Office for Outer Space Affaires (UNOOSA), International Astronautical Federation (IAF) and various universities. One of the goals is to provide an educational service for radio amateurs and universities also involving the Global Educational Network for Satellite Operations (GENSO) ground station network initiative. The service is aiming for narrowband services starting at 1.2 kbps. It was initially intended as a service for developing countries, but it can have a wider impact if made operational and available. It is suggested as a component for relaying data from maritime sensors [44]. In order to be useful for an Arctic setting, the future satellite(s) must be launched into polar orbits.

The US Army also have demonstrated the use of small satellites to cover the communication gap where GEO is not reachable due to, for example, power limitations [45, 46]. The small satellites leverage lower cost, low development time and tailor made adaptability to a given scenario. The aim of this project, named "SMDC-ONE", is also to launch a small fleet of satellites for a single purpose.

A technical survey by National Oceanic and Atmospheric Administration (NOAA) from 2006 [47] describes their evaluation of excising satellite systems to meet their needs. Orbcomm and Globalstar are mentioned in the survey, but even if they provided networked data, the data throughput is very low, ranging from 100 bps - 9600 bps.

The two last years, several M2M and narrowband IoT services and constellations have been proposed and are in an early stage of planning or development. From the very limited information that exists about these projects, most of them seem to target the mass market, very cheap, small and low-rate sensors. Swarm Technologies, Sky and Space Global, Hiber Global, Astrocast, Helios Wire and OQ Technology can be named [48, 49]. Not all of these will cover the polar areas, and most of them aim to allow for very short messages per user per day only. See detailed features in Appendix C.

In Antarctica, several satellite systems provide communication, for example, for the research stations on the continent [50, 51]. There are a few fundamental differences between solutions employed there and a system for a sensor network. One fact is that since Antarctica is a solid continent, installations can be made more permanent, thus larger, and the bases have access to more power. Access

through Tracking and Data Relay Satellite System (TDRSS), Skynet and bundled Iridium channels can not be expected for independent sensor systems.

Broadband Initiatives

At present time there are no broadband services available for the Arctic area. A few planned systems might provide such services in the future. Examples are the Norwegian Arctic Highly Elliptical Orbit (HEO) initiative [52], or the mega constellations OneWeb and Starlink. The first launch of test satellites for the mega constellations is expected to happen in 2018, and ground infrastructure is under construction [53]. OneWeb will, among other services, offer Long-Term Evolution (LTE) services, used for mobile data communications. A gateway-terminal is needed to connect user equipment to the satellite constellation. The GW will share the network with local users, or to connect to the satellites directly. A contract with a telecom provider will be needed. Information available through OneWeb news archive indicates that they plan IoT services by 2022, without specifying any technical details. See more information and sources in Appendix C.

The Arctic HEO initiative aims to use two satellites in an HEO-constellation in order to provide continuous coverage over the Arctic area, by offering a service comparable to regular GEO systems, specifically, the Inmarsat service. Keplers KIPP [54] aims to demonstrate Ku-band services from a CubeSat, also stating the Arctic area as a region of interest.

In a report from 2018, the Norwegian Defense Research Establishment (FFI) presents an feasibility study of the use of small satellites to provide broadband in the Arctic [55] on X, Ku or Ka-bands. This is an interesting low-cost alternative for the HEO program, employing a limited number of smaller satellites to provide coverage to the Norwegian Arctic area. This reports also points to the challenge that these high frequencies requires antennas and power levels that represents a challenge for small nodes, leaning to that these high frequencies are impractical for sensor nodes use.

Broadband services are not highlighted in this work, except that the mega constellations are used as an example for an alternative mission architecture in Section 3.3. The broadband systems (including also a Ka-service from Iridium NeXT) use Ka or Ku band, which requires large terminals with tracking. They are therefore not practical to install on a sensor node.

2.3.2 New Space and Small Satellite Constellations

Another term for *new space* is *agile space*, as, for example, used by Los Alamos National Laboratory (LANL) [56] (2015). The agile philosophy should be used when doing missions where low cost is sought for, and high reliability is not

needed. This excludes, for example, manned space flight and critical systems for infrastructure. Especially, this philosophy seeks to reduce the non-recurring engineering costs, as they usually account for a huge share of the total mission cost, compared to the pure hardware and unit costs for small satellite systems. Requirements should be carefully defined, in order to fulfill the minimum acceptable mission, but not aim for the limit of what is possible. Careful consideration on definition of mission requirements may lead to significant savings. The level of risk accepted must also be considered as this can heavily affect the cost. Extra costs can be incurred when accepting (too) little risk, or savings can be gained when accepting high(er) risk. For the mission discussed in this thesis, the potential need for station keeping in a fixed constellation is one example of a requirement that should be careful considered in such a context. The authors of [56] also point out that by using Commercial Off-The-Shelf (COTS) components, the level of integration is also changed, which will lead to even more cost reduction. In addition, COTS components increase capability, as we are then able to use the most recent components. Even so, COTS components must be used carefully to not take on too high risks. A design philosophy allowing rapid design and deployment will then also help in qualifying COTS components for future missions, or, disqualify them for use in space. Radiation testing may be required, to qualify new components. Radiation damage due to Total Ionizing Dose (TID) is usually not a challenge for LEO missions, but handling Single Event Effect (SEE)s is required.

Over the last couple of years, much literature can be found about new concepts for formation flying, distributed satellite systems, and small satellite constellations. In their survey from 2018 [57], Liu and Zhang present recent research activities. Much focus is on formation flying of distributed satellite systems, where cost reduction, system performance, efficiency, and reliability improvement are highlighted. A distributed satellite system is a system where the utility is spread over a number of member satellites in a swarm or in a formation. No single satellite is destined to solve the whole mission objective on its own, and the mission should not fail due to failure of a single satellite either. The satellite system can then be changed or upgraded by changing configuration, removing or adding members to the group. The benefits of distributed systems are also discussed in [58], and in another study from 2018, the authors discuss methods of deploying satellite swarms in perpetuated orbits [59]. This study also recognizes the small amount of published material on how to launch and control swarms.

A general discussion on suitable orbits and constellations for small satellites is presented in [60], where the author compares properties of some relevant orbits. The various orbits discussed vary from one single plane, through streets-of-coverage and Walker patterns [29, Chapter 7.6]. This survey also points at the advantage of setting up a swarm consisting of several similar satellites, spreading

the work load, risk and enabling interchangeability amongst members. The author defines a swarm to be formation flying spacecrafts. How to design constellations for achieving global, zonal and regional coverage is discussed. The survey also exemplifies how to employ GEO satellites to relay TT&C between a small set of ground stations to a fleet of LEO satellites. From a systems engineering point of view, the survey points out the importance of being careful when defining a given figure of merit, for example, related to coverage. Which value is given as the minimum required elevation angle for a system will change the required number of satellites needed to reach the given figure of merit. This again, will influence the cost and operation.

How to launch and populate a swarm are discussed, by looking at launch availability with a focus on accessible orbits, mainly from US launch sites. The challenge of populating several orbital planes from one common launch by exploiting the nodal drift is described. This is also discussed in [58]. This is a slow process, and takes several months, and requires thrusters to lower and increase the orbital height.

Distributed satellite systems are also discussed in [61] (2018), where the authors define a swarm as a "free-flying distributed system"[2]. A key point is that complexity and capacity can be added to the system by adding more space crafts to the swarm. The survey mentions state-of-the-art within several fields, such as *cross links* (inter satellite links), either for transfer of data between a satellite and ground through other satellite systems such as TDRSS, Globalstar, Iridium or Orbcomm. The paper also discusses communication needs for IoT, where it is concluded that a good carrier sense-scheme for multiple access must be created. Some effective implementations, such as in the standard as IEEE 802.11 protocol, do not have a space equivalent.

Another version of distributed systems is presented in the paper from Surrey Satellite Technology Ltd (SSTL). They suggest using several spacecraft as a multi-mission science platform [62]. The mission and configuration should be justified by scientific drivers, and then the proposed swarm concept, consisting of larger mother satellites and daughters, can be adapted to a variety of mission needs. This is a different type of mission philosophy compared to a distributed system consisting of similar satellites only.

A topic discussed by several authors is how to deploy and manage a set of small satellites, which often have limited capabilities. In a recent study from 2018, NASA discusses various technologies for spacecraft propulsion [63]. The study focuses on co-operative satellites in swarms, and discusses different sets of tools to maintain the operation of the swarm. The study proposes use of thrusters to

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[2]This differs from the definition used in this thesis, where *free flying swarm* means satellites that flies without any station keeping.

enable small maneuvers so that the member satellites stay within a defined range from its reference. This study also points to the benefit of letting a mission consist of several smaller space crafts opposed to the traditional way of building one large satellite to carry out the mission alone. In addition to how to maintain the swarm or constellation, deployment strategies for the individual satellites are also discussed. A point worth mentioning, is that it is suggested that all (similar) satellites will experience the same drag over time, so the focus is on the relative motion due to the dispersion at deployment. It is also argued that disregarding how carefully the swarm or constellation is deployed, dispersion will happen eventually, and active measures are needed in order to maintain a specific formation.

The authors of [64] suggest using relative velocity stemming from spring separation for the initial setup of a formation. Maintaining the formation must be done actively in this case too.

From an operational perspective, the swarm or formation must be commissioned and maintained after launch. How Planet manages to do commissioning of several satellites at once is presented in [65]. They employ the agile aerospace philosophy and test driven design. There are experimental satellites in each flock of satellites, to serve as technology validation for future missions. The aim is that operations can be automatic from day one with no more than three operators, and even hands-off[3] at weekends and at nights.

NASA introduces a tool for planning and performing swarm station keeping (SODA - Swarm Orbital Dynamics Advisor). The use of this tool for different deployment strategies and swarm types (clusters of satellites) is discussed in [66].

Drag Management

In order to maintain the constellations or formations discussed above, two methods are generally considered; either thrusters or active drag management.

The use of differential drag management for operation and constellation management of Planet satellites is described in [67]. Orbit determination and station keeping are identified as difficult operational challenges. One solution aiding this, is a method for two-way UHF radio ranging by using three ground stations. This enables the operator to achieve better and quicker orbit estimates, compared to using only TLEs. Station keeping is performed by drag management, i.e. changing the along-track facing area of the satellite. Since the satellites have deployable solar panels, an up to 5:1 drag ratio change is possible to achieve. The paper shows an example on how to keep a fixed separation between the satellites by performing active drag maneuvers approximately once per week.

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[3]Meaning un-supervised operation

A more sophisticated way of doing drag management is proposed by the authors of [68]. A system consisting of active actuators can increase and decrease the effective drag area of a satellite, by deploying or retracting four perpendicular long tapes. The device can be mounted on a CubeSat. Suggested uses can be to passively stabilize flight, to perform station keeping by changing drag, or to initiate de-orbit after mission lifetime.

2.3.3   Hybrid and Integrated Systems with Satellites and UAVs

The past years UAVs have been proposed as enablers for ad-hoc and extended communication systems, for example, for disaster management or as a part of smart cities [69]. Hybrid networks, employing the relative proximity and short links to one or several UAVs and the regularity of a satellite link is also a central topic in this thesis, and recent publications about this topic can be found in literature.

In a paper from 2018, the use of UAVs to aid both terrestrial telecommunication coverage as well as satellite coverage is discussed [70]. Typical scenarios discussed are ad-hoc and extended communication services for disaster management. The authors propose an architecture where UAVs are used as a gateway between ground and satellites. Since the UAVs operate closer to the ground compared to satellites, they are able to provide higher data rates for smaller terminals. For resource allocation demand-assigned TDMA is proposed. This kind of coordinated access reduces randomness and losses due to collisions.

Other proposals to use UAVs for disaster management, search-and-rescue and how to increase their coverage range can be found in [71, 72]. These architectures do not include the satellite segment.

The paper [73] proposes an architecture making use of the combination of UAVs and satellite communication with Inmarsat. In addition, the paper discusses how to identify and transmit the most useful and important information over marginal links.

A very recent study from 2018 describes the integration between UAVs and satellites, with a focus on the network stack challenges [74]. This is a continuation from [75], where the use of Constrained Application Protocol (CoAP) and IP technologies is discussed. In [74], the combination of UAVs and GEO-stationary satellites are discussed, so even if that specific scenario is not applicable to the work in this thesis, the review of the network stack is of great interest. The use of UAVs as data mules in an IoT perspective are discussed in [76, 77], with some example implementations shown.

Other concepts, such as High Altitude Platform (HAP)s and High Altitude Pseudo Satellites (HAPS) are also getting some acknowledgment in the literature and industry. These are old concepts, but they are recently gaining some momen-

tum through projects such as Airbus with their Zephyr high-altitude UAV [78] that may be a concept that can be applied in some areas, together with ThalesAlenia Space Stratobus ariship [79] and Google Project Loon balloons [80]. Similar solutions can prove useful in an Arctic context [17]. However, these projects seem to target remote areas over populated areas, in order to provide under-served populations with network services. The relevance for the Arctic is uncertain, but the development needs to be followed.

Current and future capabilities and challenges for CubeSat based communications system are discussed in [81]. In [82], the authors discuss how various platforms (satellites in different orbits, balloons and drones) can cooperate in providing, for example, internet services.

2.3.4 Networking Technologies for Small Satellites

Several authors have discussed the use of new types of satellite networks, and how to adapt to, and manage the challenges from using well-known communication protocols, such as IP in satellite networks. Several of these papers are from the last few years. A general description of various potential services where satellite links for IoT services are given in [83]. The authors also acknowledge the lack of specific research and recognition of the potential this field have.

In a survey [84] from 2013, the authors discuss the use of satellite based sensor networks for a variety of services. These services are monitoring remote areas, emergency communications, communications for Supervisory Control And Data Acquisition (SCADA) systems, critical infrastructures and the environment. Traffic from this kind of services can be characterized as *event driven* and *periodic* (bursty) traffic. The survey suggests the use of a network stack consisting of IEEE 802.15.4 (or similar) lower layers, IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) for networking and ZigBee for higher layers. The use of DVB-RCS2 link types are discussed.

The services are classified by how high data range they require (low, medium and high rate), and how delay/disruptive tolerant the services are. Most relevant for our case, is the surveillance of remote areas (as well as environmental monitoring). These services are expected to fall within the low data rate regime (up to 50 kbps) and have medium to high tolerance for disruption. For such systems, sub GHz frequencies are recommended. TDMA is suggested as a suitable access scheme. The authors point out that disruptions due to outages (coverage gaps) must be handled.

An older survey from 2009, covers some of the same topics from a different perspective. The survey considers networking challenges for small satellites for Earth Observation (EO) and telecommunication applications [85]. The advantages

of distributed systems, and how swarm members can interact and be configured are discussed. A network stack based on common Internet protocols + the AX.25 HAM link layer protocol is proposed. Both TCP and AX.25 are found having some flaws and shortcomings in implementations, especially implementation of TCP in its original form is advised against. From this, we can take that a different protocol stack should be investigated.

Not only direct satellite-to-sensor or -user is discussed. In a paper [86] from 2015, the authors describe a technology demonstrator mission for investigating the use of UHF for communication in the Arctic areas. A CubeSat employed with communication systems for relaying data from the polar area through a GEO stationary satellite, over radio links supporting IP, is described. Relay of data through the TDRSS-system is discussed in [87]. This paper also discusses various coding and modulation schemes that can be used for satellite networks. The author recommends that if higher order modulations are used, modulations that require highly linear amplifiers should not be used, since they lead to power inefficiency in amplifiers.

The use of Internet and IoT-protocols is recently discussed by several authors. The authors from Pumkin suggest that this is very useful with respect to integration with other Internet connected systems, as well as integration of sub systems and components in the satellite [88]. Standard and open-source software stack can be run by COTS processors suitable and used for small satellite missions. NASA also promote the use of Consultative Committee for Space Data Systems (CCSDS) and other open standards to reduce mission cost [89]. The author of [90] argues that many customized protocols currently used, are inflexible, not scalable nor applicable in other missions. The use of IP protocols is promoted to allow for easier integration with surrounding systems. For adding even more flexibility to the radio hardware also, using SDR is suggested.

Using IoT-protocols as 6LoWPAN is also proposed in [91] (from 2013). In this paper, a sensor platform for wireless sensor systems (local clusters) with back-haul through satellite is discussed. This architecture is proposed for wireless sensors in remote areas, relaying data back via satellite. Recently, CoAP and 6LoWPAN for use in constrained maritime VHF networks have been investigated [92]. An overview of the use and implementation of 6LoWPAN is given in the whitepaper [93], underlining its strong relations to the IEEE 802.15.4 link layer[4].

A very recent study from 2018 [75] describes a possible network stack for M2M and satellites. The focus is on the network stack challenges. The use of CoAP and IP technologies is discussed, and DVB-RCS2 is proposed to be used as the link layer. In [74] adaptions to CoAP on how to transition from re-

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[4]6LoWPAN re-use, or generate, the IP-address based on the hardware address. This enables the header compression for 6LoWPAN packets.

quest/response operation to subscribe/publish operation for a small satellite scenario are discussed. The use of CoAP has also been suggested and evaluated for broad band satellite links in [94].

Since there currently is no standard solution integrating the communication between different vehicles in remote locations, systems are often based on specific hardware and applications. Many of them primarily consider messaging over point-to-point links, such as serial links and star networks where there is little need for "true" network protocols.

One example is the Goby Underwater Autonomy Project [95], which defines an autonomous architecture designed for marine robotics focusing on heterogeneous inter-vehicle communication. It was created as a replacement for MOOS [96], while also providing an interface to it. Goby is based on ZeroMQ [97] and supports serializing methods such as Google Protocol Buffers (Protobuf) [98] and Lightweight Communications and Marshalling (LCM) [99]. COSMOS [100] is another project that focuses on constrained scenarios, namely small satellites. It resorts to a network architecture that separates the space and ground segments, giving emphasis to space and employing the NACK-Oriented Reliable Multicast (NORM) Transport Protocol [101] and the LCM library. Similar to Goby or MOOS, the LSTS Toolchain [102], from the Underwater Systems and Technology Laboratory, also provides a suite of tools and protocols for autonomous vehicles, employing their own LCM protocol.

Despite past efforts in integrating heterogeneous resource-constrained devices, the presented solutions are focused on very specialized environments. For instance, even when resorting to standardized protocols, there is no integration with the Internet as we know it today. These proposed systems provide local networks that can be connected to the Internet, but not in a seamless way and disregarding other protocols and formats such as the Efficient XML Interchange (EXI) format [103].

Protocols such as LCM and ZeroMQ will make use of any form of transport layer, be it a serial link or a TCP/IP-like network. However, other solutions such as NORM rely on IP, which can be aligned with increasingly popular IoT. Similarly, another popular solution for constrained environments and the IoT is the CoAP, which provides its own link format [104]. It is designed for constrained nodes and networks, supporting secure connections as well as a number of extensions such as HTTP mapping [105] and group communication [106]. Moreover, by taking into consideration the developments of the IPv6 over Networks of Resource-constrained Nodes (6lo) working group [107], it can provide optimizations which are ideal for interconnecting heterogeneous networks. In fact, the use of standardized protocols, such 6LoWPAN for interconnecting devices with different capabilities, can also provide a solution for issues such as address attribution [108].

2.3.5   Summary

Table 2.6 list some key features; pros and cons, for the discussed satellite communication systems, while Figure 2.6 shows a quantitative assessment of these. The narrowband IoT constellations will provide connectivity to a vast number of users (sensor nodes), however the individual data rate will be very low, on the range of one kb per day. The mega-constellations and the Norwegian HEO proposal may require too large terminals to be usable for sensor nodes. Our proposal does not aim to connect a huge number of sensor nodes, but to fill the gap between the narrowband IoT and the large broadband systems.

Table 2.6: Key Features of Satellite Communication Systems

System Type	Pros	Cons
1: Narrowband IoT, including VDES	Support for many users Energy effective	Very small data rate per user Not continuous coverage Shared system, no own control Not operational
2: Mega constellations	High data rate Support for many users Continuous coverage	Not operational Too large terminals? Shared system, no own control
3: Iridium	Operational system Many available services	Costly and power hungry Shared system, no own control Poor performance in Arctic?
4: Norwegian HEO	Continuous coverage High data rate	Will require large terminals with antenna tracking High output power
5: Our proposal	Dedicated system, full control Adapted to user needs Shorter deployment time Make use of COTS and standards	Development effort Carry all risk and cost Standards not available for all components/functions

Evaluation of the Satellite Communication Systems

From the above sections, and the sum-up in Figure C.1 in Appendix C, it is not possible to identify any clear candidate that may be used for a communication architecture with the requirements listed in Section 2.2. None of the excising systems can provide a sufficient bit rate to fulfill requirement *SR-013* and at the same time fulfill coverage of the Arctic; requirements *SR-002, MC-001*. Iridium can achieve a data volume 75 GB per year if transmitting continuously, but that is still below requirement *MC-002*. Iridium NeXT may provide the data volume needed, but to a very high power cost (c.f. Appendix C.2), hence violating *MC-003*.

Of the proposed solutions, only OneWeb seem to both cover the Arctic and
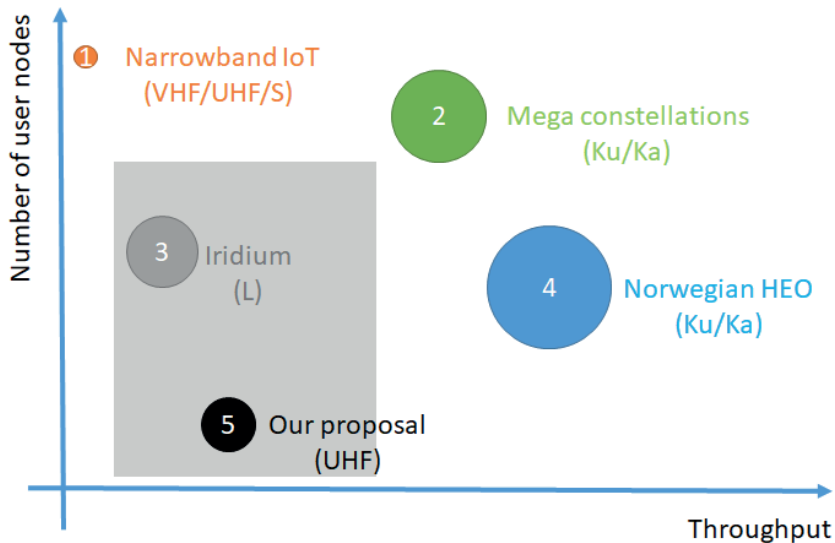
Figure 2.6: Qualitative assessment of expected properties for different classes of satellite communication systems. The sizes of the circles are related to the expected energy requirement for the user terminal. The service gap is illustrated by the gray box.

also indicate that they support small terminals. However, specifications for these terminals, such as size, data rates and power consumption, are not available information. Therefore a clear conclusion can not be drawn. Starlink may be one other option, but initial phases (from 2020) will not cover the Arctic. The IoT proposals are of various make, some of them have entered a testing phase. However, all of them fail to meet requirements for bit rate and data volume.

New Space and Constellations

The benefit of applying the agile space philosophy, and thus design space missions based on distributed systems, is supported by several authors [57, 58, 60, 61].

As pointed out in [56, 60], system requirements and definitions of figures-of-merit should be carefully evaluated and considered, in order not to set requirements that could, for example, drive up the project cost inadvertently. In our architecture proposal, the choice weather or not to require multiple satellites to be deployed in a fixed constellation needing thrusters, can be said to be such an element. Thrusters will enable station keeping and better spacing of the spacecrafts. The satellites should then never overlap, and an increase of the available network throughput is

expected. However, station keeping with thrusters will heavily drive the unit cost of each satellite, in addition to influencing orbit knowledge requirements.

Initial population of the constellation can be achieved by adjusting the deployment spring and release direction [64]. However, dispersion and separation of the member satellites in a constellation will happen regardless of how careful the initial deployment is made [63]. The same authors also argue that similar satellites will, on average, experience similar drag. From this it follows that either measures must be taken to perform station keeping operations, or the mission must accept the variability in coverage due to the dynamics of the swarm.

For station keeping, drag management can be useful, but it requires a very good orbit estimation [67]. The simplest way of performing drag management operations is to change the cross-section of the satellite in the direction of the velocity vector by rotating the satellite. This is a simpler design than using a separate device as [68].

Network Topics

When selecting the appropriate protocol stack for new systems, interoperability, standardization, user base, active use and development must be considered, in addition to quantitative parameters as network efficiency, throughput, load capacity and so on.

Several works promote the use of open technologies and common standards to ensure interoperability, as well as using SDR for flexibility [89, 90, 88]. However, the protocols and standards chosen must be carefully evaluated to ensure that they fit the purpose. Common protocols as TCP and AX.25 have some short-comings and are not recommended [85]. 6LoWPAN and CoAP seem to be chosen by many [75, 74]. The lack of a suitable, non-proprietary, link-layer protocol is addressed in [61, 83]. An adaption of the DVB-*S2 standard, currently used for Ku/Ka-bands, may be an alternative for the link layer [74, 83].

High-order modulations requiring linear amplifiers should be avoided due to complexity and poor power efficiency in transmitters [87].

Interaction with UVs

Most discussed scenarios where UAVs are used, are either to make use of a communication link to a GEO satellite, or using UAVs to extend coverage from terrestrial systems, or act as a relay for a terrestrial system [70, 71, 72, 73]. Tighter co-operation between satellites and UVs, integrated into one common architecture, is to the best of the authors knowledge, not described.

The use of IoT-protocols as CoAP for UAV operations are supported by very recent work, as [75, 74].

2.4 Tools and Equipment

This section presents the set of tools that has been used during this work. This encompasses both standard simulating tools, and also toolchains that have been developed for specific purposes. A hardware testbed has also been developed. The development of the tools has been a cooperation with Associate Professor David Palma at the Department of Information Security and Communication Technology at NTNU and PhD candidate Artur Zolich at the Department of Engineering Cybernetics at NTNU.

2.4.1 Satellite System Simulators

To simulate satellite orbits and pass visibility between sensor nodes and satellites, two tools have been used, the Systems Toolkit (STK) from Analytical Graphics (AGI) [109] and a toolchain based on open-source libraries for the Python framework.

Systems Tool Kit

STK is a powerful graphical simulation platform capable of simulating a wide set of vehicles and interactions between them. Satellites, Unmanned Aerial Vehicles (UAV)s, ships, airplanes, ground vehicles and ground stations are typical members of a scenario. The objects can be assigned different properties. For example, radio communication equipment can be attached to them. Then the visibility between the objects and the properties of radio links can be evaluated. In this work, STK has been used to visualize satellite orbits and satellite swarms. Coverage and radio link properties have been evaluated.

Python Toolchain

A Python toolchain based on `pyephem` library [110] for astronomical calculations and `matplotlib` [111] for plotting has been developed and used for several orbit simulations, especially the satellite swarms described in Chapter 4. This has also been used in the implementation of the Layer-3 forward-looking routing introduced in Section 5.1.6.

2.4.2 Network Emulator

A network emulator was developed to realistically evaluate the feasibility of using a freely-drifting swarm of small-satellite nodes as part of a sensor network. The emulation made use of real network protocols. This was combined with the results

from the Python simulator, creating a hybrid testbed, combining both simulation and emulation. See further description in Section 5.4.

2.4.3   Configurable Testbed

In order to conduct experiments based on the architecture proposed in Section 3.1, allowing integration of several networks, a dedicated hardware testbed, based on Commercial Off-The-Shelf (COTS) equipment, has been developed. The testbed consists of four nodes, built into weatherproof, rugged boxes, with a set of two radio systems. In the current version, a short-range, high capacity WiFi link and long-range, single channel VHF radio are used. Each node is a complete system with a computer and a battery lifetime of several hours. These nodes can be deployed, for example, onboard a research vessel. The testbed nodes can be used to measure and evaluate radio link performance and network behavior by using different protocols (Figure 2.7).

Figure 2.7: Sea trial of the testbed nodes – communication sea-to-shore. Courtesy of Artur Zolich.

The first evaluation in a sea trial focused on the cooperation between an UAV and a research vessel [77]. However, the testbed nodes have been designed in order to be able to cooperate with a growing number of assets available for the research activities in the Trondheim area. Some of these assets include fixed-wing UAVs [112], Light Autonomous Underwater Vehicles, a motorboat based Unmanned Surface Vehicles (USV) and a research vessel [113]. The proposed architecture and testbed also provides feedback to the Arctic ABC-project development [28, 27]. The architecture used by this project is depicted by Figure 2.8, which resembles the proposed integrated networking scheme. This architecture

defines a system consisting of one or a few sensor nodes, and gateway nodes based on UAV and satellite nodes, which complement each other to enhance data collection in the Arctic.
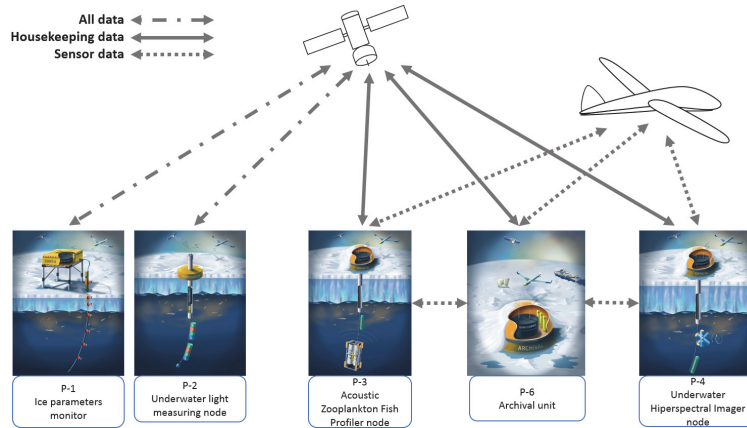
Figure 2.8: Arctic ABC data collection. Courtesy of Artur Zolich.

2.5 Chapter Conclusions

In this chapter a system engineering methodology, suitable to resolve the research questions in Section 1.3.1, is presented in Section 2.1. This is based upon well-known principles as defined in [29]. This thesis will cover parts of the first project phases, and perform the first iteration of the system design. An important part of the system design process is the requirements definition, and the initial requirements are presented in Section 2.2. The process of defining the requirements, tracing back to the research questions, is shown. A review of existing and proposed satellite communication systems, as well as network technologies and other heterogeneous architectures comprising of sensor systems, UVs and satellites is presented in Section 2.3.1.

From evaluations in Section 2.3.5, it is found that none of the current communication systems, nor any of the proposed, seem to be able to fill the communication gap identified, while taking into account the requirements defined for a mission supporting sensor networks in, for example, the Arctic area. Existing systems thus fail to meet *RQ1*, and this motivates further research into new satellite systems.

A complete solution on which network stack needed for answering *RQ1* is not found, and papers describing interactions between UVs and satellites and their co-operation are limited to range extending or other limited scenarios. By this, we

state that an overview-approach towards a fully general communication architecture, consisting of satellites and other network nodes, to cover the Arctic communication gap is needed. Even though our approach is focusing on Arctic topics, most of the challenges with respect to network technologies and co-operation between satellites and UV can be generalized to be used in a multitude of scenarios in remote areas.

The next chapter will follow up this, by defining a communication architecture that can support the defined set requirements. Further, Chapters 4, 5 and 6 treat different parts of this architecture in more detail; discussing satellite orbits, the network stack and the radio channel, respectively. Chapter 7 puts the parts together and the satellite system design is presented.

Chapter 3

Proposed System Architecture

To solve the research and engineering challenges identified through the research questions presented in Section 1.3.1, as well as the needs of the mission requirements identified in Section 2.2, a *communication architecture* is proposed in this chapter. Topics for the network design related to this architecture are further discussed. The system design process presented in Chapter 2 is applied. The communication architecture will encompass a *space mission architecture*, which in turn should be as generic as possible, so it can be applied as a solution for several individual missions.

In this chapter, three space mission architecture are presented, and one of them is selected for further study and design. The chosen space mission architecture must be integrated with the network architecture presented in Section 3.1.

3.1   System Architecture and Definitions

As described in Chapter 1, the lack of infrastructure in maritime and Arctic regions, makes operations such as retrieving scientific data complicated and expensive. It is common that manned missions must collect data from remote sensors. To some extent, existing satellite links can be used, but as shown in Section 2.5, none of the existing or planned communication systems seem adequate. All are subject to challenges with respect to availability, energy and link capacity.

The proposed architecture will be an integrated network-of-networks, consisting of terrestrial links between sensor nodes, satellite links and links between sensors and UV. These communication technologies will not always be available since satellite links are intermittent and UV links may be available only during special data retrieval missions. At a given point in time, individual nodes in the network should utilize the available links best suited to transmit their data.
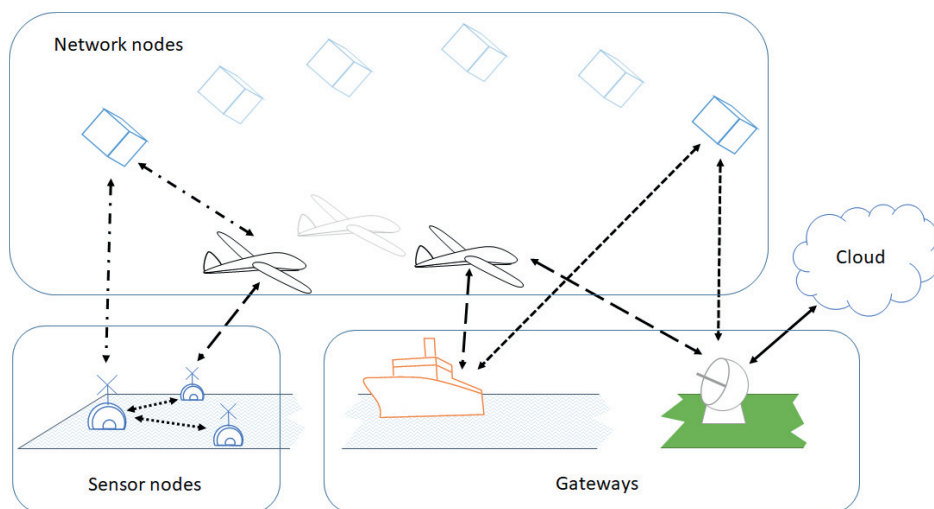
Figure 3.1: Co-existence of heterogeneous communications and vehicles.

Maritime operations can be quite diversified and encompass a multitude of distinct scenarios. For instance, both dense and sparse deployments of nodes for environmental monitoring may be envisaged. An example of a heterogeneous deployment is presented in Figure 3.1. This figure shows how nodes with different capabilities interact, and defines a network architecture hierarchy combining a multitude of data sources, communication nodes, networks and users. It is a heterogeneous distributed networked system, comprising several types of data sources - the *sensor nodes*. These can be surface nodes, floating and drifting nodes, submerged nodes and flying nodes - all named *network nodes*. The nodes can be interconnected in various ways and for various purposes. Depending on the scenario, nodes such as UAVs and ships, can have more than one of the three roles. All traffic will be coordinated through one or several *gateways* depending on the type of network node.

The aim of this work is to define a state-of-the-art architecture for networking and data exchange in remote locations, and the work has been presented in the included paper (Appendix A.5) [32]. Small satellites and UVs (Aerial, Surface, or Underwater) should cooperate in order to make data retrieval processes more efficient and globally available. Even if a specific satellite mission is assumed to serve only one or a couple of end users, the presented architecture and suggested technologies make use of generic and standardized equipment and communication protocols *when possible* and meaningful. This will ease integration with other systems as well as deployment of similar systems and satellite missions later on.

3.1.1 Reference Scenario

A reference scenario with multiple agents consists of sensor nodes, unmanned vehicles, satellite nodes and gateways (i.e. fixed or mobile stations capable of communication with UVs or satellites). One or more Science Command and Control (SC&C)-centers will also be part of this reference scenario, responsible for coordinating operations. This entity is not depicted in Figure 3.1 as it will likely be connected to existing infrastructure, communicating directly with gateway stations. In addition to this, and not shown on the figure, the satellite itself will be controlled through a satellite operation center. This will be responsible for satellite operation and TT&C. This can be a part of the Gateway (GW), or be at another location remotely controlling the satellite.

Figure 3.1 shows one gateway station that represents the edge of available communication infrastructure. In a deployed network, there will usually be several gateways with various purposes adapted to the vehicle(s) they serve. These will be interconnected using the Internet and will provide a wireless link to the various nodes, for example, satellites and UVs. Additionally, in order to reduce the access time of data from sensor nodes, the choice of which gateways to use or their placement should be tailored and adapted to the scenario.

Small satellites independently deployed or in swarms (see Chapter 4), are seen as a potential solution for improving communications in maritime environments, where infrastructure currently is lacking. The potential gain of using such swarms is further discussed in [114, 115] and evaluated in [116, 117]. Freely drifting swarms will allow for more frequent visits for nodes within a target area. However, the duration of the coverage period is still limited. The mean time without coverage is a function of the number of satellites in the swarm.

UVs traveling near the sensor nodes can also be used to collect data, as well as to deliver configuration messages. This approach uses not only autonomous unmanned vehicles for planned visits to sensor nodes [118, 119], but includes also opportunistic interactions with other vehicles (e.g. transport ships) to increase connectivity. Even though unmanned vehicles can act as relay nodes, when sufficiently close to an infrastructure, their primary goal will be to act as data mules, being responsible for gathering sensor data and delivering it to supporting infrastructures [113, 118, 119, 120, 121].

Parts of such heterogeneous network integrating terrestrial links and UAVs and/or satellite are described in [35, 34, 33], using small satellites swarms as a feasible alternative for remote maritime operations [114, 115].

Aiming at investigating the performance of network protocols, sensor nodes, swarms of small satellites and corresponding gateways, an emulation tool has also been proposed [116]. In [77], a comparison between emulation of a scenario and experimental results from a sea trail is presented.

3.1.2   Capabilities of Various Vehicles

Cooperation between satellites and unmanned vehicles is a great synergy in order to enrich data-transfer options, as well as overall coverage. Various types of unmanned vehicles and satellites are characterized by different capabilities. There are three main categories of autonomous vehicles that can perform advanced operations in the maritime environment, in addition to satellites, as listed in Table 3.1. UAVs, USVs, also referred to as Autonomous Surface Vehicles (ASV), and Autonomous Underwater Vehicles (AUV). All vehicles can be equipped with communication assets that allow fast data transfer between them and network nodes in their proximity.

UAVs can cover significant distances in a short time thanks to their speed in the air, while being able to fly directly to the area of interest. However, their endurance is limited, usually from some hours to a few days. On the other hand, some types of USVs, powered by renewable energy, can travel a virtually unlimited period and cover great distances. However, their speed will usually be significantly lower when compared to flying vehicles. Last but not least AUVs may be the slowest among all mentioned vehicles. These however, can reach nodes unavailable to other types of vehicles, e.g. under the ice layer.

All vehicles require a certain level of logistics related to their deployment. This can vary from an update of instructions sent to the vehicle, up to a complex operation involving a number of crew and complex arrangements, e.g. a vessel cruise, or an airspace reservation. In all cases, data collection or data-muling is exposed to a variety of uncertainties. Available data-collection using UV depends on multiple factors such as vehicle and crew readiness, economic viability, regulatory framework, traffic in the area and even weather conditions.

Satellite links seem to fill these gaps when the data mules cannot be used. These links are usually slower and only available for shorter periods compared to communication links provided by UVs. However, they are predictable as availability of satellite and their data transfer capabilities are known well in advance. In the end, a network based on a synergy of satellite and unmanned vehicle nodes presents a user with multitude of possible ways to download its data from remote locations. In order to further enhance the network, especially reducing the round trip delay, inter-satellite links can be used to relay data between satellites in order to reach a gateway quicker. In this proposed architecture, inter-satellite links are not included due to the increase in the requirements for the on-board power system and to the attitude control system. This increases both complexity and cost of the satellite platform. In addition, with only a few satellites serving the system, inter-satellite links will be scarce and cannot be used. In a denser constellation or swarm of satellites, inter-satellite links can be of use.

Table 3.1: Overview of capabilities of various Unmanned Vehicles

	UAV		AUV			USV		
	Smaller (< 25 kg)	Larger (>25 kg)	Light AUV	AUV	Gliders	Renew. Energy	Boats	Vessels
Small-scale (0-10 km)	✓		✓	✓			✓	
Medium-scale (10-100 km)		✓		✓	✓	✓	✓	
Large-scale (100-1000 km)		✓			✓	✓		✓
Global-scale (>1000 km)		✓			✓	✓		✓

3.1.3 Compliance with Mission and System Requirements

The proposed system shall meet several requirements as defined in Section 2.2. First, it should *enable interoperability* between different communication technologies, which will be useful to *mitigate network partitioning*. In particular, it will provide multiple degrees of communication coverage and performance.

Maritime operations are characterized by intermittent connectivity, therefore the system must be *robust and resilient* to these conditions. This also means that delays due to outages can be accepted in this system, if the data can be held and re-transmitted later. Loss of data is not desirable. The system shall include *delay/disruptive tolerant semantics* in the network-substrate, allowing the usage of distributed systems similar to the ones used across the Internet. This means that message acknowledgments must be employed, either on a link-to-link level or on a higher level (end-to-end message transfer verification). The level on which this functionality should be implemented depends on chosen (higher-level) protocols, requirements for timeliness[1] and complexity in implementation.

Communication shall be *accessible to all nodes in a scalable fashion*. Due to the heterogeneity of services and actors, the system shall also provide *distinct levels of communication quality* according to the priority assigned to different data sources.

Although satellite link availability is known well in advance, the use of UVs gives some additional constraints on system operation. Their use is prone to additional cost and can be jeopardized by weather conditions, or service-provider availability. For that reason, their use must be properly planned, and the system

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[1]Link-to-link verification may reduce the time for end-to-end message verification if communication losses are handled at an early stage

shall allow the user to *select or automatically select, the most efficient data-route* based on a predefined metric, e.g. cost-per-bit or delay sensitivity.

The overall solution shall be *extensible in alignment with standards and protocols* developed for the Internet. This will allow maintaining an up-to-date, stable and secure system for current and future developments in maritime operations.

3.1.4 Proposed Architecture

The architecture must include hierarchical roles for different nodes, ensuring a scalable and organized structure, presented schematically in Figure 3.2.
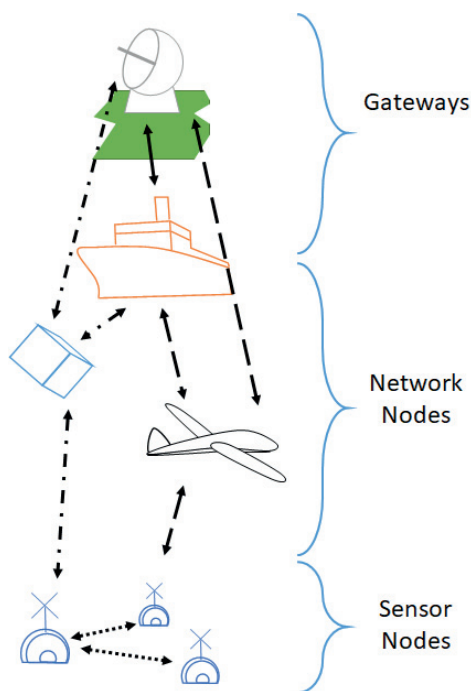
Figure 3.2: Top-level view of the Network Architecture. Some of the vehicles can have multiple roles in different configurations of the network.

This architecture consists of three main classes of nodes with distinct roles[2]: **Gateway (GW)**, **Network node (NWN)**, and **Sensor node (SN)**. An integrated solution for networking in remote locations must consider multiple communication technologies and interoperable interaction between such nodes. In order to meet

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[2]Note that the terminology used here is consistent from a satellite communication point of view. The definitions may differ with respect to for example a network perspective, such as in [32].

the proposed objectives and requirements, chosen components and their configuration should comply with existing standards and be customizable. Additionally, the architecture must support dynamic changes in its topology due to the variability of conditions in, for instance, maritime scenarios (e.g. intermittent links and mobility).

Gateways have access to a vast amount of resources, such as a large vessel or nodes that are part of an infrastructure. Additionally, Gateways will be permanently connected to the Internet, which allows them to keep a synchronized perspective of the network, regardless of the distance between them.

Gateways could also be equipped with several communication interfaces, using different technologies, enabling higher levels of connectivity with different vehicles. They will be the main interaction points for unmanned vehicles and satellite nodes, which are Network nodes, and will be responsible for interfacing the various NWNs and providing connectivity to the SC&C center.

Gateways can be collocated with the SC&C-center, however the SC&C may also operate from elsewhere, provided that it has connectivity with all GWs. The SC&C must perform all the required planning and configuration decisions that will improve the system's performance and resource usage. Storage of the collected data must also be handled by the SC&C, therefore GWs will not only serve as a forwarding point for the SC&C decisions, but also as a back-haul for all the gathered data.

Network nodes are manned and unmanned vehicles that are integral components of the proposed network architecture. These will link the GWs and any other nodes in the network. The focus for the proposed architecture is to exploit different networking options for reaching isolated nodes in remote locations. For example, unmanned vehicles such as UAVs can be considered as on-demand NWNs for high bit rate transfers, while small satellites can be used to periodically retrieve or deliver smaller amounts of data (e.g. status information).

UAV network nodes can be used to carry or relay data from and to the SC&C center. This should be enabled by at least two different communication technologies, one focused on high bit rates and another on achieving longer coverage ranges for relaying data. Such heterogeneity will allow NWNs to act as data mules for delay tolerant data, or simply as relays for critical data.

Satellites can be an important resource for reaching more isolated sensor nodes, reducing the need for data collection by vehicles. LEO satellites are typically characterized by periodic coverage, providing approximately 10 minutes of link access

every 90 minutes[3]. However, this may be improved by resorting to constellations or swarms of small satellites, combined with well-designed placement of the gateways. This would allow a satellite to downlink received data and requests to one gateway, which in turn forwards them to the other station so that it can intercept newly arriving satellites.

The NWNs, satellites or vehicles, will not only collect data from the sensors, but also deliver any data that may have been requested by the sensor nodes. Additionally, configuration messages from the SC&C center to the SNs will also be sent throughout the network of nodes. Vehicles should complement each other, leveraging on their distinct hardware characteristics and specific behaviors or conditions as described in Section 3.1.2. Since NWNs can be hosted on various platforms, the use of standardized protocols will be important for ensuring the interoperability between them, resorting to mechanisms such as Route Advertisements or common addressing based on IPv6.

On some occasions, it is possible for a NWN to act as a relay node, forwarding all received packets directly to an infrastructure node. An example is a satellite passing over the sensor field while at the same time being in contact with a gateway. However, since a direct link to the gateway infrastructure may be nonexistent or limited in resources (e.g. a long-range low bit rate link is perhaps not be able to relay all the collected data in real-time), NWNs must be able to act as data mules, collecting all possible data and delivering it later when closer to the infrastructure.

Sensor nodes are envisaged as quasi-static nodes that aim at collecting scientific data from a given area, though mobile nodes can exist. This area can be covered by a single node or by a cluster, where nodes may be able to communicate with each other.

The sensor nodes can be deployed in different locations. They will be the main source of data that should be forwarded towards the SC&C. These nodes are typically constrained, with limited energy, processing power and even communication capabilities. However, communication limitations typically result from the lack of energy availability, which can be mitigated by diligently combining different radios. For example, low-power and low bit rate radios can be used locally between sensor nodes, or for activating more resource-demanding radios when a NWN is nearby. The proximity between sensor nodes may allow multi-hop routing so that data can be forwarded to nodes directly connected to a gateway. This can, for example, either result from routing messages sent by a NWN acting as a router, or from Software-Defined Networking (SDN) flows installed by the SC&C.

The design of the satellite links in this architecture is one of the main efforts of this thesis, and the following chapters are covering this.

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[3]Given a node or ground station placement so the satellite can be seen for every pass.

3.2   Operational Considerations - Data Delivery and Data Flows

In general, two types of data must be transmitted between the satellite and the sensor nodes. One type of traffic is the user-data and/or commands corresponding to higher-level operations of the system. The second type of traffic is necessary signaling data that must be allowed, for example, to allocate channel resources and coordinate data between sensor nodes and the satellite.

Definition 1 *Auxiliary traffic needed to allocate or change resources (frequency, modulation, time-slots and more) is called* **signaling**. *Signaling also comprises, "non-user data"-traffic necessary for higher-level operation.*

Figure 3.3 shows a simplified view of the dataflow in an operational context. Sensor data (-··-) will be collected by the sensor nodes (SN), stored in memory awaiting a satellite pass and then transmitted to the satellite (NWN). The satellite will store the data in its memory before transmission to the ground station (GW) during a pass. This system should act as a kind of delay-tolerant network. From the ground station, the data for various end users will be distributed over the Internet or other relevant networks according to agreements and concurrent system integration.

In addition to the sensor data, commands to the sensor nodes (···) will be transmitted from the SC&C, through the gateway and the satellite. This data will be delivered to the SC&C, represented by the end-user entity in the figure. Resource allocation and other signaling such as message verification, ACKnowlegde (ACK)/Negative ACKnowlegde (NACK)/Automatic Repeat reQuest (ARQ) will be resolved on a link-to-link basis (– – –). The satellite payload will therefore decode all messages before they are stored and then forwarded on the downlink radio system. TT&C may be allocated to the satellite bus radio system (- - -), signaling, sensor node data and sensor node command links can be allocated to the payload radios. Also see Section 7.1.2.

In order to best exploit the limited bandwidth resources, sensor nodes must compress and code the data for transmission in the best way. It is a trade-off between (the need for) data processing in the sensor nodes vs. end-user data processing. Processing will reduce/condense the amount of data and hence save bandwidth capacity. With the availability of efficient but low-power processors today, as much processing as possible should be performed by the sensor node in order to reduce the data volume to transmit. However, original data should be re-constructable, or be available on request, in case the on-board processing malfunctions.
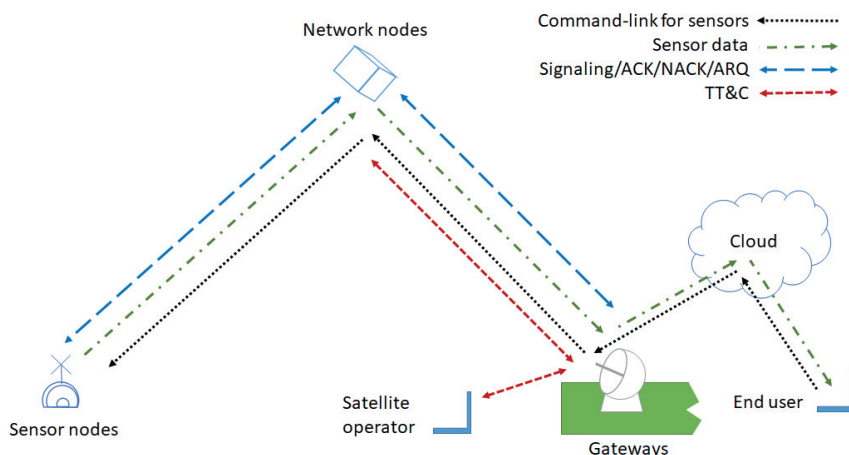
Figure 3.3: Model of the dataflow in the system. Sensor data flows from the sensor nodes to the end users (– $\cdot$ –). Control-messages flow from the end user to the nodes ($\cdots$). These messages are relayed through the satellite. Each link has its own signaling channel (– – –) that handles message verification and so on. Also, the satellite operator uses the TT&C-link (- - -) to operate the satellite.

The degree of autonomy in the network is also open for discussion. The network architecture should serve a number of various sensor systems and end-users. Therefore, a fully operable communication system should be autonomous with respect to when and how aggregated data from sensor nodes is delivered to the end users. It should however be possible to pre-program the scheduling and sequencing if special needs arise, such as alarm events. A simpler scenario is considered in this thesis, where a request-response behavior is evaluated, see Section 4.3.3.

3.3   Satellite Mission Concepts

In Section 3.1, we presented the architecture chosen for this thesis work, but several types of satellite concepts can be chosen to complete this architecture. The following will present three options.

All of these various solutions may fulfill the requirements for the scientific mission. In order to solve the communication challenges for a scientific mission in the Arctic, we can mention two candidates of satellite mission concepts. Either we propose a system based on small satellites in LEO orbit with more specialized communication payloads (concepts I & II), or we can rely on the proposed mega

constellations from, for example, Starlink from SpaceX, and OneWeb[4] (concept III). For these two classes of concepts (dedicated mission or an architecture based on mega constellations), the space segment will differ significantly. Also, potential throughput, requirements and constraints for the ground systems may be different. Furthermore, the architecture based on small satellites can make use of a 3rd party communication system such as VDES (concept II), or propose a new mission-dedicated system (concept I). Finally, the space segment may consist of one satellite or a swarm or constellation of satellites.

3.3.1 Concept I: Based on Dedicated Small Satellites

This concept is the main focus of the work presented in this thesis, and it stems from the research questions in Chapter 1.3.1. The satellite hardware market has matured over the years, and the cost of launching small satellites will be reduced as several organizations try to overcome the hurdle of efficient, timely and cheaper access to orbit. With this in mind, we should open up for very *mission centric* satellites, where a dedicated space segment can be a part of virtually any relevant project. The main part of this mission will be one or more small satellites, launched in one or more orbital planes providing coverage to the sensor nodes in question. Since this is a new design starting from scratch, most of the mission elements can be evaluated in a trade study.
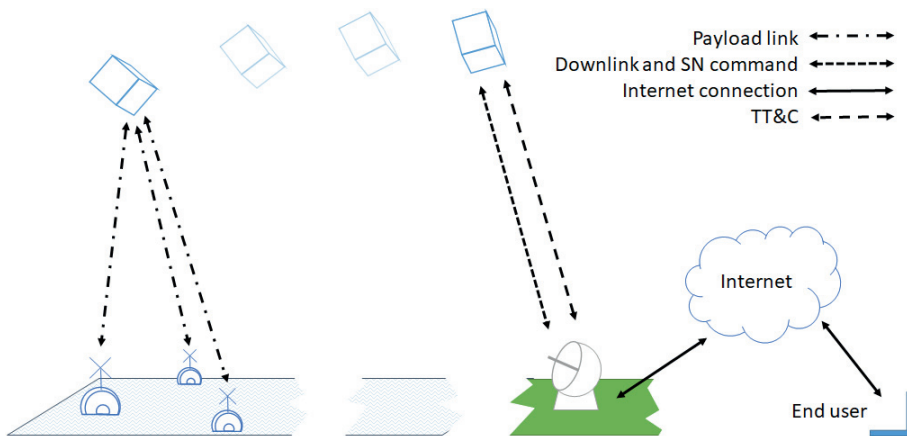
Figure 3.4: Concept I and II; small satellite UHF or VHF links (the use of these frequencies will be justified in Section 6.1).

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[4]None of these are operating at the time of writing, but as they are supposed to be operating within a couple of years, they can be interesting candidates for an Arctic sensor program.

Figure 3.4 shows conceptually how this can be set up. The TT&C-link is for telemetry and command between the ground station and the satellite. The UHF or VHF-links between satellite and sensor nodes as well as the downlink and sensor node commands will be used both for sensor data, command and housekeeping to and from the sensor nodes as well as network management for the communication system. All sensor nodes may have a connection directly to the space segment. The satellite(s) will store-and-forward the received data until the satellite(s) are within coverage of a ground station.

3.3.2   Concept II: Based on VDES

The VHF Data Exchange System (VDES) communication system [122] is a newly proposed service mainly for ship-ship and ship-shore communication. It will extend the Automatic Identification System (AIS)-service and be an integral part of e-navigation for ships. In addition to maritime service, this system could also provide the space segment infrastructure needed to support a sensor system in the Arctic. Since our satellite mission will be a secondary user of this infrastructure, the payload and satellites are also defined by others. Therefore, fewer of the mission elements are subject to possible tradeoffs in this concept. However, many of the generic studies performed here, for example, relating to different orbits, constellations and swarms are relevant for VDES. In some way, this concept is a particular implementation of Concept I. This is shown by Figure 3.4. The main differences between concepts I and II will be the implementation of an RF-link between the sensor nodes and the space segment, in addition to how data distribution and access is implemented.

3.3.3   Concept III: Based on Mega Constellations

In the past few years, the concept of *mega constellations* has gained quite some interest. Huge industrial actors as SpaceX, Facebook, Virgin and OneWeb are competing or teaming up to be the first provider of planet-wide internet connection through a plethora of satellites. This has the potential to be a game-changer of many dimensions, also for scientists wanting to get access to their scientific data from the Arctic. However, few technical details are known about any of these systems, and incorporating this space segment in an architecture proposal might be premature. On the other hand, the concept of these mega constellations and the game-changing service they may provide, is highly interesting and should be given some consideration.

For this concept, hardly any of the mission elements in Table 2.2 are subject to any real tradeoffs. The *subject* will however be subject for a tradeoff: For concept I and II, it is envisioned that each individual sensor should be able to connect directly
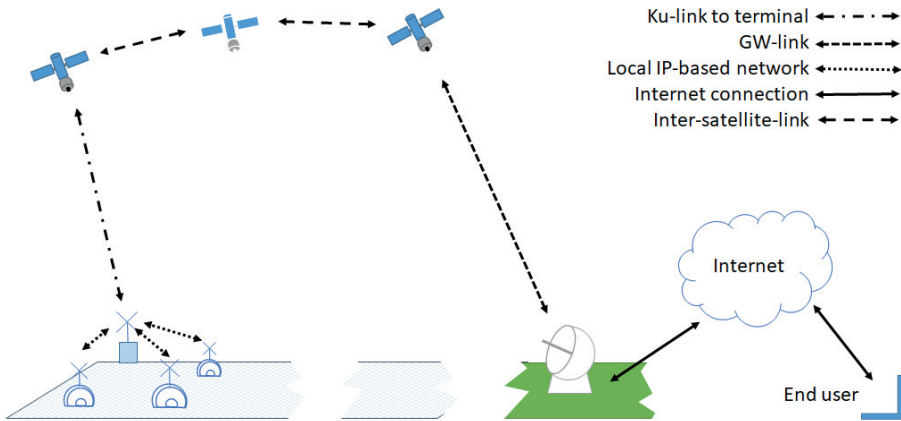
Figure 3.5: Concept III, based on mega constellations. All links will be defined by the mega constellation service.

to the space segment. For concept III, this might not be possible. OneWeb, for example, is said to only deliver infrastructure for cellular network providers, and access to the network must be granted through a roaming agreement. Also, the mega constellations will use higher frequencies that can lead to the requirement for a larger ground terminal that must act as a gateway base station for the sensor nodes. This means that this might be a viable solution for larger sensor nodes operating in clusters, rather than for individual sensors far away from each other, radio tags or various UVs. Such a solution is depicted in Figure 3.5.

3.3.4 Evaluation of the Mission Concepts

Table 3.2 shows the mission architecture elements and if these elements are subject to tradeoff or not. These elements were introduced in Section 2.1.3, and follow the definitions from [29, Chapter 2.2].

It is important to note that decisions on one element can enforce a decision on one or more other elements. For example, the decision if whether or not it is very important for an entity to operate and maintain control over its own system, may rule out the use of existing ground communication architecture. The decision will then lock or limit how other elements can be traded.

In Table 3.3, some of the mission elements are broken down into more detailed parts. For example, the *communication architecture* in Table 3.2 is split into several elements to visualize trade-offs for *frequency*, *coverage*, as well as *data delivery and access*. The three architecture options shown in Table 3.3, should all fulfill the main requirements of a scientific data recoding program. The point of this step in

Table 3.2: Mission elements that can be traded.

Element of mission arch.	Tradeable?	How and why
Mission concept	Yes - limited	Should be open to a variety of sensor systems and space segments
Subject	Yes	Fixed/drifting sensor nodes, UVs
Payload	Yes - limited	Will depend on the system type/mission concept
Spacecraft bus	Yes - limited	Possible for a dedicated system
Launch system	Cost only	Choose minimum cost for near-polar orbit
Obit	Yes	Varying number of satellites and planes
Ground system	Yes	Several options depending on chosen system type
Comms. arch	Yes	Depending on system type, physical size and energy requirement
Mission ops	Yes	Level of autonomy and delay/timing in data delivery and data harvesting can be traded. Importance of own control over schedule and ops.

the design process is to be open and agnostic with respect to the space segment in the first design phase.

It is important to show that in order to bring forth the full communication infrastructure for use in the Arctic, several variants of the space segments can be utilized. Common for all three architectures is that they all are new; they do not exist at the time of writing. Also, architecture I and II have a lot of commonality.

The different system types all have their potential strengths and weaknesses that can be used to evaluate them in the trade study. In addition to the space component, technology for the sensor nodes must be considered, including inter-communication, energy constraints, and throughput. The choice of architecture option will also impact these topics. In this thesis, the system type II and III serve as examples for comparison with the dedicated small satellite architecture, type I, that has been chosen as the architecture we focus on.

From Table 3.3 a large number of architecture options can be identified, but the true number of options might be both lower and higher. Lower, since some of the options are inter-linked, such as that near continuous coverage will only be possible for systems I and II if a swarm or constellation of satellites is deployed. The number of options might also increase if other elements such as the make of the sensor nodes is included. A selection of a few options is made, and then their utility will be analyzed with the sensor nodes in mind (see Section 7.3).

Selected Options   As shown, only one combination of options exists for system III (A3-B3-C2-D2-E3-F1-G3), resulting in one possible mission architecture. For

Table 3.3: Satellite architecture options

System type	Opt.	I: Custom	II: VDES	III: Mega const.
Orbit	A1	Single satellite	Single satellite	
	A2	Swarm	Swarm	
	A3	Constellation	Constellation	Constellation
Frequency	B1	EESS (UHF)		
	B2		VDES (VHF)	
	B3			Ku
Comm. arch (nodes)	C1	Direct to node	Direct to node	
	C2	Via GW-node	Via GW-node	Via GW-node
Ground system	D1	Dedicated		
	D2	Commercial		Commercial
	D3		VDES-infrastruct.	
Coverage	E1	Store and fwd.	Store and fwd.	
	E2	Near continuous	Near continuous	
	E3			Continuous
Data delivery and access	F1	Internet		Internet
	F2		VDES-infrastruct.	
Programmatic	G1	Full control		
	G2		Secondary user	
	G3			Commercial

system type I (and II) more sets of options, leading to several possible mission architectures, are available. Some options are exclusively selected for one of the systems. All orbit options (A1, A2, A3) will be considered:
[single satellite, swarm, constellation]. In this thesis, the use of a UHF Earth-Exploration Satellite Service (EESS)-band (B1) will be considered, however VDES (B2) might be an alternative. It will be assumed that all sensor nodes are able to *connect directly* to the space segment (C1), but this decision is in reality up to the owner of the sensors. Furthermore, the use of a *commercial ground system* (D2) is assumed, with (D3) as the alternative for VDES. Also, the communication payload will be of the *store-and-forward* type (E1) in either case, even if the forward delay can be close to zero.

In total, this gives three main options - depending on the orbit - with variations on the payload (system type I or II). In total, six mission architecture options (since options in B and D are linked) are available:
A{1,2,3}-B{1,2}-C1-D{2,3}-E1-F1-G1. For the detailed study the three options A{1,2,3}-B1-C1-D2-E1-F1-G1 are selected.

3.4 Chapter Conclusions

In this chapter, design of a new *heterogeneous network architecture*, that fulfills the mission- and system requirements defined in Section 2.1.3, is presented. Several concepts for the space mission architectures[5] can be chosen as the space component of the network architecture. Through a discussion and evaluation of three main satellite mission concept types (c.f. Section 3.3), one option is chosen for further study. This satellite mission concept is based on using small satellites to enable connectivity between sensor nodes and end-users through GWs.

This network architecture is new in its definition as no such architecture is found in literature (c.f Section 2.3.5). Even if the reference scenario in this thesis is based on sensor nodes in the Arctic area, the architecture and its components can be applied in a variety of missions and scenarios combining remote sensor systems and unmanned systems with small satellites.

The architecture partially answers research questions *RQ1 – RQ3*, defined in Section 1.3.1. The architecture primary discuss the interoperability between various agents related to *RQ1*. In addition, the final part of *RQ2* is addressed, on how this architecture will aid Arctic activities. However, Chapter 4, Chapter 5, and Chapter 6 will present more detailed properties and designs on small satellite swarms and constellations, network properties and the radio link, respectively. Chapter 7 will discuss a possible implementation of the space segment for a small satellite system in order to fully cover all parts of the research questions.

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[5]Mission architecture is defined in Section 2.1.3)

Chapter 4

Small Satellite Swarms

In this chapter, the concept of constellations, and of swarms of small satellites, are introduced and discussed. A system consisting of only one satellite offers limited coverage and capacity. For a dedicated communication system for the Arctic, coverage and capacity will scale nearly linearly with the number of satellites. In addition, re-visit times and therefore end-to-end delays can be reduced (depending on implementation) by adding more satellites.

The concept of free-flying satellites in a swarm is introduced as an alternative to a constellation. In this thesis, a *satellite swarm* is a number of satellites, part of the same distributed system, but with no means of maintaining any formation or relative distances. In the literature, a swarm may be used for a cluster of satellites that work together within a smaller volume. Satellites in a constellation are expected to have thrusters in order to maintain their position in the constellation. This calls for a much more expensive satellite bus because a propulsion system is expensive, and will put further constraints and requirements on the mechanical and the ADCS.

An alternative to thrusters are differential drag techniques, thus controlling the satellite's drag by actively changing its cross-section normal to the velocity vector. Wings, orientation or sails can be used to achieve this. This method is currently being tested on missions such as the Sky and Space Global *3 Diamonds*[1]-mission as well as by Planet. By actively changing the satellite cross section, the drag force will change, and this can then help changing or maintaining the individual separation between satellites. This requires active operation of ADCS. If the satellite's pointing direction towards the Earth or other objects must be maintained all the time, drag management can be harder to enforce. For a communication payload as proposed in this thesis, the satellite must point its antenna towards the sensor nodes when operating, but when the satellite is not above the area of interest, it's orien-

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[1]https://www.zdnet.com/article/sky-and-space-completes-nano-satellite-testing/

tation may be changed to accommodate the drag management. Planet are actively using drag management to maintain a more defined constellation [65, 67]. Station keeping based on drag management will reduce the satellite altitude quicker compared to station keeping with thrusters, thus the initial altitude must be high enough to accommodate the full mission life time.

An orbit architecture is proposed, based on the comparison of two satellites in a normal "static" or "fixed" constellation vs. three satellites in a free-flying swarm. A static constellation implies that the distance, or angular separation, between the member satellites is kept constant, while for the free-flying swarm the distance between the satellites changes constantly. The resulting swarm from this chapter is used as basis for the network emulations discussed in Chapter 5. Most of the work from this chapter has been presented in included papers (Appendix A.3, A.4) [114, 115].

4.1   Satellite Orbits

The following sections will discuss the basics behind various types of typical satellite orbits, and present examples of use. Also, justification for when to make use of, or not to use, specific orbits for this type of communication architecture will be given.

4.1.1   Orbital Elements

Earth orbiting satellites are often described with elliptical Keplerian orbits, which is a model to describe a classical two-body system. To define an orbit, as shown in Figure 4.1, six orbital parameters are used [29]:

Ω right ascension of the ascending node (RAAN)
ω argument of the perigee
ν true anomaly
i inclination
a semi-major axis
e eccentricity

In addition to these parameters, a reference plane and a reference direction is needed to define the orbit reference frame. The coordinate system is GEO-centric. The Earth's equatorial plane is used as the reference plane and the reference direction is pointing towards the vernal point, denoted γ in Figure 4.1. Today, this direction points to the constellation of Pisces [123].

The Kepler elements for all known satellites in orbit are published by CelesTrak [125] by files of the Two-Line Elements (TLE)-format. These files can
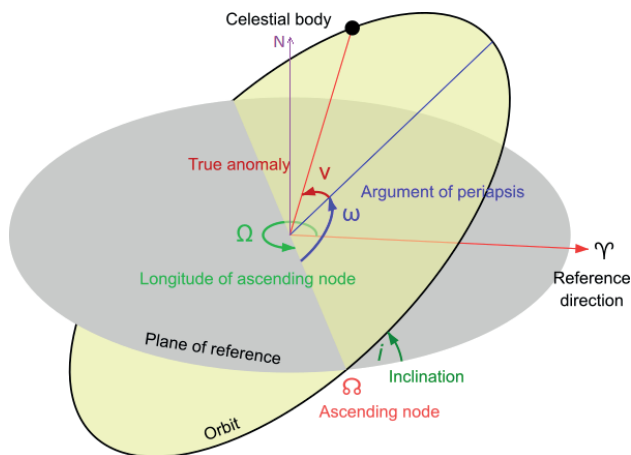
Figure 4.1: The Keplerian elements explained. The equatorial plane (grey) and reference direction γ is shown. Adapted from [124].

then be used as input to, for example, antenna tracking software or orbit simulators such as *pyephem* or Systems Toolkit (STK).

4.1.2   Relevant Types of Orbits

Depending on the specific mission requirements for the space mission, and its mission profile, several orbits can be considered. However, some orbits hold special properties and therefore have their main uses. A brief comparison is given below, and various orbits are shown in Figure 4.2.

Geostationary Orbit

A satellite in the Geostationary Orbit (GEO) is popularly characterized by the fact that for an observer on the Earth, it appears like the satellite is kept stationary in a fixed point in the sky. Satellites in this orbit have an inclination of 0°, i.e. at the equator plane, and an altitude of 36000 km. For an observer situated in the sub-satellite point on equator, the satellite will appear straight overhead. As the observer moves further north (or south) the elevation angle will decrease. At 81.3° North, the satellite is dipping below the horizon. Practical use of the satellites is limited north of 75° latitude. This means, from an Arctic perspective, that the use of GEO satellites is limited. The GEO-orbit is typically used for providing telecommunication and broadcast services. The Geostationary Transfer Orbit (GTO)-orbit is used in order to inject a satellite into the GEO-orbit.
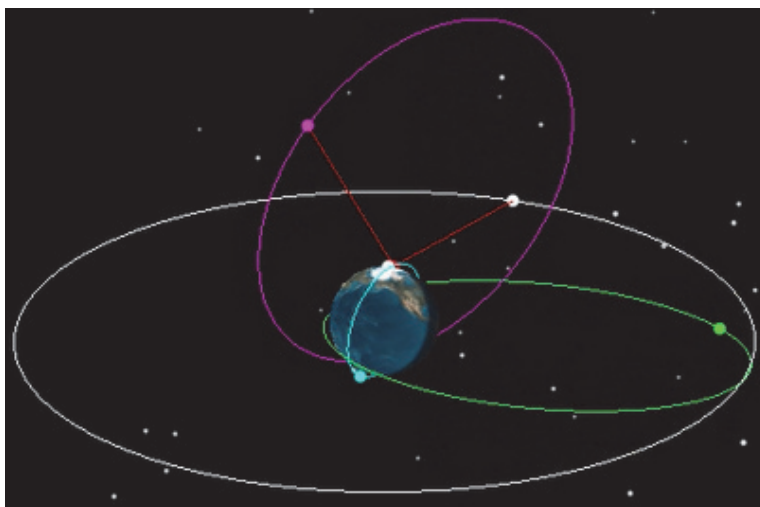
Figure 4.2: Various satellite orbits. White: GEO, Green: GTO, purple: HEO, turquoise: polar LEO.

Highly Elliptical Orbit

By carefully designing a very eccentric orbit and also taking orbital perturbations (see Section 4.1.3) into account, satellites can be placed in a HEO in order to linger for a longer period of time over a specific area. However, the satellite will not be completely stationary relative to an observer on Earth, as it needs to do a full orbit around the Earth. Therefore, more than one satellite will be needed in order to provide continuously coverage over an area of interest. Systems using two or three satellites can be designed. HEO satellites are typically used in communication systems, for example in the Russian Molnya system [126, Chapter 2.2.1]. One of the drawbacks with the HEO-orbit is that the distance from the user on Earth to the satellite is very long; up to 42000 km for the Molnya orbit. This is a considerable distance compared to around 2000 km between a user and a "low" LEO satellite at low elevation. In the Arctic perspective, a communication system employing the HEO-orbit seems useful since the Arctic area can be favored when designing the coverage area.

Nevertheless, the orbit has its disadvantages. Due to the large distances, expensive high-power satellites must be used. The distance complicates closing the link from a low-power sensor node to the satellite. Also, the great distance causes long round-trip delays which makes real-time operations difficult, even though coverage is continuous. Adding to this, the satellites also cross the van Allen belts [126, Chapter 12.4.1.3], increasing its exposure to high-energy radiation considerably.

However, this can be avoided for some types of HEO orbits, by carefully choosing the orbital parameters e and T [127, Chapter 4.3]. A mission to HEO will also call for a dedicated launch, compared to the plentiful ride-share options to LEO. All this calls for a more expensive satellite bus, a much more expensive launch, and in total more a costly mission.

Low Earth Orbit and Polar Orbits

The Low Earth Orbit (LEO) is a wide type of orbits with an altitude between 300 and 2000 km. The orbital period at 500-800 km is around 90 minutes. Satellites in this orbit can have any inclination. By placing a satellite in a polar orbit, meaning a inclination close to 90°, the whole Earth will be covered by the satellite by successive revolutions [126, Chapter 1.4].

Sun-Synchronous Orbits

The Sun-Synchronous Orbit (SSO) is a subset of the polar orbit which is designed with a daily node drift in Ω (or right ascension of the ascending node (RAAN)) equal to the Earth's daily movement around the sun. Due to this, the angle between the orbital plane and the sun vector connecting the satellite orbital plane and the sun, is constant. This causes the satellite to pass over the same point on the Earth at approximately the same local time every day. For an Earth Observation mission this will give the same illumination condition at every measuring point. In many applications, this is beneficial. Therefore, ride-share access to this class of orbit is frequent. The orbit can also be designed so the satellite is illuminated by the sun all the time. This is called a dusk-dawn orbit. The inclination (i> 90°) needed to give this effect is a function of orbit altitude (more precisely the semi-major axis, a) and the eccentricity, e, [29, Chapter 6.2.2]. For a communication network, the properties of the SSO are of less importance, however the dusk-dawn orbit may be advantageous for energy harvesting.

4.1.3 Orbital Perturbations

All satellites will experience a set of forces causing orbital perturbations. Perturbations are caused by, for example, gravitational pull from 3rd bodies, effects due to the non-spherical Earth as well as atmospheric drag. For satellites in orbits from GEO and lower, the effect due to the non-spherical Earth dominates the drift in the parameters Ω and ω, while for higher orbits the effects from 3rd bodies (moon, sun) dominate [29, Chapter 6.2].

These effects can be used to design orbits with special properties. Examples are the Molyna-orbit with zero perigee (ω) drift, and sun-synchronous orbits,

where the drift of the RAAN (Ω) is matched to the Earth's movement around the sun in order to keep the angle between the sun to orbital plane fixed.

For satellites in LEO below 800 km, atmospheric drag will be the dominant force that affects the kinetic energy, and therefore affects true anomaly and orbital height [29, Chapter 6.2.4]. The drag experienced by a satellite will reduce the orbital height and inevitably bring the satellite back to Earth. Drag is a function of the satellite's mass/volume ratio, sun activity, orbit height, angle-of-attack and other parameters.

Solar radiation will also affect the satellite's orbit, in two ways. First, the solar radiation pressure will assert a force on the satellite itself, in most cases this effect is negligible, if the satellite has a small surface [126, page 71]. The variation in solar radiation due to the sun cycle will have a greater indirect effect; high solar radiation will cause the atmosphere to expand, hence the drag will increase.

4.1.4   Orbit Propagators and Simulation Tools

Orbit propagators represent solutions to the equations of motion for two or more bodies moving relative to each other, subject to a variety of forces. In simulation tools such as Systems Toolkit (STK), the implementation of the various orbit propagators are mathematical models used to predict orbits ahead of time. These propagators have different properties and complexities and may or may not include some of the perturbations presented above. A simple propagator only describes the orbit as a two-body problem, and therefore the orbit is treated as a Keplerian orbit. Other propagators can take effects caused by J2 and J4 perturbation into account. These effects are of higher order and are due to Earth's oblateness. This leads to node drift during simulations. However, in STK [128] none of these propagators include drag or solar pressure. For short simulation periods, such as typically one day for a communication system, the different propagators will produce similar results and the two-body propagator can be used. J2 is typically used for simulations over some weeks, and J4 for simulations over years as they have long term effects on the satellite.

For predicting the future orbits of exciting satellites, the Simplified perturbations model (SPG4) is used. This takes a Two-Line Elements (TLE)-file as input and implements effects such as J2, J4, drag and more. Objects in orbit are also actively tracked and their TLE-data is regularly updated as the TLE-predictions are typically valid for some days [129].

The Python simulations carried out in this work uses a propagator similar to SPG4. Simulations in STK uses SPG4 when working with existing or historical satellites, a two-body propagator is used for short simulations, and J2 for longer simulations.

4.1.5 Orbit Choice Proposal

For a communication system, a few orbit related trade-offs are possible. Availability of launches, orbital height and inclination are of the most important ones.

Various types of satellite orbits were introduced above. Most small satellites, like CubeSats, are usually launched in the lower parts of LEO, typically between 300 km – 800 km. There are several reasons for this; the satellites are small and preferably made as cheap as possible, which also relates to their lifetime. Due to the drag in the lower part of LEO, the satellites eventually de-orbit, thus fulfilling any re-entry requirements. Also, launches to LEO are frequent and at a reasonable cost.

Several orbit classes exist within the LEO domain. In our case, only *polar orbits* are considered, as they are needed to cover the Arctic, c.f. requirements defined in Section 2.2 (*MC-001*). Within this constraint, the Sun-Synchronous Orbit (SSO) is a much used orbit type. Again, several sub-classes of SSO exist. For a communication system, the fact that the satellite passes overhead at the same time every day is of less importance. However, launches to various SSO-orbits are quite frequent, due to the popularity of this orbit for Earth Observation (EO) missions.

Orbital Altitude

Satellites at higher altitudes have a lower orbital velocity than in lower orbits, they move slower with regards to an observer on the ground. This means that a satellite in the higher orbit will cover an area for a longer time. However, the re-visit time will also be longer. In addition, a higher altitude will lead to longer propagation delay and longer ranges that require a better link budget. Satellites below 400 km will, due to the atmospheric drag, have a very short lifetime in orbit, on the order of months. To balance the lifetime in orbit and the requirement of a maximum lifetime in orbit of 25 years [130] after End of Life (EOL) (*MC-006*), the usable altitude range will be from 400 – 600 km, without equipping the satellite with a de-orbit device.

Inclination

In order to cover the Arctic (*MC-001*), the satellite must be in a polar orbit with an inclination typically between 80°– 100°. The much-used SSO has an inclination of approximately 98°.

Launch Availability

Access to space is also a critical element. Most CubeSats are launched as secondary payloads, meaning that their owners cannot change the orbital parameters nor launch time after a launch booking has been made. In practice, this means that the project team must choose from a list of available launches, picking the launch that best fits the mission profile while taking into account orbit altitude, inclination, cost, time and schedule, and other factors. Due to its popularity for EO missions, launch availability to SSO with altitudes between 400 – 600 km is frequent. For more special orbits such as HEO, none or only very infrequent launches are available.

Chosen Parameters

Based on the discussions above and fulfillment of defined requirements, the parameters listed below are chosen for our system design, and used for most examples, simulations and calculations in the following. The most important drivers for each parameter are listed.

Altitude   500 km (orbit life-time, launch avail., link budget, pass duration)
Orbit type SSO (launch availability)
Inclination 98°(given by altitude and orbit type, covered area, launch availability)

Justification and Discussion of Orbital Height   Early in this work, the first simulations on CubeSat swarms were carried out using a modified TLE-file for the AAUSat-3 satellite. This is a satellite with an altitude of 780 km. These simulations are presented later in this chapter, and are also the foundation for the satellite component of papers [114, 116, 117, 115]. Even if it was later discovered that a lower orbit may better fit this mission, the initial data-set was kept to ensure consistency over the period of work.

This case is also an example of the need for an iterative design process (c.f. Section 2.1). The link budgets in Section 6.8.3 also show calculations for an orbit of 500 km height. At an elevation of 10°, there is a 3 dB difference in the free space loss between a 500 km orbit and a 800 km orbit.

The orbital period for a satellite in 500 km circular orbit is approximately 94 minutes, and for a satellite in 800 km circular orbit, it is approximately 100 minutes. The swarm behavior as discussed in Chapter 4.2 will be similar for a 500 km orbit compared to the 800 km orbit used.

As an orbit of 500 km corresponds better with the requirement to de-orbit within the 25 years, as well as that the availability of launches between 450 and 600 km is good, this choice is the most likely in a practical scenario.

4.2   Freely Drifting Satellite Swarms

In this section we will discuss how a *swarm* of satellites can be deployed in order to achieve good coverage properties by employing small satellites without station keeping capabilities. In this work, a *swarm* means a set of satellites that move independently relative to each other. All satellites in the swarm are in the same orbital plane. Another definition of this word used in literature, is describing satellites kept closer together in a group, and that the satellites interact with each other. The term *constellation* in this work means a set of satellites in one plane, where the satellites are evenly spread and uniformly distributed.

There are many arguments for deploying distributed satellites, such as swarms of small satellites. One is adding redundant capacity to a group of satellites, such as the camera satellites by Planet. Some of the cheap satellites might fail, but service is maintained due to a high number of satellites. Another reason is deployment of satellite clusters for communication, where the smaller satellites communicate with a larger "mother satellite" for downlink purposes. This scenario is discussed in [81, 131].

In [132], Guy Zohar proposed how to evaluate and describe the swarm from deployment until the operational phase. The term *clusterness* is introduced to describe the form of the constellation. This is a number describing how the satellites are separated.

$$Clusterness = \frac{||\sum(\theta_{max} - \theta_n)||}{(N-1)\theta_{max}}, n = [1...,N-1] \tag{4.1}$$

θ_n is the separation in true anomaly between two neighboring satellites (n and $n+1$), N is the number of satellites and θ_{max} is the ideal angular distance between N satellites, defined in [132] as $\theta_{max} = \frac{360}{N}$.

When the clusterness is 0, the satellites are evenly separated in the orbital plane, when the clusterness is 1, all satellites are at the same location. Clusterness is only a description of the swarm at a point in time. If the clusterness is calculated over time, we can plot the values and track the development of a swarm as it changes with time. Here, the duration of the coverage gap is chosen as the metric describing the swarm.

4.2.1   Orbital Properties

Free-flying satellites, such as CubeSats without any propulsion system, should not be called a constellation, but rather a freely drifting swarm. The CubeSats, if deployed from a common launch vehicle, will likely be released in arbitrary directions due to upper stage movements and arbitrary placement of the deployment pods on the upper stage. This will give them slightly different velocity leading

to different orbital parameters, and therefore cause them to drift relatively to each other. The satellites will also experience drift due to orbital perturbations, as introduced in Section 4.1.3. Due to this, a uniform distribution is difficult to achieve and maintain [63, 64]. A location on the Earth will be more frequently covered by using more than one satellite, but the period between two contacts will vary. Due to the continuous drifting of the satellites, long coverage gaps will occur when the *clusterness* is close to 1 (similar to using only one satellite). Depending on the satellites' orbital periods, the time period with successive long gaps will vary - spanning days to weeks. It might be desirable to design the swarm in such a manner so that this time period is as short as possible, or happens infrequently. Some examples are shown in Section 4.3.2. The satellites' motion is predictable over a moderate period[2] of time so the network utilization can be planned and scheduled according to the current coverage pattern.

Methods to create a swarm distribution that helps reduce the gaps between contacts; both averaged over time, and also by limiting the time when the clusterness is close to one, are presented here.

4.2.2 Deploying the Swarm

Even if the size of the CubeSats is quite limited both with respect to power and volume, for example for thrusters, there are emerging technologies, i.e. micro-thrusters [63, 133, 134, 135] that can provide propulsion for CubeSats. Three ways for deploying the swarms are discussed here.

Define and control deployment times and/or directions

In this scenario, we envision a number of similar satellites deployed from the same launcher, into the *same orbital plane*. They will be deployed with slightly different orbital periods, due to a relative velocity change given when deployed from the launcher's upper stage.

As discussed by several authors [58, 63, 64, 132, 136], one way to control the constellation build-up will be to control timing and direction when the satellites are deployed from their upper stage. If the satellites are deployed with the same angle relative to the main direction of motion, for example directly aft, the satellites will have very little relative velocity to each other. The constellation can then be achieved by precise control of the deployment time, in order to deploy a uniform constellation. The drawback is that this system has no feedback, so if for some reason the timing was a bit wrong, or if the satellites were deployed with an angle

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[2]By use of Two-Line Elements (TLE) and the SPG4 propagator.

relative to the direction of motion, they will start to drift slowly and the constellation will break down. The time this takes will depend on the relative velocity. If the velocity difference is small (for example less than 1 m/s), the constellation will break down[3] slowly. This process can take several months. If the planned lifetime of the system is short, this might not impact the service. If the expected system lifetime is longer, the duration of the degraded service, a clusterness near 1, will also be long. Hence, a higher relative velocity seem desirable.

One-go Thruster

As an expansion of the above scenario, we can imagine that the satellites are either deployed at the best effort or in a tighter cluster. Then a one-go thruster could be used to give the satellites a varying amount of ΔV in order to initiate the swarm behavior.

Controllable and re-fireable thruster

If the satellite lifetime is long, the small drift experienced by the satellites will eventually lead to constellation breakdown, in spite of timely deployment [63]. To mitigate this, we can envision satellites employed with thrusters that can be fired several times in a controllable manner to perform the station keeping task. The thrusters can also be used to re-shape the constellation if required. This is the most flexible, but also most expensive solution. These procedures will also need careful estimation and tracking of the satellites' orbital parameters [65, 67].

The satellite tracking measurements must be precise in order to be useful. The resulting estimations can be presented to the satellite operator in the form of TLEs [125] or in other forms, for example from the proposed DGSN [137] network, or a dedicated ranging system as presented by Planet in [65, 67].

The DGSN approach increases the observation points and thus leads to measurements that will help make a better estimate for the orbital parameters on an early commissioning stage, in order to not waste satellite lifetime. After the correct relative positions between the satellites are derived, the thrusters can be fired in order to lock in the constellation. Scenarios and strategies are discussed in [135], which also discusses the current state-of-art for a selection of thrusters.

A similar approach can be followed for active drag management. Both for using thrusters and drag management, orbit knowledge is important, as well as the need for a very capable ADCS, in order to control the direction of the thruster firing, or orienting the satellite to control the drag.

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[3]Meaning that the clusterness will approach 1

4.2.3   Managing, Coordinating and Using the Swarm

The satellites in the swarm can be considered individual satellites, rendering operation easy. However, as the layout of the swarm is constantly changing, the network properties will also change. Depending on the number of satellites, load sharing and other smart techniques for better scheduling and resource allocation should be implemented in order to get the most capacity from the swarm at all times.

Coordination

When the number of satellites and swarms and even swarm-of-swarms grow, several important topics arise. Allocation and coordination of radio frequencies will be one important and challenging issue. In addition to the traditional solution of transmitting data from one satellite to the ground, there could be inter-satellite relays to help reduce the load on the frequency spectrum on ground. These relays can either be a larger satellite part of a swarm or satellites in higher orbits, depending on the area to cover. These topics are addressed in the article [81] that points at some issues and proposes recommendations on how to mitigate frequency coordination and registration.

Tracking and Identification

Tracking of individual swarm member satellites is essential operation and management. In addition to services like the tracking of space objects by NORAD, new proposed services like DGSN [137, 138] with IoT-capabilities could increase the amount of tracking data. Satellite Laser Ranging (SLR) is a technique employing lasers to get very accurate tracking and ranging of satellites. It has also been proposed to add a "reflector tag" on the satellite, to achieve effective identification of a satellite in orbit, even if the satellite is dead in orbit [139]. As mentioned, companies like Planet are using their own tracking/ranging stations [67].

4.3   Simulations of Selected CubeSat Swarms Cases

The following show examples on how deploying an uncontrolled, or random constellation [140], increases the coverage and level of service for an Arctic communication system. The main case presented is a swarm of three satellites, compared to two satellites in a static constellation. The two satellites are separated by 180°, meaning the coverage gaps are always approximately 20 minutes, depending on the orbital period and the minimum required elevation. The observation point (a GW) is placed in the Arctic, namely in Longyearbyen, Svalbard. Longyearbyen

is located so far north so all satellite passes of a polar orbiting satellite are visible from this location. This is a representative location both for the SNs and the GWs. The simulations show how the constellation of satellites develops and forms (evenly spread satellites, *clusterness* near 0), break downs (clustered satellites, *clusterness* near 1) and re-shapes in a deterministic pattern. Modified TLE data[4] are used as input for the orbit propagator. The simulation is run over an extended period of time, so the validity of the TLE is pushed. However, this will show the general behavior of the swarm. The following show examples on how deploying an uncontrolled, or random constellation [140], increases the coverage and level of service for an Arctic communication system. The main case presented is a swarm of three satellites, compared to two satellites in a static constellation. The two satellites are separated by 180°, meaning the coverage gaps are always approximately 20 minutes, depending on the orbital period and the minimum required elevation. The observation point (a GW) is placed in the Arctic, namely in Longyearbyen, Svalbard. Longyearbyen is located so far north so all satellite passes of a polar orbiting satellite are visible from this location. This is a representative location both for the SNs and the GWs. The simulations show how the constellation of satellites develops and forms (evenly spread satellites, *clusterness* near 0), break downs (clustered satellites, *clusterness* near 1) and re-shapes in a deterministic pattern. Modified TLE data[5] are used as input for the orbit propagator. The simulation is run over an extended period of time, so the validity of the TLE is pushed. However, this will show the general behavior of the swarm.

To evaluate the level of service, the duration of the gap between two consecutive satellite passes in addition to a qualitative discussion on the gap distribution are used.

In the simulations, we assume that deployment direction (0-360°) as well as deployment velocities in the range of (0 ± 4m/s) can be achieved by the launch provider. In addition, the simulations give the same origin of all satellites. In order to estimate the relationship between relative velocity and orbital period, we can do some calculations based on the orbit equation and the following relationships [123, Chapter 6.3]:

$$r = \frac{h^2}{\mu} \frac{1}{1 + e \, cos(\nu)}, \tag{4.2}$$

where r is the distance between the satellite and the center of the Earth, h is the relative orbital angular momentum per unit mass (which is constant for all

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[4]The TLE-data used is AAUSat-3 with epoch 13 Feb 2014 12:35:42.657. The TLE is retrieved by use of Systems Toolkit (STK) [109].

[5]The TLE-data used is AAUSat-3 with epoch 13 Feb 2014 12:35:42.657. The TLE is retrieved by use of Systems Toolkit (STK) [109].

positions along the orbit), μ is the Earth's gravitational parameter, e is the orbit eccentricity and ν is the true anomaly.

$$e = \frac{r_a - r_p}{r_a + r_p},$$

(4.3)

where r_p and r_a are the orbital radii at perigee and apogee, respectively.

The relationship between the orbital velocity v and h can be written:

$$v = \frac{h}{r}.$$

(4.4)

By using the equations above, and having knowledge about the initial apogee and perigee heights as well as the Earth's radius, we can deduce the orbits' semi-major axis a, and finally find the orbital period T:

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

(4.5)

Table 4.1 shows an example of orbital periods as a function of relative velocity at deployment. Satellite 5 is based on the TLE of AAUSat-3.

4.3.1   Orbit Calculation Example

Figure 4.3 shows the concept of an orbit transfer. In this case, a satellite in a circular orbit is given a Δv in its perigee (for a circular orbit, the perigee can be in any point along its track). As the satellite gets a higher kinetic energy, but also has to return to the same point in orbit (perigee), its apogee height/radius (r_{a2}) must be raised. This will then also change the orbital period, which is what we want to achieve.

The following calculation shows the method to derive the new set of orbital parameters when giving a satellite 4 m/s Δv. We take AAUSat-3 as our entry point, which has the following perigee radius:

$r_p = r_{p1} = r_{p2} = 768 + 6378$ km $= 7146$ km.

In perigee $\nu = 0$, so (4.2) reduces to

$$r_p = \frac{h^2}{\mu} \cdot \frac{1}{1+e}$$

combining this with (4.3) and then solve for h we find:
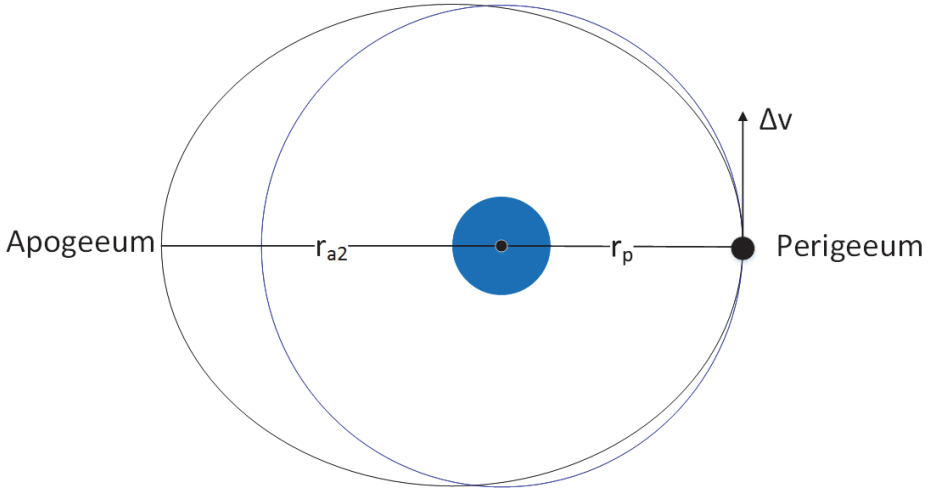
Figure 4.3: Orbit transfer. Starting with a circular orbit (blue) where apogee radius, r_{a1}, equals the perigee radius, r_p, which in turn has to be equal for both orbits. After the added Δv, the satellite ends in the new orbit (black), with a new apogee radius, r_{a1}. The figure is not to scale.

$$h_1 = \sqrt{2\mu}\sqrt{\frac{r_a r_p}{r_a + r_p}} \tag{4.6}$$

$$= \sqrt{2 \cdot 398600} \cdot \sqrt{\frac{7146 \cdot 7164.17}{7146 + 7164.17}} \tag{4.7}$$

$$= 53406.1 \text{ km}^2/\text{s} \tag{4.8}$$

Further, we find the orbital velocity in perigee for orbit 1, and then find the new v_{p2} and h_2 for the second orbit by adding 4 m/s:

$$v_{p1} = \frac{h_1}{r_p} = \frac{53406.1}{7146} = 7.4736 \text{ km/s} \tag{4.9}$$

$$v_{p2} = v_p + \Delta v_p = 7.4736 + 0.004 = 7.4776 \text{ km/s} \tag{4.10}$$

$$h_2 = v_{p2} \cdot r_p = 7.4776 \cdot 7146 = 53434.9 \text{ km}^2/\text{s} \tag{4.11}$$

Then we can solve (4.6) for the new r_{a2}. alt_{a2} is the new apogee altitude:

$$\frac{h^2}{2\mu} = \frac{r_{a2} \cdot r_p}{r_{a2} + r_p} \tag{4.12}$$

$$h^2 \cdot r_{a2} + h^2 \cdot r_p = 2\mu \cdot r_{a2} \cdot r_p \tag{4.13}$$

$$-h^2 + 2\mu \cdot r_{a2} \cdot r_p = h^2 \cdot r_p \tag{4.14}$$

$$r_{a2} = \frac{h^2 \cdot r_p}{2\mu \cdot r_p - h^2} \tag{4.15}$$

$$r_{a2} = \frac{53434.7^2 \cdot 7146}{2 \cdot 398600 \cdot 7146 - 53434.7^2} \tag{4.16}$$

$$r_{a2} = 7180.55 \text{ km} \tag{4.17}$$

$$alt_{a2} = r_{a2} - 6378 = 802.55 \text{ km} \tag{4.18}$$

The new semi major axis then becomes:

$$a_2 = \frac{r_p + r_{a2}}{2} = \frac{7146 + 7180.55}{2} = 7163.275 \text{ km}, \tag{4.19}$$

and the new orbital period can then be found by (4.5):

$$2\pi\sqrt{\frac{a_2^3}{\mu}} = 2\pi\frac{7163.275^3}{398600} = 6033.63 \text{ s} \tag{4.20}$$

This calculation was carried out for a set of satellites, Table 4.1 shows the resulting orbital period and other parameters for these, where satellite 9 corresponds to the example above.

Table 4.1: Orbital period as function of ΔV. Perigee for all satellites is 768 km.

Sat#	ΔV [m/s]	Apogee height [km]	Eccentricity	Period [s]
1	- 4 m/s	771.83	0.00026781	6014.23
2	- 3 m/s	775.66	0.00053565	6016.65
3	- 2 m/s	779.49	0.00080353	6019.07
4	- 1 m/s	783.33	0.00107144	6021.49
5	0 m/s	787.17	0.00133939	6023.92
6	+ 1 m/s	791.01	0.00160738	6026.34
7	+ 2 m/s	794.85	0.00187540	6028.77
8	+ 3 m/s	798.70	0.00214346	6031.20
9	+ 4 m/s	802.55	0.00241155	6033.63

As observed from the Table 4.1, over a small range of ΔV, the relationship between orbital period and ΔV is nearly linear. At this orbital height, a velocity increase of 1 m/s will extend the orbital period with ≈ 2.4 s. The difference in orbital period between the fastest and the slowest considered satellites is 19.4 s.

4.3.2 Simulations and Evaluation Methodology

The simulation is using Python with the `pyephem` library [110] for astronomical calculations and `matplotlib` [111] for plotting. `pyephem` takes drag into account while running the simulation.

The location of the satellite link user on the ground is near Longyearbyen, Svalbard at 78° 13" 23' N, 15° 37" 36' E (local horizon is not taken into account). The satellites are modified versions of the TLE for AAUSat-3 with epoch 2014-02-13.

All sets of period differences between the nine satellites in Table 4.1 were run, and a selection of four interesting cases is presented.

Assumptions made for the orbital calculations and simulations:

- Assume the launcher's upper-stage is in circular orbit
- The ΔV is given solely by varying deployment directions (along the velocity vector or in the opposite direction) as well as the tension of the springs or similar mechanisms of the CubeSat deployers. Assuming $\pm \approx 4$ m/s is physically feasible.
- The new orbital period is found by simple calculations similar to an orbit maneuver (as a Hohmann-transfer).
- The simulations are based on the TLE of AAUSat-3, and then the parameters *orbits per day* and *e* of the satellite object in `pyephem` are changed accordingly.
- The simulations show when the satellite is visible from the ground node. A minimum elevation angle of 5° is defined to be required. This implies that the ground node is placed on a plateau with no obstructions in the horizon. A higher elevation might be needed in practice to assure a good communication link.
- Assume all satellites are deployed from the same launch, in the same plane.
- Since all satellites are in one plane only, it is fundamental for the analysis that the users are able to see all passes of each satellite. If this is not the case, there will be long gaps due to the fact that the user cannot see any of the satellites in the given plane, for a duration of more than 3 orbits, depending on latitude.
- When two (or more) satellites have overlapping footprints, the pass duration will be adjusted for the overlap. So the total pass duration will assume use

of one, and only one, satellite at the time. The gap between passes is then defined to be 0.

4.3.3 Swarm Simulation Results

By varying the combinations of the three selected satellites, different gap distributions are found. Some of the interesting results are presented in this section. This information can be used to design a satellite swarm, with a desired set of properties. The best result found, is the one where most of the gaps are shorter than 35 minutes.

Table 4.2: Selected simulation results

Satellites	Gaps < 35 min	Gaps < 20 min	Gaps < 10 min
Case 1: 1, 2, 4	70.8%	59.0%	44.8%
Case 2: 1, 3, 9	75.1%	55.1%	44.0%
Case 3: 1, 5, 9	80.6%	55.7%	39.8%
Case 4: 1, 4, 7	80.1%	56.2%	39.9%

All satellite combinations were simulated, and Table 4.2 lists results for four selected cases. The cases are evaluated on the distribution of gaps shorter than 35 minutes as well as how long the period where longer gaps are experienced is.

Figure 4.4[6] shows how the constellation develops over time in the worst case – where the distribution of long gaps is the greatest. Figure 4.5 shows a better case and Figures 4.6 and 4.7 show two of the best cases. As seen, the gaps vary from 0 to around 90 minutes, and the shape of the constellation development is quite different for the four cases.

The table and the figures can be used in order to assess which of the three cases suits a given space mission profile best. If the mission is for communication, as our case is, it is probably beneficial to choose Case 3, for two reasons: This case has, overall, more gaps shorter than 35 minutes, compared to the other cases. In addition, the duration of the period with long gaps is shorter, but occurs more often. The main drawback with Case 1 is that it has a long period in the middle of the simulation period with fairly long gaps. It is also important to note that long gaps will be followed by either a very short gap, or an overlapping pass.

Case 3 and Case 4 represent similar statistics with respect to the percentage of long gaps. We see from Figures 4.6 and 4.7 that the main difference is that Case 4 has fewer occurrences of long gaps. But these occurrences last longer. In addition,

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[6]The extra line at around 48 days is due to the change from winter to summer time during the simulation period. This also applies to Figure 4.7.

since the relative velocity between satellite 1 and 7 is less than satellite 1 and 9, Case 4 might be easier to practically achieve during deployment.

Figure 4.8 shows the histogram of gap distributions for Case 3. Since all the overlapping gaps are given the value of '0', they stand out. The most important point to be made here, is that the vast majority of the gaps, in all cases more than 70%, is shorter than the expected gap between two satellites in an ideal, static constellation.
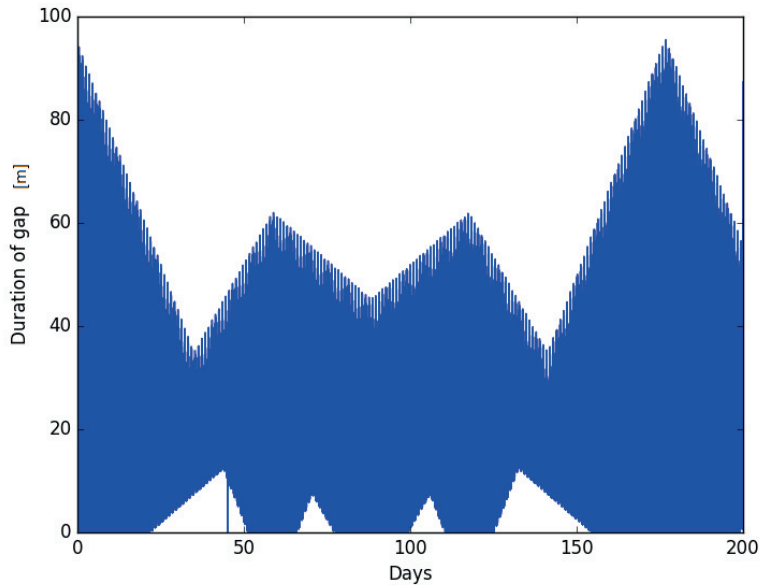
Figure 4.4: Case 1: Largest periods of gaps

This shows that instead of launching two satellites in a static constellation, three satellites can be used, and minimum 70% of the gaps will be shorter than what a gap between two fixed satellites is.

In order to maintain a fixed constellation, propulsion will be required. The minimum requirement is enough propulsion to lock the constellation after deployment. The best case will be to have a re-fireable thruster so active station keeping can be maintained. Even if this station keeping does not have to be very accurate for a small satellite in this application, the inclusion of a propulsion unit will be a large cost driver. It will also influence the complexity of the mission. A propulsion system must be included for each satellite, which in turn leads to stricter requirements for the ADCS. Development time is increased, and the mass and volume of the satellite will increase. Most propulsion systems are based on pressurized
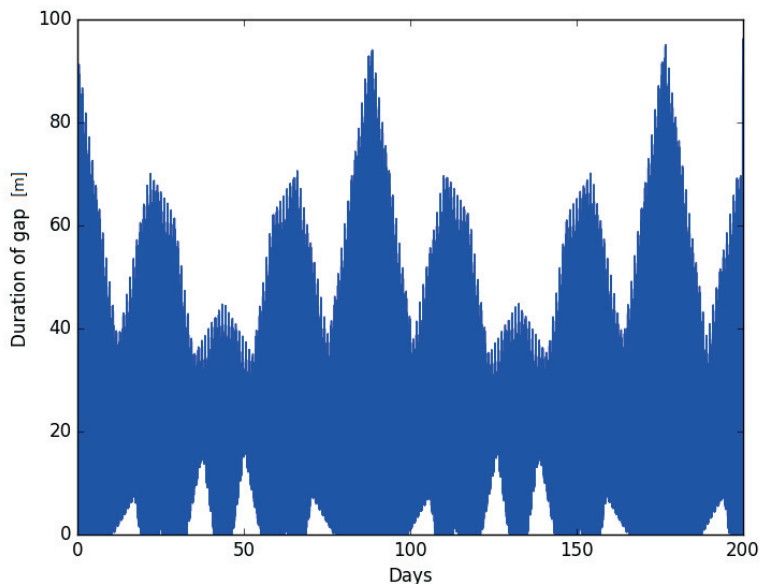
Figure 4.5: Case 2: Medium good distribution of gaps

vessels that require special handling, testing, verification, and approval from the launch operator. This leads to increased cost during these phases. The operational cost and complexity will also increase. In total, this will lead to an increased system cost with respect to volume, power and subsystem requirements, direct hardware cost and launch cost.

Adding one extra satellite to the swarm (in this example three instead of two) also represents an increase of cost. However, since the satellites can be launched without on-board propulsion, they will be smaller. The ADCS can be made much simpler, thus reducing the cost per satellite significantly.

The satellite orbits are predicable, at least over a modest period of time, therefore it is possible to plan the usage of satellites accordingly. When gaps are overlapping, the user(s) will have longer continuous satellite access (implies handover to next satellite).

One final point to be made about a distributed system of small and "cheap" satellites, is that it has strength in numbers. By adding one more satellite to the mission, the chance of mission success increases. If one of three satellites fails, the mission will still be better off than if only one satellite is operational.
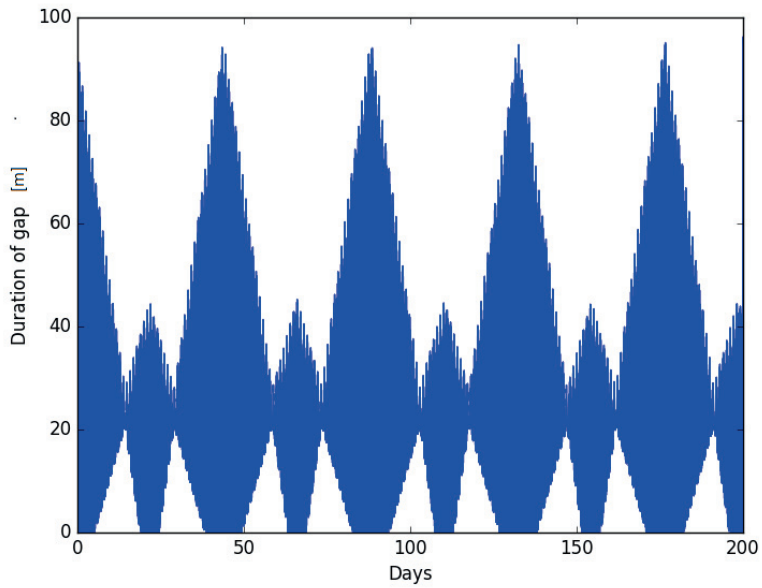
Figure 4.6: Case 3: Best distribution of gaps
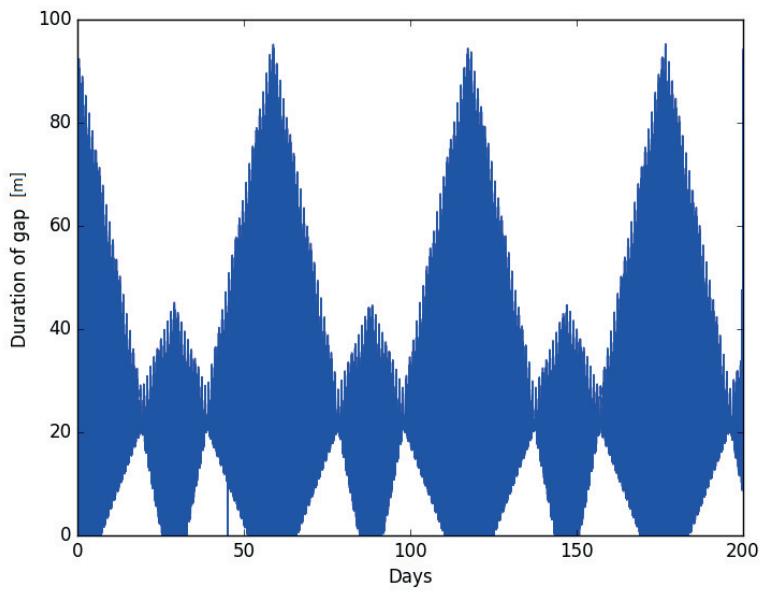
Figure 4.7: Case 4: Good distribution of gaps
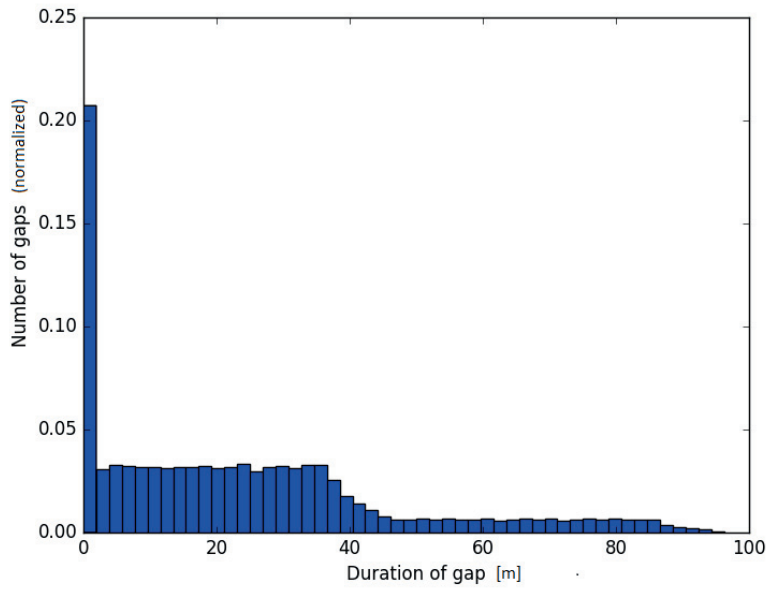
Figure 4.8: Gap distribution histogram for Case 3

4.4 Chapter Conclusions

The first part of this chapter presented various satellite orbits, and defined realistic values for the most important orbit parameters in Section 4.1.5. The selected orbit parameters support the research questions (*RQ2*, *RQ3*) and the relevant mission constraints. For example, the Arctic coverage is stated in *MC-001*, hence a polar orbit is chosen. Launch availability, cost and the requirements for orbital life time (*MC-006*), positions a Sun-Synchronous Orbit (SSO) orbit at 500 km as a likely and useful candidate. 500 km is a reasonable choice, with respect to the link budget, as will be discussed in Chapter 6.

In the second part of the chapter, the concept of a freely drifting swarm was introduced. This means the use of satellites without any station keeping. These satellites will be cheaper than satellites with thrusters, which allow for even more launched satellites within the same budget. This also aligns with *RQ2* and *RQ3*.

For *RQ2*, in order to benefit from satellites in one plane, the ground nodes must be placed far enough north to be able to see all passes from all satellites. This assumption aligns with the mission constraint *MC-001* from Table 2.4; that the system shall cover the Arctic area. If the any NWNs are placed further south, there will be long gap durations when all satellites in the plane are out of view [116].

Deploying several small satellites for one mission, increases coverage, system reliability and reduce access times. This ties back to *RQ3*, on how several satellites can be used to overcome the limitations of each individual satellite.

A set of satellites having slightly different orbit altitudes is defined, based upon realistic and achievable orbit deployments. The re-visit duration (coverage gaps) from swarm members is simulated and analyzed, and initial parameters for the swarm is presented, based on the simulation results. It is found that making the swarm more dynamic, i.e. letting the member satellites have a larger relative velocity, gives the best properties of the swarm. This means having as few long coverage gaps as possible. The varying duration of these gaps results from the cyclic behavior of the constellation shape/reshape. Coverage gaps with duration on the order of one orbital period will occur when the satellites in the constellation are overlapping. This situation will last for days or weeks, depending on the properties of the swarm. However, this duration with successive series of long gaps should be made as short as possible. The situation can be optimized when designing the swarm, by adjusting the release velocities.

From the set of velocity combinations, the best case has been selected. It is shown that in that case, 70 – 80% of the gaps are shorter than the expected gap from a two-satellite constellation. This means that the duration of reduced service due to overlapping satellite footprints is short, and might be acceptable. In Chapter 5, the statistics of the swarm v.s. the constellation is further investigated

from a network point of view. The extra member(s) of a freely drifting swarm
compared to a static constellation, adds redundancy and capacity to the system.
This helps increase the level of coverage without the need for complex on-board
spacecraft systems, such as thrusters[7] and high-yield ADCS. The reduced cost of
each satellite without thrusters can therefore enable the launch of more satellites
into the swarm, for added redundancy and capacity. Table 4.3 sums up the pros
and cons for each alternative.

Table 4.3: Swarm and constellation trade-offs

	Pros	Cons
Swarm	Redundancy (more satellites)	Varying coverage
	Added network capacity	Varying network performance
	Simpler and cheaper satellites	Overlapping footprints occurs
	Shorter re-visit times	
	Easier operation	
Constellation	Constant network performance	More expensive and complex satellites
	More capable satellites	More complex operations

The final trade-off to be decided is if the inevitable period of overlapping foot-
prints, thus slightly reduced network capacity in periods and changing coverage
performance, can be balanced by added capacity and shorter coverage gaps in
other periods, as well as redundancy, reduced cost pr. satellite and easier opera-
tion. The assumption is that the described swarm will be beneficial, and Chapter 5
will continue this analysis from the network perspective.

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[7]Thrusters can be replaced by drag management, thus reducing the hardware cost, but still re-
quiring a capable ADCS and more complex operations.

Chapter 5

Network

Through this chapter, topics on the network stack and network protocols will be discussed. A selection of possible network protocols is made and justified. This network stack is the basis for simulations presented here, and in the included papers (Appendix A.6, A.7) [116, 117]. The presented network stack must support research questions and mission objectives from Chapter 2, especially *RQ1* and *MO-001*. All Mission Requirements *MR-001 – MR-007* and the general System Requirement *SR-001* represents requirements that describe parts of the network behavior, and impact network design. The design process must comply with System Requirements *SR-014, SR-015, SR-017*.

While comparing satellite links with terrestrial links, satellite links have some very different properties compared to short-range radio links and cabled links, which have an impact on the network protocols. For example, the propagation delay due to increased distance is large, especially noticeable for GEO-satellites, which will have a propagation delay of at least 240 ms. For LEO-satellites the propagation delay will be shorter, but as the satellites move relatively to the user, dynamic effects such as Doppler shift, shadowing by obstructions, varying channels due to varying distance and propagation properties must be handled. Link-loss when the satellite is below the horizon, or handover between satellites, must also be addressed. This means that many well-known and commonly used protocols developed for more static channels are not suitable, or must be used with caution.

Several published papers and standards discuss protocol stacks for satellites links [141, 142, 143] (c.f. Section 2.3.4). The chosen network architecture must suit the particularities of the communication architecture when it comes to traffic and data type, number and dynamics of nodes, number of satellites, available link capacity, and Quality of Service (QoS).

Many traditional methods for media access are designed for data traffic prop-

erties as tight real-time demands[1] and continuous connections and data streams. In a remote sensor network the traffic needs not have a strict real-time demand, compared to voice applications where the end-to-end delay cannot exceed a few hundred ms [142]. Depending on the nature of the sensor nodes, the sensors may not utilize the satellite link for a very long period of time; the traffic will be *bursty* by nature [84].

As for the number of nodes, this might be dynamic, but slowly changing. The communication system will be designed to fit one (or a few) end-users and their equipment. It will therefore be possible to register most types of sensor nodes in the network, at least nodes that require a return link. Small sensors like RF tags for tracking of animals or assets might be exempt from this general rule, should they be supported in the network at all.

The different users in the satellite network can have different traffic requirements. Some users might want to only transmit small data messages a few times a day, other users might wish to transfer larger amounts of scientific data for each and every pass. However, as the expected dynamics of the nodes are low (i.e. few and slowly moving nodes) prediction of the traffic should be possible.

The choice of network layer protocols is important, as this also has implications for lower layers. Use of the Internet Protocol (IP) (v4 or v6) can be desired in order to ensure interoperability of both terminals and dataflows to and from other networks.

A satellite network has its peculiarities, not present in the cabled types of networks. These features impact the functionality and feasibility of using common standards. One example of this is the problems related to TCP on-top of IP. This topic has been addressed several times, for example in RFC2488 [144]. The long delay present in satellite networks impacts how acknowledgments are handled, and if the transmitting node does not receive the acknowledgment within the defined timeout, the TCP protocol at the transmitter will interpret this as network congestion or erroneous transmission of a link-layer frame. The TCP-protocol reaction to either of these erroneously interperted situations will reduce the data rate throughout the system [142, 145].

Throughout this chapter, the following definitions are useful:

Definition 2 *A structured chunk of data on the link-layer is called a **frame**.*

Definition 3 *A structured chunk of data on the network-layer is called a **packet**.*

Definition 4 *A structured chunk of data on the application-layer is called a **message**.*

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[1]For example: Voice, video conferences, live remote control of equipment

This chapter will first study the fundamentals of the networks stack. Then a network stack is proposed, and finally an implementation of this network stack is evaluated as a part of the architecture presented in Section 3.1, combining simulations of satellite orbits defined in Chapter 4 and a network emulator.

The effort needed to study and define the network stack for this, and similar architectures will require different competences. In the work described in this chapter, the authors' contribution is to provide details of the satellite part of this architecture, and how to link this to the rest of the network. This has been input to the collaboration with experts for network and unmanned vehicles. The role of the satellite expert is to bring forth properties and impacts of various satellite orbits and radio channel properties. The network expert can then better propose a suitable protocol stack, define metrics for network evaluation and setting up evaluation software. Without this type of cooperation, the design of an architecture as discussed in this thesis will be less realistic. In this particular case, this collaboration resulted in several papers (c.f papers E – G in Appendix A).

5.1 The Network Stack

In the following sections a proposal for a network stack will be presented. The emphasis is on ease of interoperability between different nodes in the networks as well as interoperability between various networks. The network stack will be presented with that as the primary driver, however the specific *implementation* of the network stack and protocols is given less consideration.

5.1.1 Heterogeneous Networks

The network architecture presented in Section 3.1 is a heterogeneous network resembling the architecture concept I from Section 3.3. Unmanned Vehicle (UV)s and other vehicles as ships are also considered as Network nodes in this network. The space component is based on satellites in a polar orbit.

Figure 5.1 shows a simple layout of a IoT-compatible network stack model, corresponding to the Open Systems Interconnection - OSI model [146].

The definition and implementation of a network stack is a complex topic. The use of existing protocols (for example as used for IoT) potentially gives easy interoperability with excising systems, but has to be traded against custom implementation that might be more efficient and better to use for a narrowband satellite link. Discussions and work presented here are also be found in the papers [32, 116, 117]. There it is argued that all sensor nodes should be reachable through the Internet, and therefore common internet protocols should be used. The use of a network stack as described below also means that the satellites must be fully regenerative;

IoT Compatible Network Stack

7: Application Data sink/source	DTN CoAP
5/6: Session/ presentation	
4: Transport	UDP
3: Network	6LoWPAN Routing
2: Link - framing	FEC/CRC Mult-access
1: Physical RF ch.	ModCod FDMA/TDMA
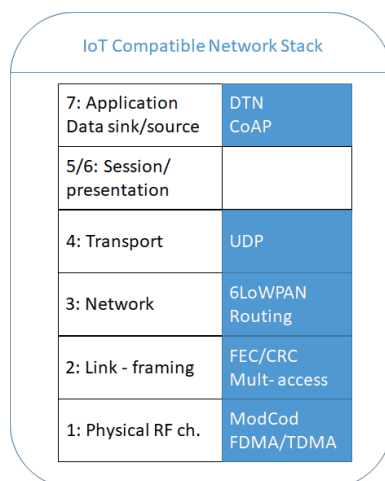
Figure 5.1: Simple layered network stack model with example functions and protocols, derived from the commonly known OSI model.

as all nodes in the network must be able to handle the messages and interact with neighboring nodes.

5.1.2 Cross Layer Design

Traditionally, one layer only interacts with the layers above (if any) and below (if any) through a defined set of interface functions. However, in order to best adapt the total system yield to changing conditions, and changing user needs, some degree of *cross layer* design will be needed [141, 142]. This means that one layer interacts with a layer more than one place above or below in the network stack.

One simple example is if we want the Physical Network Layer (PHY) to adapt to changing conditions of the radio channel, using methods for Adaptive Coding and Modulation (ACM). There can be several reasons for wanting this: One is that the link budget is designed to cope with temporarily poor link conditions (see Section 6.8 on Link Budgets). During normal conditions, this leads to underestimation of the link margin and poor exploitation of the link, hence valuable throughput is wasted. This means that the link should be capable of adapting to changing conditions. Also, a node might want to transfer a type of data that must be error-free, or sometimes the node wants to transfer data where (small) losses are acceptable. In all cases, this calls for interaction between the PHY, Media Access Control (MAC) and application layers. If the link quality is good, the PHY might instruct the application-layer to generate more data. In the opposite case, the PHY might want to instruct the application to generate less data, in order to

prevent buffer overflows and losses due to that. When transitioning from data with a reliability requirement to data without this requirement, the application layer can instruct MAC to ease requirements for ACK/NACK/ARQ, which potentially could waste both time and channel resources.

A further argument for employing a cross layer design, or even remove some of the traditional layers, is that each layer in the network stack adds additional overhead to the system. One could then argue that, for example, avoiding network and transport layers (see Figure 5.1) and further more combine layers 5 to 7, it will be possible to remove the overhead introduced by network protocols. However, this can lead to a higher implementation cost in the higher layers; as the application must take care of everything; from network, routing and keeping track of delivered and non-delivered messages. The gain of relying on standard implementations for network protocols is also lost. The increased overhead from standard protocol implementations must be weighed against the higher implementation cost. The overhead from standard protocols is further discussed in Section 5.5.5 and in [117].

5.1.3   Network Layers

Layer one is often denoted Physical Network Layer (PHY), and is in our case the radio link. Its properties are the selected frequency, bandwidth, power levels and so on. Layer two is the link or Media Access Control (MAC) layer. Here, the data frames transmitted over the radio channel will be created. Mapping/demapping of modulated/de-modulated bits from the PHY takes place here. Layer 3 & 4 are responsible for addressing, routing and reliable transport of the data packets to the end user. Higher layers present, in the defined format, data to the end user.

5.1.4   Layer 1 - Physical Layer

Some of the properties of the physical layer, such as power levels, modulation(s), frequency and allowed frequency bandwidth, are covered in Chapters 6 and 6.8.3. Adaptive links are discussed in Section 6.6.

Other Layer 1 related topics include how to divide the physical channel resources among users, by means of multiple access methods such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) or use of spot beams for one or several users. The mentioned access methods can be combined in different manners that vary with system, application and time. These methods are Layer 1 properties, but in some way they can be said to implement functionality (granting user access to the channel), normally thought of as a Layer 2 task.

5.1.5   Layer 2 - Link - Medium Access Control-Layer

This layer has two main tasks: Number one is granting users access to the radio resources. The second is ensuring that the traffic on the radio channel is transmitted from sink-to-source error free in the most efficient manner. The total data throughput capacity in a small satellite such as a CubeSat is fairly limited. Also the pass duration is relatively short, on the order of 10 minutes, so efficient use of the radio resources is important. Therefore, the use of link-layer (or channel) coding is common.

The traffic from the nodes can be said to be *bursty*, meaning the traffic from one node only occurs for a short period of time during a day, or a period of coverage. This implies that a fixed allocation of channel resources, either by time-slots or different frequency channels will lead to waste of resources, as they are not used for most of the time.

Medium Access and Random Access Methods

The sensor nodes will need to transmit various forms of messages. Both longer messages containing scientific data and short status messages (telemetry) will be needed. Both types of messages can in addition be *regular* or *random*, with regards to when and how often the node wishes to transmit a message. The mode of operation for the node might also change during the period of operation, as a function of time of day or year, time passed, events occurring and so on.

Based upon how sensor data is generated, two modes are defined:

Definition 5 *A node producing larger amounts of data on a regular basis can operate in* ***assigned mode***.

Definition 6 *A node producing smaller amounts of data on non-regular (random) basis can operate in* ***random mode***.

Random Mode   In order to accommodate the nodes operating in *random mode*, as well as new nodes, the system must allow for Random Access (RA). However, since much of the traffic in this kind of system can be predicted, not all traffic should to be initiated over an RA-channel, as this will waste time during setup and channel assignment.

A well-known RA-method is ALOHA. This method allows the nodes to speak when they have data to transmit. It is shown that a method as slotted ALOHA will only yield a channel efficiency of around 36% [147], meaning valuable channel resources are wasted. Several articles discuss this topic, as well as other suitable random access methods [143, 148, 149, 150].

Assigned Mode   The nodes operating in *assigned mode*, have fixed and pre-determined access to channel resources, either by assigning them a fixed frequency channel (FDMA), a fixed time-slot (TDMA) or a combination of these (separate FDMA-channels which in turn are divided by time slots). The time slots or channels are part of layer 1, but the control and assigning of these resources are taken care of at layer 2. If all nodes use their assigned resources all the time, the channel can be utilized efficiently and congestion-free. However, if the nodes are not using their assigned resources, these are wasted. Therefore, this way of allocating channel resources is best when the load is split in a defined way between the nodes.

Another way of designing a (near) congestion-free system is to base the traffic management on the satellite polling the nodes. This will be like a client/server-based request-response system, where the node can be viewed as the server (data source), and the satellite as the client (data user). This way, we will not allow for any random access to the channel. The consequence is that this will impede deployment of new nodes, as new nodes should be able to register to the network.

A middle ground is to split the time between a signaling, or random access channel, and strict allocation of the channel resources. A given fraction of the channel is set aside for random access or other signaling. The duration of the random channel frame must be decided so it is long enough for the random access period to be usable, and short enough for the random access period to repeat itself a sufficient number of times during a pass over a sensor node.

During a pass, the satellite will use its acquired knowledge about the sensor nodes, as well as requests received during the signaling-period, to allocate resources to the sensor nodes. This can be done in two ways: The first method will be to use fixed time-slot allocations similar to a dynamic TDMA system, and then grant the sensor nodes access to a given number of time-slots. If the data transfer is obstructed for some reason, and the transfer of data is not complete within the allocated number of frames, the node must wait until the next pass.

In the second method, the satellite will poll each sensor node, and instruct it to send a fixed amount of data. The sensor node then has access to the channel until the data is transferred, until a timeout is reached or until the satellite has moved out of sight. A timeout mechanism is necessary if an error should occur during data transfer, in order to not block other nodes during the whole pass. When data from one node is transferred to the satellite, the satellite will issue a polling request to the next sensor node.

At the end of each pass between the satellite and the sensor node, the next contact should be agreed, in order to minimize the load on the random-access channel. This way, only new nodes, or new and un-expected events have to be announced through the random-access channel.

Link-Layer Coding (FEC)

The radio channel will never be able to transfer data error-free. Noise will impede the signal, and bit errors will be introduced. These errors must be detected and corrected for. Data produced by the sensor nodes should reach its destination unchanged and eventually error free. In the following we will use the term "error-free" for the data obtained after error correction, meaning they are "error-free" to the extent of meeting the data quality requirements of the end user.

A decision must be made on where, and how, consistent data transmission checks should be performed. In order to ensure integrity and consistency of data, the link layer should at least employ an integrity check of received frames by using Cyclic Redundancy Check (CRC). In addition, to increase the probability of receiving an error-free frame (or to save transmitted power), additional coding can be added, commonly called Forward Error-correction Code (FEC). These codes work by adding redundant bits to a link-layer-frame, in order to enable recovery of some erroneous bits in the received frame, and then decode the whole frame correctly. The strength of the code depends upon how much redundancy is added. This indicates that it exists a trade-off between receiving a frame error-free and the usable bit rate, as the information rate is reduced due to introduction of redundant data. In combination with FEC, different varieties of ARQ can be used in order to request any missing frames due to link outages or FEC failure. In the ideal case, the link layer should provide near loss-free communication. This in order to ease the requirements for higher order protocols, such as IP. This also implies that all nodes in the network, including the satellite, must be fully re-generative. All messages must be de-coded and checked in order to fulfill necessary error handling within acceptable time limits.

Discussions on how the coding influences the link budget are presented in Section 6.8 and in Section 7.3.2. Coding will increase the link margin, but it also reduces the end user goodput.

Confirmation of Message Delivery

The implementation of message integrity checks will result in the need for ACKnowlegde (ACK)/Negative ACKnowlegde (NACK) messages. Should this be implemented on the link-layer or on the network/transport layer or on the application layer? Should it be an end-to-end check or link-to-link (node-to-node) check? If network layer frames (See Definition 2) are evaluated on end-to-end transmission over a multihop network (for example, sensor node to satellite to gateway to end-user), an error introduced on any of those links will cause an erroneous transmission. Due to the nature of the network architecture and coverage; end-to-end transfers may take a long time; sometimes several hours. Then, the NACK must

also be transmitted back the same or a similar route. A re-transmission must be issued and the process will start over again. This leads to potentially very long delays (minimum three end-to-end transmissions) as well as the need for buffering of old data on the sensor nodes.

A more efficient procedure is to evaluate the traffic on a link-to-link basis, meaning that a receiver node demodulates and decodes the received packet from its neighbors in the multi-hop-link. This calls for a "smarter" receiver in the satellite, but the end-to-end transmission times will be significantly reduced. The transmitted message can be deleted from buffers when reception in the next network node is confirmed. Since the architecture must have delay tolerant properties; meaning that any node on the route must take custody of the data regardless if it is decoded or not; link-to-link based FEC and ARQ resolving will not increase the need for buffers in intermittent nodes significantly. Decoding of data is common in highly integrated radio systems for small satellites, and radios based on Software Defined Radio (SDR) will intrinsically decode any received message. This is further discussed in Section 5.5.6.

Short Messages The use of link-layer codes will be efficient if data from nodes is on the form of short independent packets. In this case, each and every packet must be transmitted and received error-free.

Long Messages Different strategies to code larger chunks of data exists. Which strategy to use also depends on the radio channel. If the noise can be modeled as Additive White Gaussian Noise (AWGN), link-layer coding can be sufficient. However, if the link experiences various fading phenomena that causes loss of many bits in individual frames, then, for example, several IP-packets can be interleaved. Then, bit-errors will be split over multiple IP-packets, with the possibility of reconstructing them.

Also, in general, a data network may also lose packets due to other errors than bit errors. The network can experience congestion and full buffers, causing packet drops. If a NWN experiences a re-start or power-off while it holds data, this data may be lost. Various strategies can be enforced to mitigate this. This encompasses both various coding schemes, but it also includes how to logically handle such situations. Detailed discussion and analysis of these topics are outside the scope of this work.

5.1.6 Layers 3 & 4 - Network and Transport Layers

Layers 3 and 4 take care of the routing and further transport of the data to its endpoint, possibly through several jumps and several different physical channels. All

nodes in the network must be able to take care of their routing function so they can select which packets to send forward on which channel.

By using common implementations of well-known protocols, for example, IoT-protocols such as 6LoWPAN, sensor nodes and satellites can interact easily with other agents in the connected network(s). Which protocols to use must be selected carefully. New IoT protocols are designed for networks with low data rates and where the link availability is not constant. These implement functionality that helps the already stated short-comings of, for example, TCP [142, 144, 145]. Proposed protocols, implications and implementations are discussed further in the papers [116, 117].

Transmission Planning, Orbit Propagators and Smart Routing

In order to minimize the energy consumption at the node, the contact times between the sensor node and the satellite must be coordinated. This coordination, including the smart routing, can be implemented in several ways. Two examples follow: One option is to let the node have its own orbit propagator, and receive Two-Line Elements (TLE)s [125] once in a while from all satellites[2]. Based on the TLEs and the node's geographic position, the propagator will calculate the next satellite pass, taking into account the total message propagation time to the gateway (the smart routing), and the radio can be woken up in due time.

A second option is to let the gateway or the satellite perform the calculation of the best transmit times. The satellite will then broadcast the time of the next passes during the current pass. This can be a broadcast message to all sensor nodes, transmitted at regular intervals. For the satellite, this requires that the satellite itself knows its own TLE and therefore its place in the orbit as well as the node positions, so this time can be adjusted as the satellite moves over the ground.

Another version of the last option can be to let the node and the satellite directly negotiate when the next contact will be. However, this will require much more radio traffic and will be a more complex process compared to a broadcast message. The pitfall with the broadcast option is that if the sensor node loses contact with the satellite for one or two passes where it should have had contact, it can get completely out of sync.

In that case, the node should have its own orbit propagator anyway, or it must keep its receiver on until it successfully receives a new link availability message from the satellite. It is assumed that the advanced sensor nodes will have sufficient computational power to successfully run the orbit propagator. There are readily available open source propagator libraries for Python, based on SPG4, so this can be run on any microprocessor running Linux.

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[2]TLEs are usually valid one to two weeks at the time.

Smart Routing In order to best plan in which order the nodes should be assigned which resources and when, the satellite should have knowledge about the geographical position of each and every sensor node. It can be shown that when the network has members that are not seen by all satellite revolutions, considerable reduction of the end-to-end delay can be gained if the node employs a *smart routing* method for selecting which satellite to route its data through [117]. In short, this method is forward-looking and aims to calculate which of the satellites in a swarm or constellation a sensor node or gateway should connect to, in order to minimize the delay between transmission and reception of a message. This is done so that the sensor node (or gateway) simulates the next satellite passes, form its own viewpoint and also at the target node. Based on when these passes will take place, the source node calculates which satellite can relay a message to the target quickest. This, in contrast with the *naive* routing, which will send its message to the first satellite available. The performance impacts from this method is presented in network simulations Sections 5.5.5.

5.1.7   Layers 5, 6 & 7 - Higher Layers

Even if the details of the data sinks and sources are beyond scope of this thesis work, it is important to maintain some knowledge about the implications enforced by these layers. Also, the requirement to have a delay-tolerant, error-free, data delivery leads to constraints on how lower layers should be designed and implemented. Delay-Tolerant Network (DTN)-like protocols, also CoAP, are running on the application level (level 7), so the network functionality itself encompasses all layers in the network stack.

5.2   Dynamic Network Management

In addition to the network topology changes when satellites routinely appear and disappear over the horizon, other events that call for network adaptivity, can be extreme link conditions such as solar storms, antenna icing or antenna drowning. In those cases, the risk of link loss is imminent and the link will either be present or not. Another likely case is related to the throughput requirement from a node. This can change with regards to the type of data recorded, as detection of events can trigger more data to be aggregated or that the importance of the data changes due to an event. This could call for the need of dynamic capacity allocation and/or dynamic scheduling.

   If the data to be transmitted is not urgent, the sensor node could request a slot large enough to fit its data and then the satellite (or a central network manager) could allocate the capacity. This could lead to the situation where the node will not

be allowed to transmit its data during the current pass, it might have to wait until the next pass. If the data is urgent, other nodes may have to yield their capacity.

In situations where there are several routes to reach the network (or if it is possible to make capacity requests during one pass and do the actual data transmission the following pass), one could envision a central network controller (not in the satellite) handling the routing within the network. This controller could utilize all network resources, ground/air-based and satellite. The controller's decision could then be transmitted to the network, either through the satellite or through other paths. This could lead to less service and signaling traffic over the links and therefore more capacity for user data. The network, and the links therein, will only change when needed and otherwise be static.

5.3   Network Design Proposal

The discussion above leads to two distinct design choices: Alternative 1 is to implement a network stack as discussed above, implementing support for IoT-like IP networks based upon 6LoWPAN. Alternative 2 is to implement a very simple stack, with no real network functionality, giving the need for network gateways to translate between the satellite links and the outside world. With option 2, network overhead over the satellite links can most likely be reduced a great deal; restricting the overhead to only a simple custom link-layer addressing scheme and other required header fields. Then, for example, overhead from 6LoWPAN and CoAP as well as network service traffic will be eliminated.

All network nodes or sensor nodes interacting with other networks must then have a gateway router to translate between the networks. Depending on how important a seamless operation between multiple heterogeneous networks is, this added implementation cost – and reduced overhead gain – will be a subject to trade. The layer 3 smart-routing functionality could still be implemented. Also, standard network protocols are well proven and they have intrinsic security and authentication measures. This loss of functionality must then also be traded against the increased overhead.

In the remainder of this study, it is assumed the use of an IoT network stack, due to the functionality gain this implementation gives. Results from network emulations are given in Section 5.5.5, with an estimation of expected overhead and throughput for this setup.

Selected network stack for the first design iteration

> **Layer 1** A few FDMA ch.s + dynamically allocated "slow" TDMA
> **Layer 2** Suitable frame format. Network emulations use 802.15.4
> **Layer 3** 6LoWPAN
> **Layer 4** User Datagram Protocol (UDP)
> **Layer 7** CoAP

The final design for the stack should be defined after further validation in a detailed design phase of the mission. Main decisions may be whether or not to use an IP-based protocol such as 6LoWPAN, and eventually whether to use CoAP or another Delay-Tolerant Network (DTN) protocol on layer seven. In addition, medium access and resource sharing must be carefully considered, taking into account the final expected number of sensor nodes and also other uses of the frequency resource, that can lead to interference.

5.3.1   Hand-Over Between Satellites

In this study, a link to a satellite is considered active if a sensor node or gateway sees the satellite. When the satellite is beyond line of sight, the link does not exist. This also implies that there is no direct hand-over to the next satellite; even if that satellite might be visible before the first satellite goes below the horizon; as can be the case for some configurations of a freely drifting swarm. The links are only handled on individual basis, and the DTN functionality will take care of transporting the message to its final destination.

5.3.2   Identification and Security

Cybersecurity is an increasingly important topic today, but details of this topic is considered beyond the scope of this work. For an Arctic sensor network, it is expected that all network nodes must be uniquely identified, and access must be restricted to authenticated users. An IoT-based implementation it is expected to make use of inherit functionality in standard protocols.

5.3.3   Transfer of Data to Earth Station

The satellites in the network will have a store-and-forward payload that collects data from sensor nodes, aggregates this data and then transmits it to the gateway station for distribution to the end user. If the sensor-node and the gateway are both within sight from the satellite, the delay time for this forward might be on the order of milliseconds, if the satellite simply forwards the data to the gateway immediately.

5.4   Network Evaluation and Emulation Method

The network stack described in this chapter was implemented in a network emulator in order to evaluate the properties of a network based on the architecture from Section 3.1.4.

5.4.1   Scenario Definition

A reference scenario [34] suitable for investigating the research questions *RQ1 – RQ3* and the mission objectives defined in Section 2.2.1 was defined. The scenario consists of sensor nodes and ground stations placed as shown in Figure 5.4, and a swarm of three small satellites as selected in Section 4.3.3.

5.4.2   Satellite Simulations

The contact times between satellites, ground stations and sensor nodes were calculated using the toolchain defined in Section 2.4 with realistic information about the nodes placements and regions of interest.

From the orbit simulations, a time-step list was generated, including details about link properties (i.e. one-way delay and bit rate) between all the considered node pairs. For each time-step we assume that the satellite link is capable of delivering loss-free communication, with a set bit rate and within the specified delay calculated as free-space propagation delay. The links are considered either *available* or *unavailable*.

Since the topology of a freely-drifting swarm continuously changes over time, a continuous emulation of the network would also be required over a large period of time that can span from 40 to 180 days [115], in order to cover all possible configurations.

However, since the network emulator runs in true-time, only three shorter sections of the swarm are considered, as shown in Figure 4.3.3, for the swarm configurations uniformly distributed, overlapping and trailing. For each of these sections, the network performance was evaluated over a period of approximately one day, corresponding to 14 complete passes over all the selected nodes. The obtained results are presented in Section 5.5.4 and compared against a two satellite constellation statically configured in a uniform distribution.

5.4.3   Network Emulator

The network emulator was developed by David Palma, as part of his Marie Skłodowska-Curie fellowship, the Software-defined Intermittent Networking (SINet) project.

Further details can be found in [35, 34, 77]. A schematic of its functionality and relation to the satellite simulator is shown in Figure 5.2.

The author developed the orbit simulator, and defined the data format for feeding the orbit simulator output into the network emulator. The author also contributed to emulator output analysis and interpretation of the results, including identifying results leading to the forward looking routing.
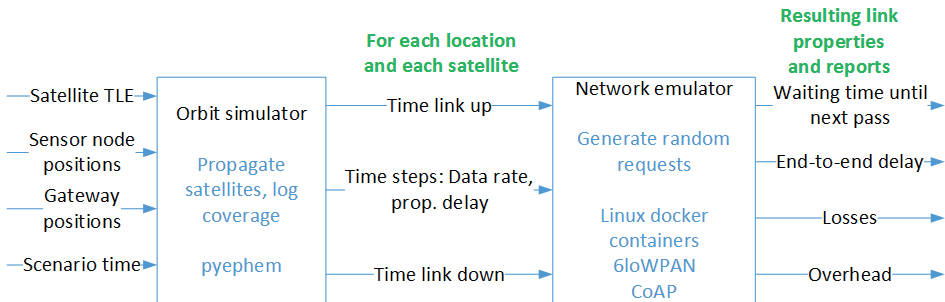
Figure 5.2: Functional model of network simulator and emulator

The used solution is capable of emulating not only several satellite nodes, but also sensor devices and ground stations, as well as the characteristics of available communication between them.

Emulation is achieved by using operating-system-level visualization, also known as *containers*, for allowing a complete execution of real software tools and network protocols.

Specifically, Ubuntu 16.04 docker containers [151] were used, created with a modified version of the *Imunes* emulation tool [152]. A set of scripts defines and enables an evolving network topology, where links are adapted throughout the emulation time, following the calculated contact periods between ground nodes, satellites and sensor nodes.

In the emulator, links between nodes have a dedicated Linux *network namespace*, isolating them from other traffic. Additionally, based on the input from the satellite swarm simulation, the bit rate and delay of each link are configured by using Linux *qdiscs*. For this purpose the *htb* and *netem qdiscs* were used.

In order to mimic the constrained nature of satellite links, the used network interfaces were based on Linux *nl802154* physical layer[3]. This allowed assessing the performance of IPv6 over narrowband links, using 6LoWPAN. For the same reason the CoAP protocol was used for exchanging data between the sensor nodes and ground stations, through the satellites. CoAPthon was the chosen implementation [153], which was slightly modified to hold requests/responses whenever no

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[3]http://wpan.cakelab.org/

link was available. The implemented behavior is similar to that expected by a DTN- protocol, but no routing protocol was used. This means that the Layer-3 smart forward looking routing described in Section 5.1.6 was not implemented for these emulations. Instead, routes were established taking into account the information about satellites and their orbits, reducing the control overhead.

Data requests were randomly generated for emulating traffic being exchanged between ground stations and sensor nodes, using the small-satellites and proxies. These requests followed a random uniform distribution between 60 and 180 seconds. The chosen destination for each request also followed a random uniform distribution, so that all sensor nodes were equally used. In addition, the payload size of each reply was constant, with a total of 512 bytes per response, which can correspond to several types of sensor network applications.

The network performance is evaluated from the *user's perspective*, meaning that the end-to-end response time is measured from the instant that a user makes a request until it receives a response. From this perspective the satellite-link availability for an arbitrary node is unknown, and therefore requests were issued randomly. If needed, these requests were buffered at the ground station gateways, following a delay-tolerant approach, until a satellite was within range. If the end-to-end response time was measured from this instant, both the maximum and average times would be lower depending on the methodology used.

5.5 Network Evaluation and Emulation Results

The emulator was used to compare the utility of a freely drifting swarm with a two-satellite static constellation. The results from this work are also presented in [116, 117].

5.5.1 Properties of the Small-Satellites Swarm

Immediately after its deployment the swarm will be in a clustered state. The footprints of the member satellites virtually *overlapping*. This results in a network with the same apparent capacity as if it only had one satellite.

Figure 5.3 shows how the swarm can develop over time. It must also be noted that the satellites seem to be overlapping from the observer on ground. In orbit, the distance between them will be large as they will have different orbital altitudes.

After some time, the satellites will increase their distances, and will practically follow one another (*trailing*). Later on, the swarm will look like a "perfect" uniformly distributed constellation (*uniform*). These configurations will not last long, as the satellites constantly continue to drift, and eventually they will again converge, overlapping, and the cycle repeats itself.
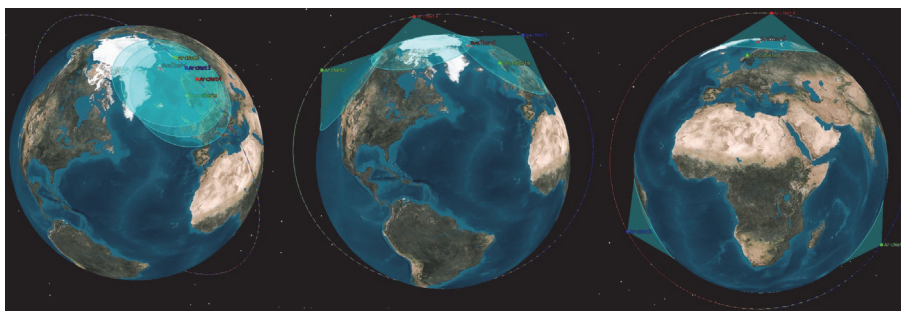
Figure 5.3: Example of what a swarm of three satellites can look like at different times. Left: Overlapping, just after deployment. Middle: Trailing coverage. Right: Uniform separation.

Since the proposed concept resorts to a freely-drifting swarm in order to provide connectivity, it is important to investigate how swarm dynamics, in particular in the *overlapping*, *trailing* and *uniform* stages, influence network performance. Since the use of CubeSats or other small satellites is envisioned, the satellite payload should be quite simple, but still flexible to meet mission requirements. Additionally, sensor nodes in remote locations will most likely be constrained, and the amount of data that can be transmitted will be limited by power at the nodes.

For the links between the sensor nodes and satellites, 20 kbps is used in the emulations. The bit rate is chosen to a conservative value, in order to support low-power sensor nodes with near omni-directional antennas. It should also be noted that when the link is active, it is assumed and treated error-free, so there are no losses due to bit-errors on the physical layer in these emulations. However, losses can occur in other parts of the network stack.

5.5.2 Ground Stations

Figure 5.4 shows a map including five relevant locations for the placement of both sensor nodes and gateways. Two gateways are considered, one placed in Vardø, in Northern Norway and another at Svalbard. The locations currently operate real ground stations for many missions, so the infrastructures are in place. Having ground stations this far north (Svalbard and Vardø) allows satellites with polar orbits to be able to simultaneously communicate with the ground station and sensor nodes, though not necessarily in all passes. In addition, a ground station at Svalbard will typically see all passes for a polar orbiting satellite, whereas a ground station placed considerably further away from the pole will not. However, operating in Svalbard may incur additional costs compared with a ground station on the mainland.

Vardø will experience long gaps in communication with the satellites, due to its position further south. These gaps last several hours as the ground station is out of reach by all satellites in the orbital plane for several consecutive orbits. As one moves closer to the equator, these outage periods increase. Therefore, by using spatially distributed ground stations, for instance connected through the Internet, the total access time can be increased. For example, placing a ground station at the Troll station in Antarctica would increase the spatial distribution, but additional operational costs have to be accounted for.

5.5.3   Sensor Nodes

For this setup, three locations were chosen, one at *Rossøya*, north of Spitsbergen, and two in the Fram strait (*GR_North)* and (*GR_South*). The Fram strait, between Greenland and Svalbard, is the region where drifting nodes, for example, from the Arctic ABC project, are expected to end up [27, 28].

In order to assess the network performance with different coverage conditions, the sensor nodes are placed in locations where all satellite passes are visible (Rossøya and GR_North), as well as locations where not all passes are available (GR_South). Due to the East-West separation between GR_south and Vardø especially, their outage periods will not completely overlap. This means that when considering a link between these nodes, a total gap larger than the gap for any of the individual network nodes will occur. The situation will get worse when the East-West separation increases. This can be mitigated by adding ground stations either further north (to see all passes and reduce the ground station gap), or by placing a new ground station closer to the sensor node longitude (to increase the overlap of their outage periods).

5.5.4   Network Delay Results

Following the proposed evaluation methodology, the presented results for the drifting swarm include its three main configurations, *overlapping*, *trailing* and *uniform*. Additionally, a weighted average, approximation of the overall network performance is included, where each of the configurations is given the same weight. This is a conservative approximation, as the swarm will be in a state between trailing and uniform distribution (i.e. shorter coverage gaps) for considerably longer periods than it will be in the overlapping state (see Section 7.3.2 and [117]). We therefore state that in practice, the three-satellite swarm network should perform better than this approximation.

The network performance of the proposed drifting swarm focuses on the average time taken from request to response ($\bar{e2e}$), as well as the highest value ($e2e^*$). Additionally, the $\bar{ACK}$ and ACK^* parameters respectively represent the average

Figure 5.4: Map showing where all nodes and ground stations are placed. KSAT Svalbard and Vardø (red dots) are used as typical ground station locations, the rest (blue dots) are sensor nodes.

and the highest duration from a request being received in a ground station and acknowledged by a satellite. This interval is, in most cases, identical to the *time-to-next-pass*, however, in some special cases it is not. For example, requests being made on the very end of a pass can be received by a satellite, but the confirmation may not be transmitted before the link between the ground station and the satellite fails.

This can influence the minimum and maximum times, and it makes the average *ACK* worse than the *time-to-next-pass*, therefore it should be interpreted as *time-to-next-useful-pass*. All *ACK* values are seen from the issuing ground station, independently of which node the request is for.

The minimum end-to-end results are not presented in this work as they are not representative of the overall performance being evaluated. This results from instants where sensor nodes and the ground stations are both in view of the satellite, resulting in direct relaying and in a minimum *e2e* and *ACK* close to zero. For similar reasons, the maximum end-to-end results are also not presented either, since they reflect only the maximum end-to-end of GR_South, which was purposely positioned so that coverage outages would occur.

The presented *e2e* and *ACK* arithmetic means are respectively within ±11 and ±8 minutes, with a 95% confidence interval.

Vardø Ground Station

The results obtained for Vardø, as the only available ground station, are shown in Table 5.1. In this table, the subscript *Ross* stands for the sensor node deployed at Rossøya, while GR_S represents a node at GR_South. The column labeled *Overlapping* corresponds to the measured network performance when the three drifting small-satellites overlap each other. Similarly, columns *Trailing* and *Uniform* respectively represent the periods when a small-satellite immediately succeeds another and when they are uniformly distributed between themselves. Finally, the *Swarm* column represents the overall performance of the proposed satellite network considering its different topologies, which can be compared against the constantly uniform distribution of two small-satellites (column *2 Sats*).

Table 5.1: Performance in *hh:mm:ss* for Vardø

	Overlap.	Trailing	Uniform	Swarm	2 Sats
Avg. end-to-end ($\bar{e2e}$)	01:42:38	01:29:02	01:15:35	01:28:48	01:44:05
Avg. time to ACK ($\bar{ACK}$)	01:01:27	00:53:46	00:45:56	00:52:48	01:06:49
Max time to ACK (ACK^*)	06:40:44	06:19:37	06:15:04	06:24:36	06:45:33
Avg. e2e at Rossøya ($\bar{e2e}_{Ross}$)	01:17:59	00:59:43	00:53:55	01:03:00	00:57:37
Max e2e at Rossøya ($e2e^*_{Ross}$)	06:22:54	06:07:20	06:05:12	06:11:24	06:28:47
Avg. e2e at GR_S ($\bar{e2e}_{GR_S}$)	01:52:32	00:59:43	01:31:17	01:27:36	02:20:15
Max e2e at GR_S ($e2e^*_{GR_S}$)	09:51:25	06:07:20	09:29:19	08:28:48	10:02:20

As expected, the network performance improves when the constellation spreads and the swarm of small satellites becomes uniformly distributed. Such improvement is shown by the arithmetic mean of the end-to-end time ($\bar{e2e}$) when requesting and receiving data from a remote sensor-node. This becomes more noticeable when analyzing average time for receiving a first ACK from a satellite node ($\bar{ACK}$), which is representative of the time a request waits until it is served. However, due to the positioning of the ground station and ground nodes, with respect to the orbit of the satellite nodes, the worst case-scenario between passes is similar for the different stages of the swarm, as expected.

In addition to the existence of outage periods for the nodes too far south to see all passes, other factors have also influenced the measured performance of the proposed solution. Since the performed evaluation used real networking conditions and protocols, processing delays and concurrency between requests originated ad-

ditional degradation for a few requests. In fact, the unexpected difference in max-imum end-to-end-time for GR_South, when comparing the *Trailing* configuration with the other two configurations, is explained by a request being received before the outage at Vardø occurs. The request can only be completed when this period has passed and the satellite is available again.

Finally, and following the motivation for the proposed approach, the obtained results demonstrate that a simpler deployment of three drifting small-satellites out-performs a constellation of two uniformly distributed small-satellites. In fact, for a heterogeneous positioning of sensor nodes, the proposed solution is, on aver-age, better even in its worst stage, with overlapping satellites. For more limited coverage of remote locations, where satellite orbits are perfectly aligned with the sensor nodes and avoid non-overlapping outage periods, the proposed solution has a slightly higher end-to-end average than the static two satellite constellation, 63 *vs.* 58 minutes. However, this is negligible when considering all the advantages from the proposed swarm, which can make use of simpler hardware and allows for easier and cost-efficient deployment and operation.

Svalbard Ground Station

The results for the topology using the Svalbard ground station are shown in Ta-ble 5.2, including the same previously described metrics. Similarly to Vardø, the registered performance improves as the swarm becomes uniformly distributed, which is in agreement with defined hypothesis. Additionally, the swarm's over-all performance, considering all its different states, is comparable to the results obtained by the two-satellite constellation, which also improved with the ground station placed at Svalbard. This overall improvement is mostly due to simultane-ous coverage of sensor nodes and the ground station, which results in the relaying of requests and responses with minimal delay.

When comparing Svalbard against Vardø, the former outperforms the latter in almost all conditions. This is verified for both the proposed solution and the two satellite constellation, as it solely depends on the ground station's positioning. However, when considering the sensor node located at GR_South, the observed improvement is not so pronounced, due to the East-West separation that also af-fected Svalbard.

Vardø and Svalbard Ground Stations

As previously discussed, well-placed ground stations may improve the perfor-mance of satellite networks, as verified with Svalbard, but it depends on existing infrastructures and can imply increased costs. The scenario with both Vardø and Svalbard ground stations aims at achieving a trade-off between existing options,

Table 5.2: Performance in *hh:mm:ss* for Svalbard

	Overlap.	Trailing	Uniform	Swarm	2 Sats
Avg. end-to-end ($e\bar{2}e$)	00:47:32	00:37:59	00:28:48	00:37:12	00:37:28
Avg. time to ACK ($A\bar{C}K$)	00:30:27	00:20:41	00:07:43	00:19:12	00:15:29
Max time to ACK (ACK^*)	01:24:16	01:09:10	00:27:44	01:00:00	00:44:52
Avg. e2e at Rossøya ($e2\bar{e}_{Ross}$)	00:33:14	00:22:52	00:10:59	00:21:36	00:19:15
Max e2e at Rossøya ($e2e^*_{Ross}$)	01:32:21	01:35:41	01:36:24	01:34:12	01:39:56
Avg. e2e at GR_S ($e2\bar{e}_{GR_S}$)	01:16:46	01:05:27	01:06:34	01:09:00	01:15:13
Max e2e at GR_S ($e2e^*_{GR_S}$)	06:44:01	06:09:04	07:07:45	06:40:12	07:24:59

taking advantage of the chosen IP-based networking protocols. For this scenario Vardø and Svalbard were connected through a dedicated link, routing requests and responses through the shortest-existing path to a satellite node. In order to distribute load, the same amount of requests was generated in Vardø and Svalbard, meaning that this link was only used when one of the stations had no satellite coverage. The obtained results are presented in Table 5.3 following the same metrics used for the previous scenarios.

Table 5.3: Performance in *hh:mm:ss* for Vardø and Svalbard

	Overlap.	Trailing	Uniform	Swarm	2 Sats
Avg. end-to-end ($e\bar{2}e$)	00:48:04	00:38:13	00:29:27	00:38:24	00:37:57
Avg. time to ACK ($A\bar{C}K$)	00:29:43	00:20:24	00:07:12	00:18:36	00:15:09
Max time to ACK (ACK^*)	01:24:18	01:31:13	01:31:29	01:28:48	01:31:48
Avg. e2e at Rossøya ($e2\bar{e}_{Ross}$)	00:34:04	00:24:13	00:13:01	00:23:24	00:19:15
Max e2e at Rossøya ($e2e^*_{Ross}$)	02:52:12	01:50:53	01:36:25	02:06:00	01:39:57
Avg. e2e at GR_S ($e2\bar{e}_{GR_S}$)	01:16:02	01:06:04	01:02:38	01:07:48	01:15:04
Max e2e at GR_S ($e2e^*_{GR_S}$)	06:44:02	06:09:06	07:07:46	06:40:12	07:25:00

By combining the two ground stations, improvements are registered in all cases, when compared against only using Vardø. This is verified not only for the

overall network performance, but also when considering sensor node GR_South. As expected, these results are very similar to the ones obtained by Svalbard alone. However, it is important to highlight that the ground station Svalbard is only required whenever no coverage is available at Vardø.

Comparing the proposed drifting swarm with the two-satellite constellation, similar performances can be observed. The constellation follows a similar orbital plan and therefore equally benefits from using the ground stations. However, it is important to stress the importance of using a standardized networking solution, such IP-based protocols, in order to take advantage of spatially distributed ground stations.

5.5.5   Network Protocols and Overhead

Table 5.4 shows overhead results from network emulation. The overhead is broken down on each layer and the protocol used. The paper [117] gives further results on this topic.

The overhead consists of pure protocol overhead, such as addresses and other header fields. In addition, the network setup and maintenance traffic, such as neighbor discovery and so on (represented by the Internet Control Message Protocol (ICMP)-messages) adds to the overhead. It is found that around 26% reduction of the throughput must be expected, with the use of an IoT network stack based on 6LoWPAN.

Note that the link-layer used in the emulation might not be directly used on satellite links, so the overhead contribution from Layer 2 protocols here may be different in a real implementation. IPv6 represents around 10.6% overhead. CoAP only accounts for 2.7% overhead, and the network service traffic (ICMP) stands for 4.5% for confirmable messages. The high value for the ICMP-overhead for confirmable messages can relate to an implementation feature mentioned in the CoAP RFC [154].

From this we see that using a protocol stack with the low-weight 6LoWPAN IoT-protocol provides a considerable gain compared to using pure IPv6. Especially, this is seen for confirmable messages, that will require more traffic due to retransmissions. For 6LoWPAN, the total overhead for both confirmable and non-confirmable messages are similar.

A note to be made; in the emulations a standard network stack is used. This means that re-transmissions are solved end-to-end. This requires more re-transmissions and takes longer time than if re-transmissions were solved on link-to-link basis. See further discussion in Section 5.5.6. Since the real links between the sensor nodes and satellites will be marginal, both due to the available data rate as well as the availability time slots, this is important to consider.

Table 5.4: Network Overhead

	Non-confirmable msg		Confirmable msg	
	Full IPv6	6LoWPAN	Full IPv6	6LoWPAN
Ethernet/15.4 (L2) *(%)*	5.803	8.661	5.422	8.579
IPv6/6Lo (L3) (%)	16.580	10.586	15.492	10.485
ICMPv6 (L3) (%)	0.950	4.730	10.638[*]	4.516
UDP (L4) (%)	3.316	0	3.098	0
CoAP (L7) (%)	7.227	2.676	5.930	2.720
Total Overhead (%)	33.876	26.653	40.580	26.300

[*] The overhead here is higher than expected due to an implementation feature, as explained in [154, page 36].

The alternative solution can be to implement a custom network stack, with fewer layers and more cross-layer interaction. Addressing could be done on the link-layer, and everything above could be functions part of the application layer. This includes planning, routing and message confirmation. To make the network interoperable with other networks and technologies, gateways that translate to an IP-type of network can be used. In the sensor nodes such gateways can be used to ensure traffic between nodes and other types of data mules. At the ground station, data from the sensor nodes must be made accessible to end users through the Internet. Table 5.5 sums up some of the pros and cons for using a standard network stack.

Table 5.5: Network Protocol Tradeoffs

Standard IoT stack - pros.	Standard IoT-stack - cons.
Interoperability with Internet devices	Need adaption of, or creation of a new link layer
Standardized implementation	Need full network stack in all nodes
Low risk of implementation errors	Losses in and higher layers still difficult to handle
Large code base, many options available	Large code base, little control over it
Short development/implementation time	Higher overhead than custom cross-layer stack
Intrinsic security and authentication	DTN is not native
Can have intrinsic resilient behavior	

Even if the overhead from standard IoT network protocols is notable, they also give other contributions to the system utility. Interoperability is ensured without increased need of development of custom solutions and the risks associated with that. Risks related to using custom systems are high development and maintenance cost and the fact that few or no other projects are using similar solutions. This can lead to outdated and less secure solutions. Standard network protocols will also

provide standard implementations of network security and so on. Due to these reasons, the overhead cost may be worth it in the end. The main drivers might be the expected need for goodput (related to the volume of data that needs to be transmitted per year), and the development cost and time for implementation of a custom network stack. In addition, the need for developing cross-network routing and translation in all NWNs that need to be linked to two or more networks.

Smart Routing

As introduced and discussed in Section 5.1.6, there are cases where a sensor node should not choose to communicate with the first available satellite. This is especially the case when a ground station that does not see all satellite passes is used, as exemplified by Vardø in the discussed cases. When the sensor node has a high east-west separation with respect to the ground station, it can then be beneficial to use orbit propagators onboard the sensor node to predict which satellite will complete the link between the sensor node and ground station in the most efficient manner.

For a case with nodes deployed as shown in Figure 5.4 with the gateway located in Vardø, it can be shown that employing the smart routing method will lead to improvement in 15% of all message transfers. The average improvements in delay will be up to 93 minutes, which is significant and correspond to making contact between the sensor node and the gateway one orbit earlier [117]. Table 5.6 shows a sum-up for the overall performance. In the case studied, the message to be transmitted was 512 B, and the links must last for at least 30 seconds to be considered usable.

In Table 5.6, the results between the *naive* routing (picking the first possible satellite) and the *smart* routing are compared. The line *First Satellite* shows the average number of seconds the transmitting node must wait in order to send its message to a satellite. Note that the table is only showing the cases where the *smart* and *naive* methods differ, so the total average wait time is much lower. The line *Start to Finish* shows the time it takes for the message transfer to complete.

Table 5.6: Performance Comparison – Overall

	Naive	Smart
First Satellite (s)	4031	4427
Start to Finish (s)	5853	5401
Same Choice (%)	–	85.2
Improvement (s)	427	4281
Total Losses (%)	2.8	3.3

Two things can be seen from this: First, by using the *smart* routing, the wait-time until the correct satellite is available is naturally longer. This is because the *naive* method always picks the first satellite available. However, it is seen that the time it takes until the message is successfully received, is lower when relying on the *smart* routing. The average improvement corresponds to 71 minutes in the case shown here.

The network emulation (the method is described in Section 5.4.3) implements a real networking stack. Therefore, unexpected behaviors due to congestion or delays led to the *naive* approach being better for some message requests. These occurrences correspond to less than 3% when both routing approaches selected a different satellite.

This functionality should be implemented in a possible realization of this communication architecture.

5.5.6 Delay Tolerant Functionality

Due to the lack of continuous coverage from a LEO system with few satellites, there are not always be any end-to-end link between the sensor node and ground station. Therefore, message delivery integrity must be ensured by DTN-functionality.

Concepts of Message Transfer

Two concepts on how message delivery is confirmed can be envisioned, as depicted in Figure 5.5. For the first method (Figure 5.5a), when a message M is transferred from one NWN, N_1, to another, N_2, the second NWN immediately takes custody of the message when reception is confirmed. Procedures for custody transfer are, for example, discussed in [155]. This means that N_1 deletes its copy of M as soon as N_1 receives an ACK that M is received by N_2. N_2 has now the responsibility of transmitting M to the next node. This continues through the number of nodes needed until M reaches the destination.

The second method behaves differently (Figure 5.5b). Here, the ACK that confirms message delivery will not be transmitted until the *destination* has received M. This means that all nodes, including the source node, will keep a copy of M until the ACK is received.

For the network architecture envisioned here, the end-to-end delay until the message reception ACK is received by the source can be on the order of several hours. If a message or an ACK (from destination) is lost and must be re-transmitted, this increases the delay even further and may fill message buffers in NWNs along the way. The benefit of this method is that if an NWN goes off-line or malfunctions, the message should not be lost.

In the case of the first method, if one of the nodes N_n is lost while it carries M, M will be lost without neither the source nor the destination knowing about it. Any network hardware will have the risk of malfunction, such as buffer overruns, nodes that are re-booted and so on. Depending on implementation, this may cause loss of data.

If the network architecture only consists of the sensor node, a satellite and a ground station, this is a simple case, where the message will be transferred to the satellite which in due time transfers it to the ground station. Only two hops are needed. The satellite can be considered a reliable and stable network node, so message custody can most likely be safely transferred between the sensor node and the satellite with little risk of data loss due to satellite malfunction, corresponding to the first method.

Message Transfers Including Unmanned Vehicles

By including various types of UVs (as shown in Chapter 3.1), another scenario can be envisioned. Here, the network functionality could be configured differently. Imagine if a UAV takes custody of a set of messages from a sensor node, and then crashes and is lost on its way back to the ground station. A UAV can potentially mule hundreds of gigabytes of data. The consequences of such a loss can be catastrophic for the project requiring the data, as neither the source nor the destination will be capable of avoiding this loss of data. This case shows that transfer of custody might not be desired. However, it also implies that the sensor node must be informed that the end-user has received the messages. It would be very costly if the UAV had to fly back to the sensor nodes only to deliver a simple ACK. This will also increase the risk of losing the UAV. Therefore, a better and more efficient solution would be to route the message confirmation ACK through a satellite link instead. Further studies of similar problems are suggested for future work.

This example also shows that interoperability spanning various technologies must be ensured. Investigation of such scenarios, where a UAV co-operates with satellites during a data collection campaign is proposed for further work.
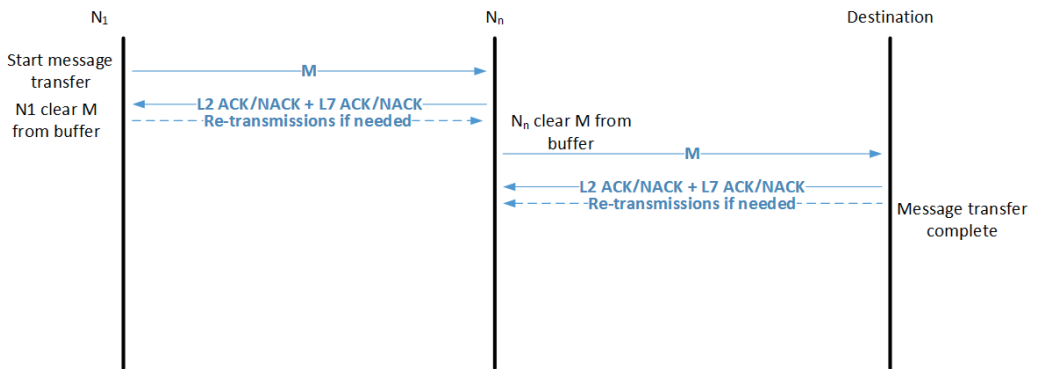
(a) Sequence of messages and ACKs when the next network node takes custody of the message after successful link-layer transmission. The message is released from the source after the first jump.
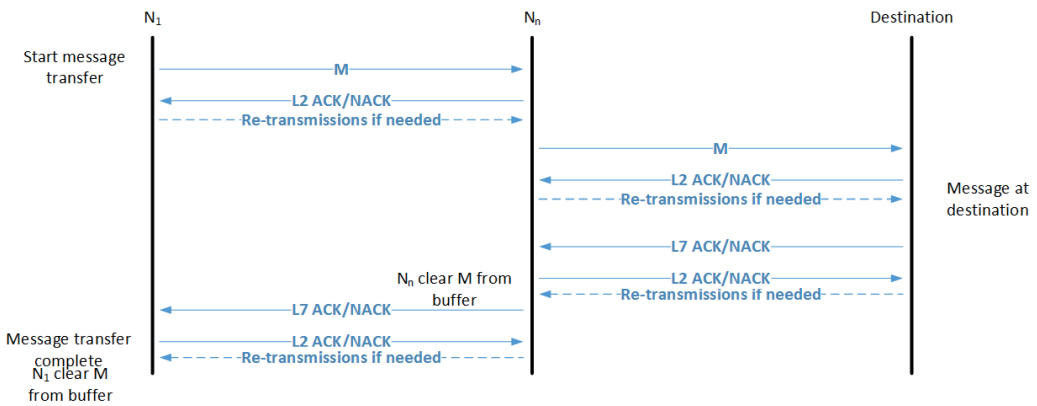
(b) Sequence of messages and ACKs. The message is not released from the source until an end-to-end acknowledge is performed.
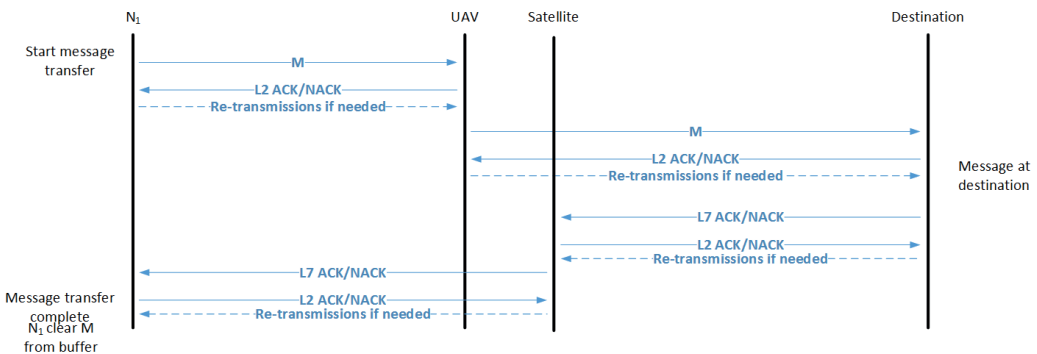
(c) Satellite and UAV working together. The final L7 ACK is relayed by a satellite link even if the UAV carries the data.

Figure 5.5: Simplified model of message transfer phases. In addition to L7 traffic and ACKs, such traffic can also be expected on, for example, the network layer (L3) too. Depending on link availability, each hop may take several hours to complete.

5.6   Chapter Conclusions

This chapter has presented arguments for using a network stack based upon IoT protocols, specificity considering 6LoWPAN and CoAP. The specific use of these protocols is also supported in contemporary literature, c.f. Section 2.3.4. The combination of 6LoWPAN and CoAP presented in this thesis seems new, and a network performance analysis as performed here has not been found in the literature. The network perspective is studied in order to answer *RQ1* (interoperability) and *RQ3* (swarm of satellites).

Related to *RQ2*, employing the standard protocols fulfills (mainly) interoperability requirements *MR-001*, *MR-006*, *MR-007* and finally *SR-015*. The network presented conforms with the requirements defined in Section 2.2. This network stack has been evaluated through a series of emulations, based upon realistic node and gateway placements, as well as realistic satellite links obtained from orbit simulations, c.f. Section 5.4. One lacking part of the network stack, is a suitable link-layer, which is also acknowledged in the literature [61, 83, 74, 83]. Adaptions of the DVB-RCS link layer can be one alternative. However, since the 6LoWPAN is very tied to the IEEE 802.15.4 link layer in order to realize the header compression, considerations must be made. A practical implementation of the network stack, wrapping the IEEE 802.15.4 inside a VHF-radio link-format, NGHam [156], is presented by David Palma in [77]. This is a quick and practical approach, but future work should analyze if overhead can be reduced by employing another link layer. This is a topic for future work.

In discussion of *RQ3*, the network performance of a freely drifting swarm of three satellites was found to be comparable to a fixed constellation of two satellites [116, 115]. This further motivates the use of simpler satellites without station keeping capabilities. The resulting approach saves resources and motivate the deployment of more satellites in orbit, increasing redundancy, coverage and reducing service degradation if a satellite should fail. The results also show that the increased delays for the swarm compared to the three satellites uniformly distributed, are less than 10 minutes in most cases, except for the maximum *e2e* for GR_S, where the swarm performs one orbital period better.

It is shown that the placements of sensor nodes and ground stations must be considered when planning a satellite network. This will have a strong impact on end-to-end time to retrieve data as a node may not be reachable in all passes [116, 117], for example, for southern placed stations that are separated in longitude. Having ground stations placed far north is also beneficial, so since Svalbard is located further north than Vardø, results using Svalbard outperforms Vardø. However, by simultaneously using both ground stations, resorting to Svalbard only for limited periods of time when Vardø is out of coverage, a performance similar

to only using Svalbard is achieved. Assuming it is more expensive to operate from Svalbard, the use of a ground station on the main land can be preferable. In addition, using (at least) two ground stations also adds redundancy to the system.

From the network emulations, we find that it will be hard to meet the 6 hour responsiveness requirement (c.f *SR-006*) for some nodes (GR_{South}). Especially when only using Vardø ground station. In that case, we see delays exceeding 10 hours. This situation can be addressed in several ways: First, it is natural to argue to use Svalbard ground station. In this case, the maximum delay is still 07:25. Second, it is possible to deploy satellites in a second perpendicular (at the poles) orbital plane. This will aid the situation. Third, if these mitigations are considered too complex or expensive, it is possible to decide to relax this requirement in the next iteration, especially for nodes far south. If the delay requirement is kept, it will become a system driver, with costly implications. As discussed in Section 2.3.2, the mission designer must be aware of such implications [56], in order to not inadvertently drive the cost and the complexity of the system higher than necessary.

Furthermore, it is important to assess the overhead imposed by the chosen protocols. As argued in Section 5.1, the flexibility and interoperability gained by implementing these standard protocols come with an overhead cost. Results from network emulation is shown in Section 5.5.5. By implementing leaner tailor-made protocols, for example, interacting directly with the link-layer and application layer, overhead can be traded against a higher implementation cost and less interoperability. IP-traffic to end-users can still be assured by use of gateways and convergence layers. However, no network node in the network will then be reachable directly over IP. The design of a tailor made stack is outside the scope of this thesis.

Finally, *RQ2* - related to capabilities of new satellite platforms - it is apparent that current processor technology enables routing and QoS in each NWN, and it is possible to run the forward routing procedure in each of the sensor systems, without any special implementation cost nor a high energy cost.

Chapter 6

Radio Channel Properties

This chapter will introduce and discuss basic radio channel properties, resulting in link budget considerations. The specific link budgets related to the payload and architecture proposals (c.f Section 3.1 and paper [32]), making use of the results discussed here, are calculated and presented in Section 6.8.3.

The system design and link budget consider topics specific for the Arctic areas. This encompasses ionospheric effects and constraints on the sensor nodes antennas.

Deriving a complete model of the radio channel(s) is an immense task if all aspects are to be considered. A signal traveling between a ground node and a satellite will be disturbed by various physical effects; such as distortions while traveling through the ionosphere and atmosphere, reflections leading to multipath phenomena, ice and snow on antennas, moving antennas on floating nodes and so on. These phenomena are discussed in the following sections. Some of them are then included as additional losses and higher margins in the resulting link budget.

Since it is expected that communication over the satellite link must be *reliable* (see Section 2.2), various link loss mitigation techniques must be employed. These can be appropriate coding and re-transmission using ARQ. If the packet loss is large, the retransmission rate will be high. This will then limit the capacity of the channel, and as an ultimate consequence lead to complete blockage of the channel. Furthermore, delays due to outages can be accepted in a data-relaying system, if the data can be held and re-transmitted later. Loss of data is not desirable.

6.1 Selection of Carrier Frequency

Several aspects must be considered when choosing a carrier frequency. This ranges from what is the use and purpose of the system, technical topics as antenna sizes and power levels, availability of components for various satellite platforms and

regulatory issues. A satellite system supporting the architecture defined in Section 3.1 will also have different definitions of the links between the sensor nodes and the satellite, compared to the link between the satellite and the gateways.

6.1.1 Communication between Sensors and Satellites

For small satellites such as CubeSats, VHF and UHF systems are commonly used. Reasons for this are the availability and popularity of amateur (HAM)radios and equipment much used in educational student satellites. In addition, narrowband, low power systems with relatively simple antennas are easy to design for these frequencies due to relatively low free-space-loss compared with higher frequencies. Since the sensors in this system are to be placed in the Arctic, energy efficiency will be key. VHF or UHF is therefore selected as a baseline for communications between sensors and satellite. For a commercial satellite service relaying data from sensor systems, HAM licenses cannot be utilized, so the regulatory aspect of frequency selection must be addressed.

The use of the proposed system architecture to support environmental sensor systems will, according to Norwegian Communications Authority (NKOM), allow classification in the Earth-Exploration Satellite Service (EESS) category. This could allow the use of UHF frequencies from 400.15-403 MHz [157, 158]. Alternative bands can be 432 MHz to 438 MHz, however, this is a shared band [157]. Figure 6.1 shows potential frequency band allocations.

Figure 6.1: Possible frequency allocations for an EESS-service. Values are MHz. Green sections indicate downlink, yellow sections indicate uplink.

In addition to the UHF-band, several other EESS-bands can be used, such as 1215 – 1300 MHz. The increased free space loss due to the higher frequency requires 9 dB higher margin, and moving higher into S-Band requires a 14 dB higher margin compared to UHF. The use of higher frequencies implies the need of high-gain antenna on user terminals (sensor nodes) in order to meet the increased free space loss, which can be impractical [55].

6.1.2 Aggregated Data Downlink from Satellite

In order to downlink aggregated data from sensor nodes, a common S-Band system (2.2 GHz) can be used. Commercial S-Band stations are available virtually all

around the world, through various ground station service providers. An S-band downlink will allow efficient and quick downlink of aggregated data in a short period of time. The Earth-Exploration Satellite Service has an allocation in the 2025-2290 MHz band [157, 158] which could be used, as shown in Figure 6.1.

6.2 Link Budget Parameters

A link budget is used to assess and evaluate the quality of communication links, and it expresses the expected signal-to-noise ratio at the receiver. The result of the link budget can be expressed as a required *carrier-to-noise* ratio ($\frac{C}{N}$), the carrier to spectral noise density ($\frac{C}{N_0}$), plus a margin, or as a *sensitivity* value.

The basic link budget equation is:

$$\frac{C}{N_0} = \frac{E_b}{N_0} \cdot R_b = \frac{G_t P_t}{L_0} \cdot \frac{G_r}{T_{sys}} \cdot \frac{1}{k} \cdot \frac{1}{L_a} \tag{6.1}$$

N_0 is the spectral density of the noise, and E_b is the energy per bit. G_t and P_t are the antenna gain for the transmitting antenna and the transmit power, respectively. This term is often denoted Effective Isotropic Radiated Power (EIRP). G_r is the receiver antenna gain. L_0 is the free space loss defined as $\left(\frac{4\pi d}{\lambda}\right)^2$, with λ as the wavelength of the carrier and d is the distance between the transmitter and receiver. T_{sys} is the equivalent system noise temperature, k is Boltzman's constant and R_b is the data rate of the system. L_a is the additional losses accounted for, and the individual factors will be identified and discussed in the following.

To fully comprehend the link budget, different parameters and their effects should at least be sized and estimated. Here, ionospheric scintillation, polar cap absorption, Faraday rotation, polarization loss, multipath and dispersion will be considered.

Different effects inflict the signal in different manners, both with respect to fading depth and the duration of the fading period. Short fading, scintillations and fading due to for example shallow multipath, stemming from reflections from the sea surface, can according to [159] be modeled as Additive White Gaussian Noise (AWGN). Common Forward Error-correction Code (FEC) codes can mitigate this fading and increase the margin. However, deeper fading will have a longer duration and cause more loss of data than the codes can handle. To mitigate such effects, signal processing techniques such as equalization, frequency and/or spatial diversity or packet retransmission could be considered. The complexity of the mitigation techniques must be traded against the gain in reliability each method gives.

6.2.1 Polarization Loss

Due to Faraday rotation, the polarization of a signal will change on its way to or from a satellite. From the International Telecommunications Union (ITU) recommendation ITU-R P.618-12 [160] we find that a 100 MHz and a 500 MHz signal will experience Faraday rotation in the order of 30 and 1.2 rotations respectively. In order to counteract the Faraday rotation, either the node or the satellite (or both) should have a circular polarized antenna. This is typically done for frequencies below 6 GHz [159, Chapter 2.5]. For the link budgets between sensor nodes and satellite(s), it is assumed that the sensor node has a vertical linearly polarized antenna and the satellite has a circular polarized antenna. The cost of this setup is 3 dB polarization loss and it is added to the link budget.

6.2.2 Dispersion

Different frequencies will experience different propagation delays through the ionosphere. Due to this effect, the signal will experience dispersion. According to ITU-R P.531-12 [161], these effects must be taken into account for wide band systems at VHF and UHF. An example shown in [161] is that a 1 μs signal can experience a differential delay of 0.02 μs, which is 2% of the pulse duration. For a narrowband application, this is of less importance.

6.2.3 Ionospheric Scintillation

The dynamics of small scale structures in the ionosphere can cause rapid changes in the amplitude and phase of a signal traveling between a satellite and a ground node. These irregular structures are due to local variations of electron density. This in turn causes the refractive index to change, which will influence the signal [159, Chapter 2.3]. The fading due to ionospheric scintillation can vary a lot; from small variations to deep fades that could cause link outages. Also, the properties of this fade vary with the time of day, the time of year, the geographical location and the sun activity.

   The scintillation effects typically occur after local ionospheric sunset, meaning that it is a phenomenon that takes place in evenings or at night-time. Typical event durations are from 30 minutes to several hours. When the solar activity is at its maximum in a solar cycle, these effects can be strong and occur every evening [161, Chapter 4.2]. The polar areas are generally less affected than the equatorial zones, but aurora phenomena can cause scintillation at high latitudes [162].

   Due to all these inter-connected phenomena, deriving a full statistical model for the ionosphere is nearly impossible, according to Allnut [159, page 119]:

> *"the concept of annual statistics is of dubious merit for ionospheric phenomena."*

The goal here will therefore be to derive a suitable average value for ionospheric scintillations margin to be used in the link budget.

A frequently used parameter to describe ionospheric properties, is the $S4$ index, which characterizes the severity of amplitude scintillation. It is given by Briggs and Parkin [163]:

$$(S4)^2 = \frac{(\langle I^2 \rangle - \langle I \rangle^2)}{\langle I \rangle^2} \tag{6.2}$$

I is the received signal amplitude and $\langle \ \rangle$ means average [159]. To find an estimate for *peak-to-peak* values, equation (6.3) is used, where the $S4$-index from equation (6.2) is used. This is an empirical formula estimated from observations [161]:

$$P_{fluc} = 27.5 S4^{1.26} \tag{6.3}$$

Figure 6.2 (from [161, Chapter 4.1]), shows one example of VHF and UHF measurements from Sweden in 2003. From this data, it is found that the scintillation indices, for VHF and UHF respectively, are between approximately 0.4 to 1.5 and 0.2 to over 1. This corresponds to *peak-to-peak* values between 3.5 to 27 dB (by using equation (6.3)). The duration of high scintillation values are several tenths of minutes. This means that the system might experience a signal fade during the whole satellite pass, with loss of communication as the consequence.

However, these *peak-to-peak* values do not provide an usable value for the link budget. The scintillations can be described by the Nakagami-distribution [161, 159], and this can be used to derive a margin. This distribution models deviations from an RMS value. The parameter for the Nakagami-distribution, $m = 1/S4$, and its cumulative distribution, shown in Figure 6.3, show for which percentage of the time the fading is worse than a set level.

Scintillation effects are typically classified into *weak* ($S4 \leq 0.3$), *moderate* ($0.3 < S4 < 0.6$), and *strong* ($S4 \geq 0.6$) regimes. Here, a value for $S4 = 0.5$ is chosen. This is in the moderate regime. If $S4$ is chosen too low, the resulting link budget might be too optimistic and higher outages or less throughput than expected will be experienced. On the other hand, if $S4$ is estimated too high, then the link budget will be too pessimistic and the full potential of the channel will not be exploited. $S4 = 0.5 \Rightarrow m = 4$ is believed to be a reasonable choice.

The red line in Figure 6.3 shows the situation when $m = 4$ (the curve for $m = 4$ is lacking in the figure from [164], so the value is interpolated between the lines for $m = 3$ and $m = 5$) and the margin, 7 dB, shall not be exceeded by more than

Scintillation indices measured at Kiruna (a), Lulea (b), and Kokkola (c) at 150 MHz
(dotted line) and 400 MHz (dashed line), as recorded from polar orbiting
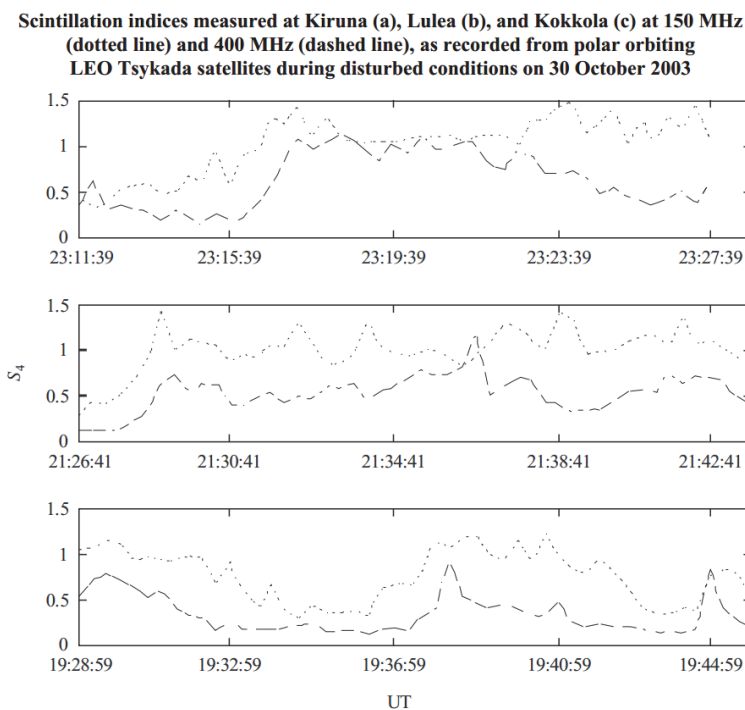LEO Tsykada satellites during disturbed conditions on 30 October 2003

Figure 6.2: Scintillation indices measured in northern Sweden. From [161, Figure 5].

1%. The blue line shows the case for $m = 4$ and a 10% level and corresponds to 3 dB. These results will be further discussed and concluded in the link budget calculation in Section 6.8.3.

Figure 6.3 shows that the distribution is very sensitive. This causes the estimate of the required margin to vary a lot with regards to the choice of $S4$. If we chose $S4 = 0.3$ (weak), $m = 11$. From Figure 6.3, we then get that an estimate for the fading margin to be between 3 and 4 dB for both 99% and 90% levels. On the other hand, if $S4 = 1$ (strong), $m = 1$, then the required margin will be between 10 to 20 dB. For even higher $S4$, the required margin will have to be huge.

It should be noted that uncertainties like this are further arguments to make use of Adaptive Coding and Modulation (ACM) and Variable Coding and Modulation (VCM) techniques to adapt the use of the channel to its real true-time properties (see Section 6.6). Implementation of these concepts are suggested for future work.

STK can implement the ITU-models for atmosphere, troposphere, rain and ionosphere. For a simple setup with a satellite in a 500 km 98° polar orbit with an UHF transmitter and a ground station receiver on Svalbard, it is found that the
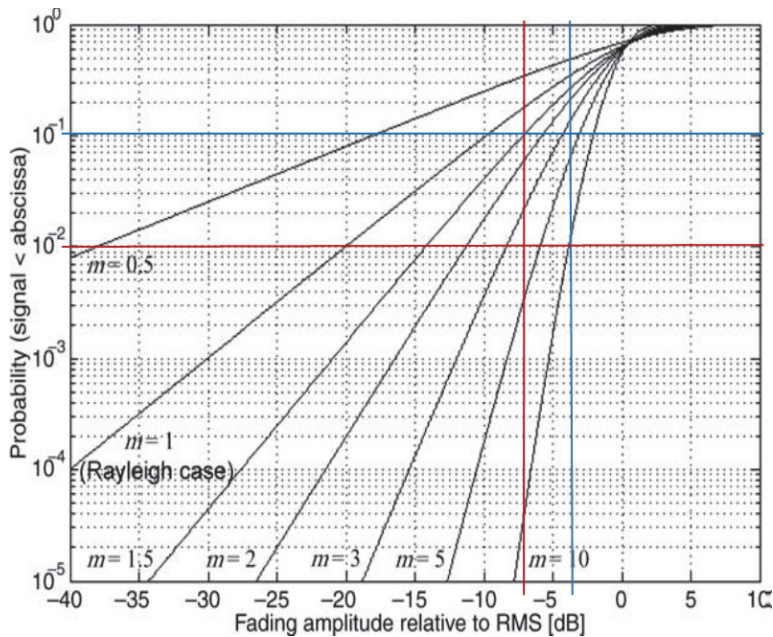
Figure 6.3: Nakagami-m distribution for ionospheric scintillation. Adapted from [164].

average level for the ionospheric scintillations is 7.3 dB. The fading value varies from 26 dB to close to 0 dB. This is plotted in Figure 6.12 on page 131. For S-band STK reports less than 1 dB estimated ionospheric loss.

6.2.4 Polar Cap and Auroral Absorption

Polar cap absorption and auroral absorption are rare events. Auroral absorption can last for hours. For elevation angles greater than 20° the signal loss at VHF is expected to be less than 1 dB for most of the time as stated in ITU Recommendation 531 [161, Table 2].

Polar cap absorption is a very rare event, usually occurring 10-12 times a year during sunspot maxima only. However, the signal loss can be significant, and the duration can be on the order of days [161, Chapter 5.2].

6.2.5 Atmospheric Effects

Other atmospheric effects such as rain fading are not present at the frequencies considered here; namely VHF/UHF and S-Band. In addition, a low amount of precipitation is expected in the Arctic areas.

When modeling with STK, it is found that losses due to atmospheric, rain, and cloud conditions are all less than 0.1 dB. They are therefore chosen to be neglected in the link budget. For very low elevation angles, tropospheric scintillation is modeled to be 40 dB loss, while for elevation angles above $> 3°$, this loss component is 0 dB. Due to these simulation results, the atmospheric effects will neglected in the link budget as we assume operating at elevation angles above $3°$. The link budget will be calculated for an elevation angle of $10°$. These effects are similar for UHF and S-Band cases.

6.2.6   Other Effects

In addition to the losses mentioned above, the system will be prone to signal degradation due to several other factors. Examples are antenna pointing errors due to misbehaving Attitude Determination and Control System (ADCS). Ocean wave movements can drown or shadow the node antenna. Icing of antennas can occur as well as multipath fading effects due to reflections from ocean or ice surface. The value of these effects is hard to estimate. A large system margin could account for some of these effects. Link losses can in some cases be expected, especially due to antenna icing and shadowing. In addition, a large (conservative) system margin will in most cases give conservative results indicating lower data throughput than what is actually possible. Again, VCM and ACM should be employed in order to make the best possible use of the link.

Since both polar cap absorption and the periods of high scintillation values are tied to periodic ionosphere activity due to solar activity, we can argue that the link budget should not account for the peak values of these two parameters. At rare and extreme events, ionospheric scintillation can cause losses greater than the system fade margin. For a non-critical communications system, it can be accepted that we lose communication during strong/extreme events. However, some losses should be taken into account in the link budget.

Another topic that must be part of the detailed system design in further project phases (c.f Figure 2.1) is interference between different radio systems that are using the same frequencies. The frequency band allocated for EESS is narrow, and shared amongst the different systems. The use of this band may change over time, and must be considered in a detailed design of the system and the payload.

6.3   Receiver Noise Calculations

Several physical phenomena lead to noise and disturbance of a signal. Traveling through the atmosphere, rain and gasses will increase the noise level of a signal. These phenomena contribute to the ambient environment and temperature the an-
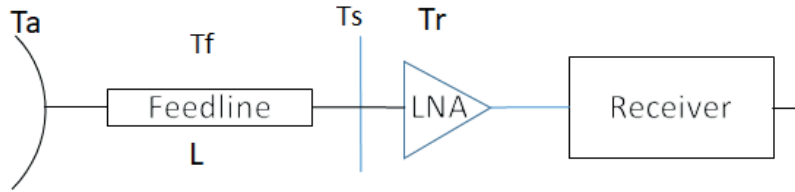
Figure 6.4: Noise calculations for a receiver.

tenna observes. In addition, the components in a receiver contribute to the noise level. Also, noise from the surroundings, it being as interference or "general" increased RF noise levels should be accounted for. However, for sensor systems placed in solitude in the desolate Arctic, this contribution is small.

An estimate of the resulting system noise can be calculated by using a model shown in Figure 6.4. In this case, we reference the system noise at the input of the Low-Noise Amplifier (LNA), after the loss from the feed-line between the antenna and the LNA.

From this, we can write the corresponding system noise temperature T_s as:

$$T_s = \frac{T_a}{L} + T_0(1 - \frac{1}{L}) + T_r, \tag{6.4}$$

where T_a is the antenna temperature, $T_0 = 290K$ is the ambient temperature denoted T_f in Figure 6.4, L is the loss (linear) in the feed-line and T_r is the equivalent noise of the receiver. The noise of the receiver can in most cases be approximated to the noise temperature of the LNA [126, Chapter 5.5.2.5], as long as the gain of the LNA is high.

6.3.1   Satellite Antenna Temperature - Uplink

The satellite antenna will, depending on the antenna pattern, see a portion of the Earth as well as the empty space. The true antenna temperature is an integral over the brightness temperature the antenna diagram "sees". For a low-gain antenna, the Earth will contribute only a fraction of this temperature. However, as a conservative estimation $T_a = 290$ K can be used [126, Chapter 5.5.3.1].

6.3.2   Ground Antenna Temperature - Downlink

For a receiving station on Earth, the observed antenna temperature will be lower, as the antenna sees the cold space, in addition to the noise contribution by the at-

mosphere. If the antenna has a broad lobe and a low elevation angle, the ground will also contribute. From [126, Chapter 5.5.3.2.1] the antenna temperature can be estimated to be as low as 10 – 50 K for clear sky conditions. Referring to [165], galactic noise must also be taken into account. Hence an estimate of 250 K for UHF and 100 K for S-Band will be used in the link budget calculations in Section 6.8.3.

Figure 6.5 shows some of the contributions to the antenna noise temperature. It is for example noise from the ground, the sky and from rain. Depending on the amount of rain clouds, all contribution from the sky might be attenuated through the rain clouds. Further, the noise temperature due to the rain clouds will then be greater. As mentioned, the contribution from for example rain will be small in our case; both due to very little precipitation and due to that UHF frequencies are not affected by rain at any great degree.
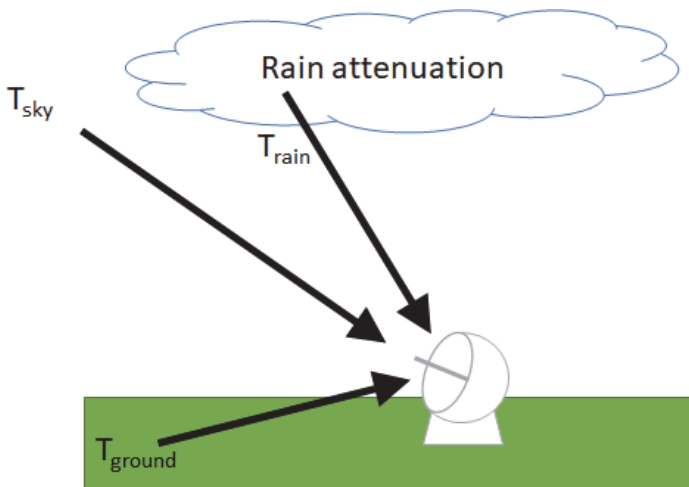
Figure 6.5: General representation of antenna noise and temperature. Several physical processes can contribute to the antenna noise. Some are shown in this figure.

6.4   Channel Coding

By introducing redundant bits in the data transmitted over the RF channel, we can increase the probability of successful decoding, for a given signal to noise ratio. The cost of this is that the introduced redundant bits reduce the usable bit rate. Various existing Forward Error-correction Code (FEC) schemes can be used. The codes have different properties; both when it comes to code strength and com-

plexity in decoding [126, Chapter 4.3]. Figure 6.6 shows typical code gains for a selection of code rates, based on Viterbi decoding of a convolution code. The figure is based on Table 4.5 in [126, Chapter 4.3.2].
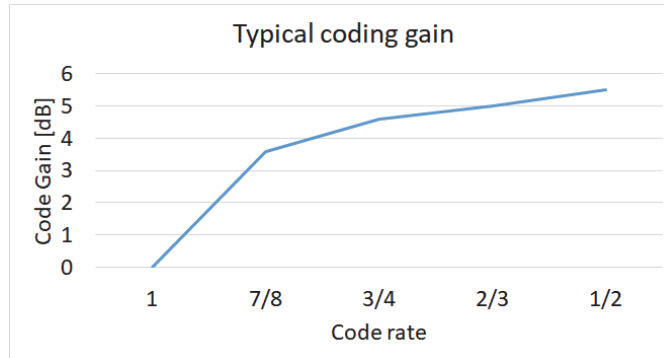

Figure 6.6: Typical coding gain. Adapted from Table 4.5 in [126, Chapter 4.3.2].

6.5   Modulation

For low-power operations, a simple, but spectral effective, modulation should be selected. Figure 6.7 shows Bit Error Rate (BER)-curves for a selection of digital modulations. As observed, the modulations BPSK and QPSK have the lowest E_b/N_0-requirement for a given BER. As QPSK transmits two bits per symbol, giving twice the data rate compared to BPSK, this modulation is chosen as baseline for link budget calculations. Due to the inherent power limitations in satellite links, QPSK and other phase modulations with constant envelope are advantageous. The modulations are little affected by non-linear effects, so it is possible to drive power amplifiers close to saturation.

6.6   Adaptive Links

The previous sections have shown that since the environment and the radio channel are changing over time, the use of adaptive links should be considered. This means that if the link budget for a given link condition, with respect to range, weather, and ionospheric conditions, has room for extra capacity compared to other link conditions, this improvement could be cashed out in different ways. For example:

- Power saving – less power is needed to maintain a link, still supporting the same bit rate
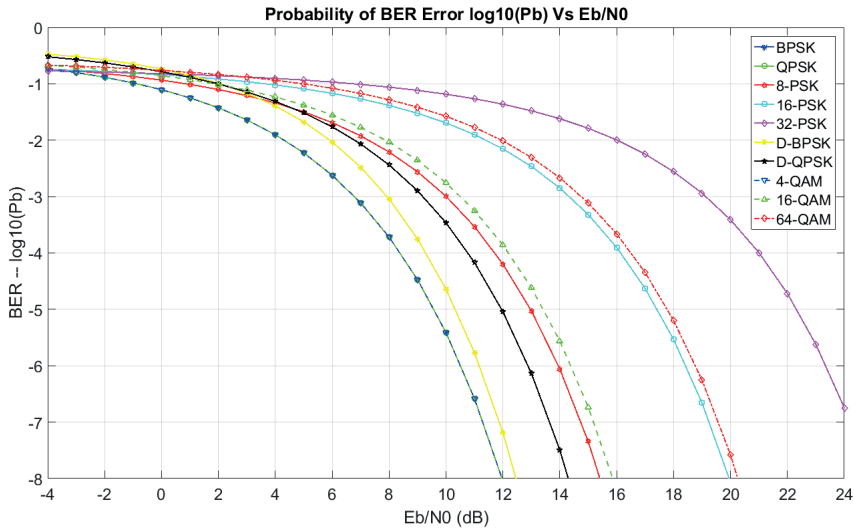
Figure 6.7: Curves for Bit-Error-Rates for a selection of digital modulations.

- Higher throughput – same amount of power used, but a higher rate and/or higher order modulation can be used when the link margin supports it

The challenging part can be how to define the signaling channel and the fall-back modes, as the contact time during each pass is quite short. The link yield is depending upon the transmit power, the distance between the transmitter and receiver and the channel properties.

6.6.1   Causes of Variability

The following phenomena cause high variability in link quality, and will enforce the justifications for the use of adaptive links.

Distance   The distance between the transmitter and receiver can easily be calculated by knowing the satellite orbit. The maximum distance for a given pass can be calculated in advance. As an example, the distance can vary between around 3000 km (horizon) and 600 km (zenith). This corresponds to around 14 dB ($20log(\frac{3000}{600})$) change in received power level. An example of this is shown in Figure 6.8. Here, the usable dynamic range is 10 dB. The steep cut-off is due to implementation of ITU-models for ionospheric and tropospheric scintillation which STK estimates to be severe for low elevation angles.
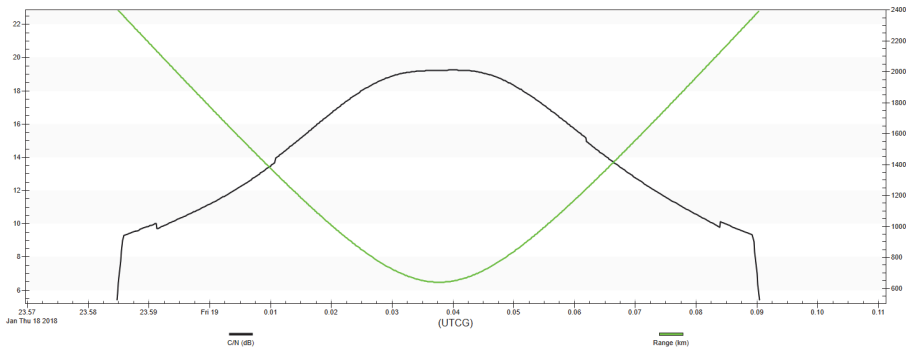
Figure 6.8: Example of estimation of received C/N during a near overhead pass. The black line is the C/N-value, the green is distance from ground station to satellite. The left Y-axis is in dB, the right Y-axis is km and the X-time unit is hours.

Atmospheric and ionospheric conditions   VHF and UHF frequencies are not very prone to effects of atmospheric variations, such as attenuation due to rain or water vapor. Also, the Arctic is mainly considered a desert. However, for south-north-moving satellites, the link might go through parts of the atmosphere that contain more vapor. In addition, ionospheric scintillations can occur as shown in Section 6.2.3. Even more, the link will also be affected by solar energy bursts. These are rare events that can be monitored and a forecast can be issued. If such effects occur, they can cause losses that are larger than the system fade margin even if very low bit rates are used. Outages due to this will be rare occurrences and should be tolerated for a system as discussed here.

Local conditions   The link can be affected by fading due to several local conditions, such as icing and wave movements if the node is floating. Reflections due to waves and local surroundings can also lead to a changing multipath environment. The value of this fading can be several dB. According to [166, Chapter 6.3], multipath can be severe for any elevation angle in a low-frequency system using low gain antennas. The impact of different parameters such as elevation angle and sea state is discussed in [159].

6.6.2   Adaptive Coding and Modulation

Since the received power level varies during the pass due to for example varying distance, the link properties are quite different in the start and end of a pass, compared to during the middle section of a pass (especially valid for overhead passes).

   In order to make the most use of channel capacity, Adaptive Coding and Modulation (ACM) or Variable Coding and Modulation (VCM) can be employed. This

can be a change of the code rate; so that packets transmitted in the start of a pass can have a simpler modulation or have a stronger code than packets transmitted when the received power is higher. This dynamics can be as high as 20 dB, according to [167]. If we slice the curve in Figure 6.8 for every 2 dB, we can have 5 different Coding and Modulation Scheme (CMS) if desired.

The extra implementation cost due to increased complexity on adaptive links must be traded against the chance of achieving more data throughput in some passes.

Variable Coding and Modulation Schemes

In order to make ACM work, the receiving node (satellite, sensor node or gateway) must constantly inform the transmitter on the quality of the signal received. One way is to compare the assumed quasi-error-free output of the FEC with the erroneous input, and derive an estimate for the BER. If few packets are received correctly, the transmitter should be requested to reduce the data rate or change to a stronger code. A time-out should be in place both in the transmitter and receiver in order to fall back to a basic CMS in case of failure of a more "advanced" CMS.

Figure 6.9 shows how the loop controlling the ACM-functionality can behave. In the satellite there will be a function estimating the received link quality which in turn instructs the sensor node to use a specific CMS suitable for the present radio channel. An implementation for an SDR is proposed in [167].

Figure 6.9: Model of ACM control loop.

Rate-less Codes - Hybrid ARQ

A method to transmit as much usable data as possible, which also enables the ability to handle varying reception properties is to employ rate-less codes. A data transfer between the sensor node and the satellite can start with a coding scheme

where data with just a little code is transmitted. However, the transmitter still makes a very long code word. If the packet is received correctly (determined by a CRC-code), then an ACK can be issued. However, if the decoding of the packet fails, then an ARQ is issued. The source will then issue an additional segment of the code word, that the receiver will add to the first received packet. This process continues until the packet is successfully decoded, or until a timeout is reached. This method is also called Hybrid ARQ [168].

6.7   Considerations on packet Lengths

The length of a packet has several implications on the yield of a communication system. To some extent this is a "free variable" left to the link designer, but in many cases this does relate to properties defined, for example, in the network stack; such as usable lengths for relevant network, frame and link protocol formats.

To describe the link properties, we define the following parameters and relations, in order to show the relationship between Bit Error Rate (BER), packet length (P_{len}) and the packet Overhead (O):

t	the time a satellite is visible [s]
R	the raw data rate available [bps]
O	the overhead in each packet [b]
BER	the bit-error-rate for the link
P_{len}	the length of a packet [b]

Furthermore we have bits per pass:

$$b_{pass} = t \cdot R \qquad (6.5)$$

and packets per pass:

$$P_{pass} = \frac{t \cdot R}{P_{len}} \qquad (6.6)$$

The relationship between bit-error-rate, BER, and packet-error-rate, PER can be written:

$$PER = 1 - (1 - BER)^{P_{len}} \qquad (6.7)$$

if the bit errors are independent, identically distributed (IID). For a radio link, this might not always be the case. If bit errors are of a more bursty nature, for example, caused by physical phenomena such as obscuring of antennas, antenna drowning, suddenly deep fading due to scintillations and so on, the IID-statement does not hold. However, in order to define a simple model for deriving an estimate for optimal packet length, this assumption is chosen. Also, this model does not

account for packet loss due to link loss when the satellite is passing below the horizon, as this will account for a fraction of a percent. Also, this model does not take multiple re-transmissions into account.

From the *PER*, the expected number of lost packets during a pass P_{lost} can be found:

$$P_{lost} = P_{pass} \cdot PER \tag{6.8}$$

$$= \frac{t \cdot R}{P_{len}} \cdot \left(1 - (1 - BER)^{P_{len}}\right) \tag{6.9}$$

Further, we find the bits lost b_{lost} simply by setting $b_{lost} = P_{lost} \cdot P_{len}$ and finally, the number transmitted, usable bits, b_{ok}:

$$b_{ok} = b_{pass} - b_{lost} \tag{6.10}$$

$$= t \cdot R - (t \cdot R(1 - (1 - BER)^{P_{len}})) \tag{6.11}$$

$$= t \cdot R(1 - (1 - (1 - BER)^{P_{len}})) \tag{6.12}$$

$$= t \cdot R(1 - BER)^{P_{len}} \tag{6.13}$$

Then taking the overhead pr packet, O, into account in order to find the number of overhead bits, $b_O = (O \cdot t \cdot R)/P_{len}$ and finally, the number of transmitted, usable bits, b_t is:

$$b_t = b_{ok} - b_O \tag{6.14}$$

$$= t \cdot R(1 - BER)^{P_{len}} - \frac{O \cdot t \cdot R}{P_{len}} \tag{6.15}$$

By dividing (6.15) by the number of bits in a pass, $t \cdot R$, the effective or relative throughput R_{eff} can be expressed by:

$$R_{eff} = (1 - BER)^{P_{len}} - \frac{O}{P_{len}} \tag{6.16}$$

We then see that this equation is dependent on the *BER*, the packet length P_{len}, and the ratio of the overhead vs. packet length, O/P_{len}.

The defined highest value for *BER* relates to requirement *SR-016*, where the assumption is that *BER* should be lower than 10^{-4}. Higher *BER* than 10^{-3} will cause delivery of data with too poor data quality for almost all applications, so they are not considered in the following. Figure 6.10 shows this effect through examples of varying *BER* from 10^{-4} to 10^{-6}, and for short to long packets. Intuitively, less overhead is preferred. It is also observed that for relatively poor links; $BER = 10^{-4}$ in Figure 6.10a; a short/medium value for the packet length is preferred. Short packets will lose too much to the overhead, for longer packets the probability of

lost packets is increasing, so there is a clear optimal point to be found. For better link conditions; as $BER = 10^{-5}$ in Figure 6.10b; longer packets are preferred. Still, an optimal value can be identified. For a good link, $BER = 10^{-6}$ in Figure 6.10c, the graph is asymptotic within the shown values. However, as argued before, if the bit errors are not true IID, long packets will suffer, and re-transmissions will require a lot of capacity. These considerations have been discussed in Chapter 5, where examples of real link and network protocols have been considered.
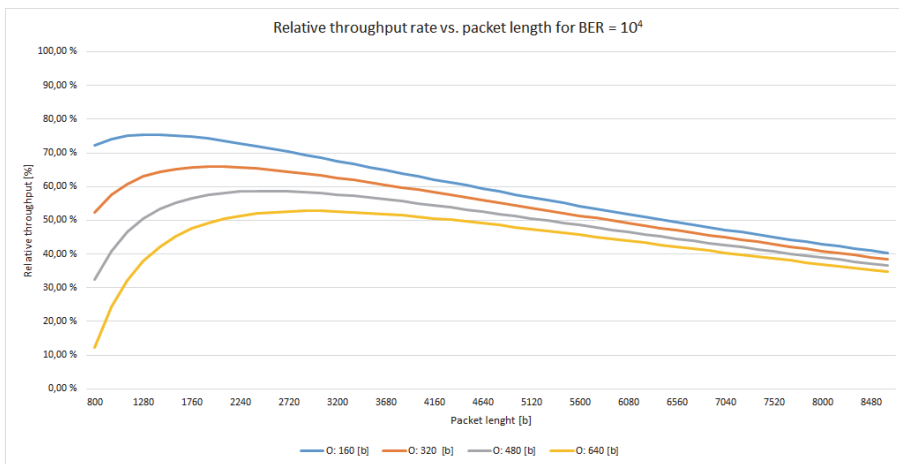
(a)
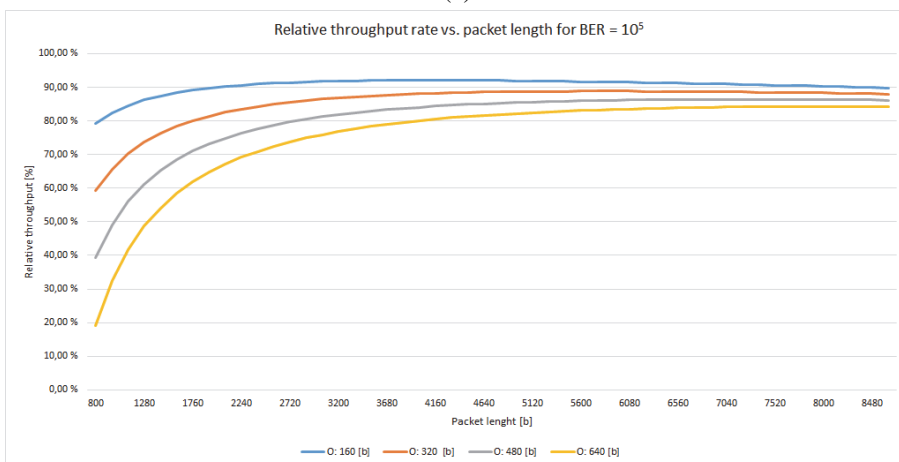
(b)
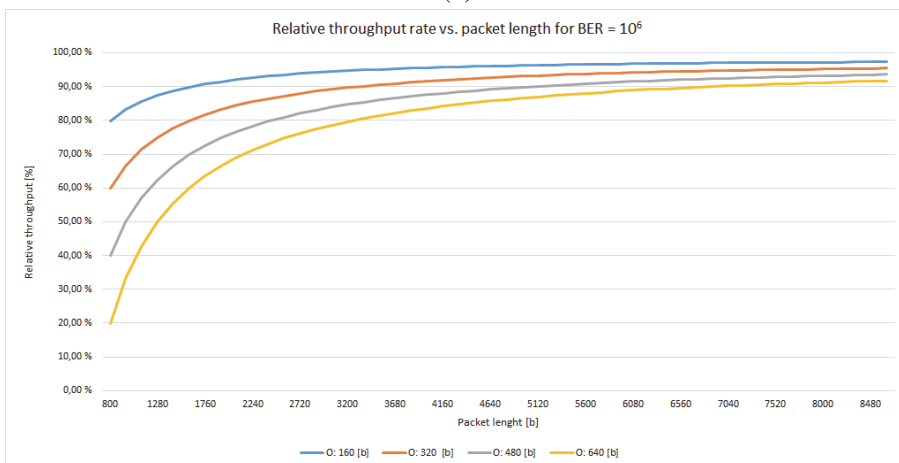
(c)

Figure 6.10: Relative throughput vs. packet lengths for a set of *BER*-values and overhead.

6.8   Link Budget Calculation

In this section, the selected values for the discussed parameters are used to derive a link budget for the up- and downlinks between the satellite and the sensor nodes, in addition to the link budget for the aggregated downlink of data from the satellite to the ground station. The TT&C-links are assumed to be the responsibility of the satellite bus provider, and they are not included in this study. The main characteristics of the link are summarized in Table 6.1 and the link budget itself, for an orbital altitude of 500 km, is shown in Figure 6.13.

The process of setting up the link budget is a good example of the iterative process described in Section 2.1.1. The first iterations of the link budget were based on assumptions, for example, the use of simple omnidirectional antennas both on sensors and satellites. By using these assumptions, the link margin became negative. Therefore, the assumptions on antenna gain had to be iterated and changed until reasonable and realistic values giving acceptable link margin were found. The consequences for the space segment leading from these new assumptions on antenna gain are the need for a more complicated mechanical design (deployable antenna) and the need for active pointing by the ADCS.

The satellite communication links considered are shown in Figure 6.11; the 400 MHz EESS link and its corresponding feeder link; the downlink of aggregated data. The figure shows the case when the satellite covers both the sensor node and the ground station. This will be true in some occasions, but not all, as discussed in Chapter 4.
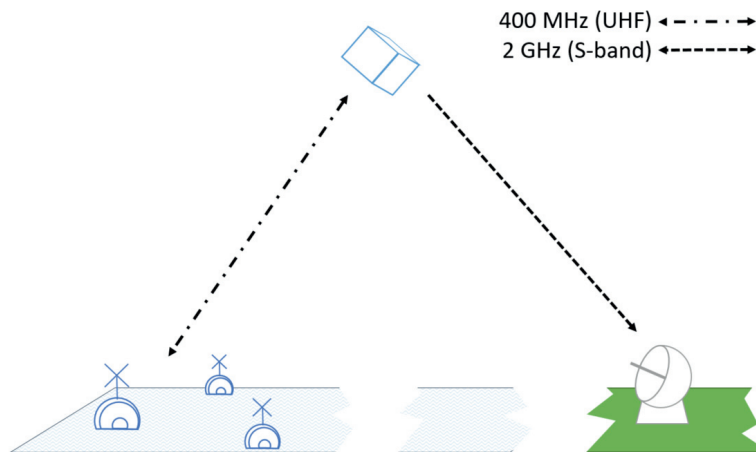

Figure 6.11: The two satellite links considered; 400 MHz (UHF) payload data and aggregated S-Band (2 GHz) downlink.

Table 6.1: Link Budget Conditions

	S-band DL	UHF DL	UHF UL	
Orbital altitude	500	500	500	*[Km]*
Frequency	2200	400	402	*[MHz]*
Data rate - alt 1	500 000	19 200	19 200	*[bps]*
Data rate - alt 2	500 000	100 000	100 000	*[bps]*
Ant. gain on sat	7	10	10	*[dB]*
Ant. gain on ground	30	2 or 10	2 or 10	*[dB]*
EIRP from satellite	36.5	39.5	n/a	*[dBm]*
EIRP from ground	n/a	n/a	27.5	*[dBm]*
Sensor G/T, ($G = 2$ dB)	n/a	-23.7	n/a	*[dB/K]*
Sensor G/T, ($G = 10$ dB)	n/a	-15.7	n/a	*[dB/K]*
Polarization loss	3	3	3	*[dB]*
Atmospheric loss	0	0	0	*[dB]*
Ionospheric scint.	3	7	7	*[dB]*

Ionospheric scintillation was discussed in Section 6.2.3 where we chose a moderate value for the ionospheric scintillation index, $S4$. This gave the need of a 7 dB margin if a 99% availability is desired, or a margin of 3 dB if only 90% availability is needed.

Since the architecture discussed here has a non-continuous coverage, it can be argued that the chosen availability can be set lower than 99%. In Section 6.2.3 it was shown that the scintillation phenomena can have durations of minutes and it therefore can be expected that a full pass might be lost. Even if this causes a loss of data transmission and an increased end-to-end delay, it should not have any critical consequences for the system as the real-time requirements presumably are relaxed, as per an end user point of view.

6.8.1   Comparison with STK Implementation of ITU-Models

The tool STK allows for implementation of the ITU-models for atmosphere, troposphere, rain and ionosphere. As a reference, a simple setup with a satellite in a 500 km, 98° polar orbit with a transmitter at 400 MHz and a ground station on Svalbard, was chosen. For Svalbard, the estimated average level for the ionosphere scintillations is 7.3 dB. The level varies from 26 dB to close to 0 dB. This is plotted in Figure 6.12. Even though the variations are high for all values of the elevation, there is a trend that communication at lower elevation angles is more affected than at higher ones. The average value is of a comparable size with the number found
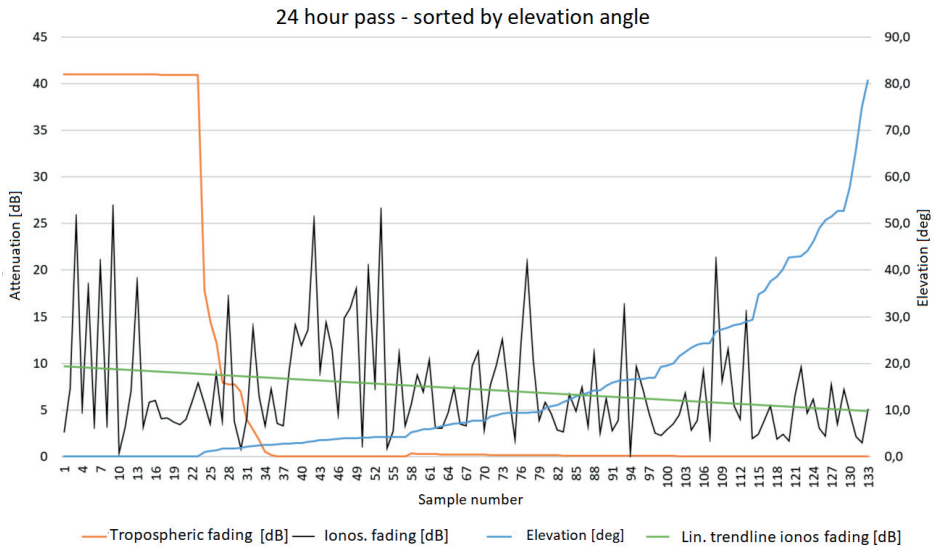
in Section 6.2.3.

Figure 6.12: Example values for tropospheric and ionospheric scintillations (black line) from the STK-implementation of ITU-models at 400 MHz. The set of samples is sorted by increasing elevation angle. The trend-line (green line) showing that higher elevation angles (blue line) are less affected by ionospheric scintillations is visible. Tropospheric scintillation is also shown (orange line).

6.8.2 Noise Calculations

In order to derive estimations for the noise levels, we refer to Section 6.3, Figure 6.4 and equation (6.4). The antenna temperature T_a is set to conservative values, 290 K for the uplink, 250 K for the UHF downlink and 100 K for the S-Band downlink (cf. Sections 6.3.2 and 6.3.1). An example value for the loss, L, between the antenna and receiver is assumed to be 0.5 dB.

We use the formula defined in (6.4), repeated here, to calculate the receiver system temperature:

$$T_s = \frac{T_a}{L} + T_0(1 - \frac{1}{L}) + T_r, \tag{6.17}$$

if $T_a = T_s = 290\,K$, this reduces to

$$T_s = T_0 + T_r, \tag{6.18}$$

Assuming we have a good LNA with high gain and a noise figure of 1 dB, $T_r = (10^{0.1} - 1)290 \ \text{K} = 75 \ \text{K}$. The resulting system temperatures can then be found:

UHF uplink:

$$T_s = T_0 + T_r \tag{6.19}$$
$$= 290 + 75 \tag{6.20}$$
$$= 365 \ \text{K} \tag{6.21}$$

UHF downlink:

$$T_s = \frac{T_a}{L} + T_0(1 - \frac{1}{L}) + T_r \tag{6.22}$$
$$= \frac{250}{10^{0.05}} + 290(1 - \frac{1}{10^{0.05}}) + 75 \tag{6.23}$$
$$= 329.4 \ \text{K} \tag{6.24}$$

S-Band downlink:

$$T_s = \frac{T_a}{L} + T_0(1 - \frac{1}{L}) + T_r \tag{6.25}$$
$$= \frac{100}{10^{0.05}} + 290(1 - \frac{1}{10^{0.05}}) + 75 \tag{6.26}$$
$$= 195.8 \ \text{K} \tag{6.27}$$

These values are used as system noise temperatures, referred to the LNA-input (cf. Figure 6.4) in the link budgets.

6.8.3 Link Budget Results and Discussion

The resulting link budgets for the different frequencies are shown in Figure 6.13. Some of the results will be discussed below, and how the link margins can be improved for the UHF links. It should also be noted that a 3 dB extra link margin is recommended by the European Cooperation for Space Standardization (ECSS) for conceptual designs [169].

Link Quality

The link budget is calculated for a 10° elevation angle, which gives a reasonable margin for the satellite-to-sensor link, but a small margin for the uplink. This could mean that the link will be prone to outages at lower elevation angles. The margin can be increased, by, for example, coding or increased transmit power. Again,

	Unit	S-band downlink (aggregated data)	UHF downlink to sensor node	UHF uplink from sensor to satellite	UHF downlink to sensor node (10 dB)	UHF uplink from sensor to satellite (10 dB)
Orbit and frequency						
Orbit height	[Km]	500	500	500	500	500
Elevation angle	[°]	10	10	10	10	10
Frequency	[MHz]	2200	402	402	402	402
Distance	[Km]	1695	1695	1695	1695	1695
Modulation and code						
Modulation		QPSK	QPSK	QPSK	QPSK	QPSK
Modulation (QPSK) (bit/symbol)		2	2	2	2	2
Code gain		0	0	0	0	0
Code rate		1	1	1	1	1
Data rate (raw)	[bps]	500 000	19 200	19 200	100 000	100 000
Required BER		1E-06	1E-04	1E-04	1E-04	1E-04
Required E_b/N0 for required BER	[dB]	10,5	8,4	8,4	8,4	8,4
TX						
Power	[mW]	1000	1000	500	1000	500
Power input to antenna	[dBm]	30	30	27,0	30	27,0
Connection Loss	[dB]	0	0	0	0	0
Cable Loss	[dB]	0,5	0,5	0,5	0,5	0,5
Antenna Gain	[dBi]	7	10	2	10	10
EIRP	[dBm]	36,5	39,5	28,5	39,5	36,5
Propagation						
Free Space Loss	[dB]	163,9	149,1	149,1	149,1	149,1
Pointing Loss	[dB]	1	0	0	0	0
Atmospheric loss	[dB]	0	0	0	0	0
Ionospheric loss (scintillation + auroral	[dB]	3	7	7	7	7
Polarization Loss (lin --> circ)	[dB]	3	3	3	3	3
Total Transmission Loss	[dB]	170,9	159,1	159,1	159,1	159,1
RX						
Power at antenna	[dBm]	-134,4	-119,6	-130,6	-119,6	-122,6
Antenna Gain	[dBi]	30	2	10	10	10
Connector/cable/filter Loss	[dB]	1	0,5	0,5	0,5	0,5
Received Power at Receiver	[dBm]	-105,4	-118,1	-121,1	-110,1	-113,1
Noise						
Noise temperature	[K]	195	330	365	330	365
Resulting Link Quality						
Signal to noise ratio, C/N0	[dBHz]	70,3	55,3	51,8	63,3	59,8
Eb/N0 for link	[dB]	13,3	12,5	9,0	13,3	9,8
System fade margin	[dB]	2,8	4,1	0,6	4,9	1,4
User datarate	[bps]	500 000	19 200	19 200	100 000	100 000

Figure 6.13: Example link budgets for UHF-links between sensor nodes and satellite and S-Band downlink.

ACM and VCM should be considered in order to use the link efficiently - this is also linked to *SR-017*.

The link is calculated with a 99% availability with regards to ionosphere scintillations, as discussed in Section 6.2.3. Lowering this to 90% will increase the margin with 4 dB. As discussed in Section 6.7 concerning packet lengths, the minimum acceptable BER is set to 10^{-4}, c.f. *SR-016*. A link with higher BER is assumed to be of too poor quality for the application considered in this thesis.

Orbital Height

As discussed in Section 4.1.5, an orbital altitude of 500 km is considered more practical than, for example, 800 km. There are several reasons for this; a 500 km orbit will inherently fulfill the de-orbit after 25 year EOL-requirement defined in *MC-006*, in addition to giving a better link budget. At 10° elevation, a 800 km orbit will reduce the link margin by 3 dB.

Transmit Power and Antenna Gains

In order to support sensor nodes (SN) with limited power resources, the transmit power should be as low as possible. Figure 6.13 shows two alternatives for antenna gains on the sensor node. Large sensor nodes can be equipped with a 10 dB gain antenna, leading to the possibility of increasing the data rate to 100 kbps.

The satellite antenna should also have around 10 dB gain in order for the link to be practical. By equipping the satellite with a high gain antenna, the satellite can support either low-rate links to simple sensors with near isotropic antennas in addition to a higher rate link to nodes with 10 dB antennas. A deployable Yagi or helix antenna with up to 10 dB gain should be feasible[1] and sufficient.

Data Rate, Coding and Modulation

The data rates in the link budget are selected to be as high as possible. By halving the data rate, another 3 dB can be added to the margin. This should possibly be the final resort, as this heavily impacts the total throughput of the communication system. The modulation is chosen to be QPSK, which has the same BER as BPSK. Higher order modulations, yielding more throughput, also require a higher signal-to-noise ratio, which this system proposal will not be able to support.

The link budgets shown are calculated for communication signals without any coding. From Figure 6.6, we find that around 3.5 dB can be added to the link margin by employing a 7/8-code rate. This is important especially at low elevations

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[1]GOMX-3 flies a 10 dB gain helix for the 1090 MHz ADS-B band, NORSat-2 files a 12 dB gain VHF-antenna for VDES at the VHF-band

and during poor conditions. By employing ACM techniques, the code rate can be reduced at higher elevation angles, so the throughput can be increased.

6.9   Chapter Conclusions

Through this chapter, the most central parts of the radio channel, and their impact on the link budget, are presented. The frequency band is chosen at 400 MHz, as this system can be identified as a EESS-application. Further, the propagation effects due to the ionosphere and atmosphere were discussed, and margins for these effects were selected. Finally, noise calculations are discussed. These parameters and numbers have been the basis for the the *first iteration* of the link budget. This couples back to the iterative system methodology presented in Section 2.1, further iterations are necessary, given the outcome of this first iteration.

The radio channel study has most impact on *RQ2* (small satellites and remote areas). The link budget calculations impacts and leads to revision of some system requirements presented in Section 2.2. In order to meet the bit-rate requirement in *SR-013*, the link budget shows that the initial values for antenna gains in *SR-008* and *SR-009* must be changed, as the link budget will not support a data rate of 19.2 kbps without 10 dB gain in at least one of the antennas. 100 kbps will not be supported without around 10 dB gain in both antennas.

The following list shows conclusions and possible further trade-offs based on the link-budget study:

- The satellite should have a high-gain antenna
- Larger sensor nodes should have a high-gain antenna
- Channel $BER < 10^{-4}$ is sufficient, lower BER can be achieved by coding
- Change the target orbital altitude from 800 km to 500 km: 3 dB increase of link margin
- Reduce expected availability from 99% to 90%: 4 dB increase of link margin
- Add FEC: 3.5 dB increase of link margin for 7/8 code rate
- Halving the data rate: 3 dB increase of link margin
- Doubling transmit power: 3 dB increase of link margin

From this list, we find that up to 16.5 dB can be added to the system margin, if design choices are adapted. However, all these changes will come at various costs. In order to meet the demands for the data volume, the bit rate should be as high as possible. Therefore, reducing the bit rate in order to, for example, save power, may not be desirable. Increasing the transmit power, either from the sensor node or from the satellite, may become too expensive, so it can be better to ease the availability expectations. FEC should be added, however, the throughput will be reduced.

In conclusion, the link budget shows that design of a radio link providing up to 100 kbps for larger sensor nodes is feasible. This contributes to a partial answer of *RQ2*.

Chapter 7

System Design and Analysis

In this chapter, the selections, decisions and conclusions from previous chapters are joined together into a full system design proposal. The design proposal encompasses a space segment that can be a part of the system architecture proposed in Chapter 3. First, the CubeSat concept is introduced and the conceptual design of a CubeSat which can carry a payload for the Arctic communication system is proposed (c.f Section 3.1 and paper [32]). Then, the conceptual payload design is presented, and the system drivers stemming from the payload design are discussed for each subsystem. Parts of the ground segment are also included here; the sensor nodes in particular.

The chapter includes an analysis of the design choices presented, and their impacts on the system utility.

7.1 Space Segment System Design

There are several small satellite platforms available on the market, and the Cube-Sat form factor is increasingly popular. This form factor has been used as the basis for several missions; tech-demos, scientific missions and commercial applications. Over the years, a well-known ecosystem of suppliers has emerged, and procedures for testing and launch services are established and mature. The form-factor itself is defined and described in the CubeSat Design Specification (CDS) by CalPoly [170]. Further, an ISO-standard was released late 2017; the ISO 19683 [130]. Finally, ESA has established a reduced ECSS framework for CubeSats.

Since the CubeSats come in various sizes, they can cover a wide range of missions from simple 1U *ping-sats*[1] to commercial missions flying powerful and

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[1]A *ping sat* is a satellite with virtually little use expect that it transmits a telemetry beacon, that

versatile 12U CubeSats with deployable solar panels. For all these reasons, we propose that the CubeSat form factor should be the basis of the space segment discussed in this architecture too. Even though the satellite bus can be assembled with *COTS* components to save cost, the function of the satellite(s) will be tailored to fit the specific needs of each mission. To this statement, it should be added that the cost range is large; from building a simple satellite from components such as Arduionos [171] and Raspberry Pi [172], through choice of components in a medium cost range to commercial and professional suppliers that offer well-tested and flight proven components.

The cost of building CubeSats is not linear. The initial cost for specification, first design and prototype development is high. However, when the design is fixed multiple CubeSats could be built to a linearly scaling cost of the hardware. This effect could be exploited, and it might be feasible to build several similar CubeSats either for simultaneous launch to increase coverage, for sequential launching to increase time of operations, or to keep spares to reduce risk.

7.1.1　CubeSat Platform Design

This thesis will not describe the CubeSat platform design in detail, but identify the main subsystems and parts are needed to complete the space mission.
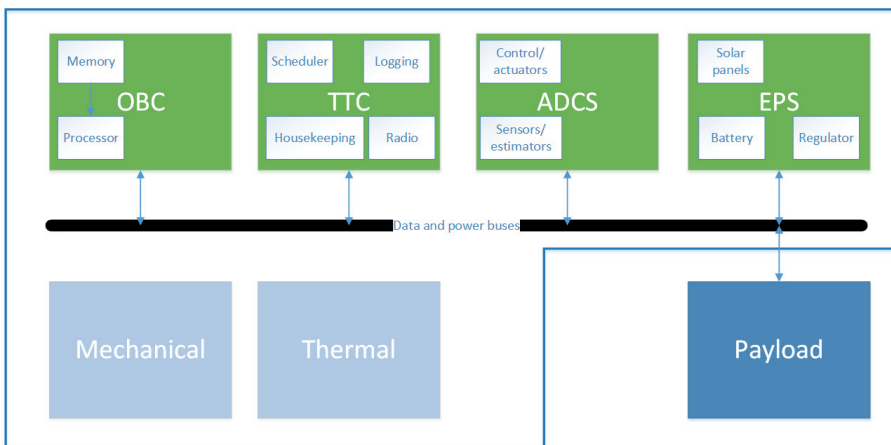

Figure 7.1: Conceptual layout of a typical small satellite architecture. Some satellites can have a propulsion subsystem.

Figure 7.1 shows a conceptual layout of a space craft. Green boxes represent subsystems that may be implemented by one electronic board or box. There are

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may or may not be changed from the ground station.

several options for optimizing the design by subsystems integration. The modularity can be achieved in software with the help of a powerful processor instead of separate sensor/processor boards for each subsystem. The most important functions are shown within each subsystem. The light blue boxes represent "conceptual" subsystems which are not on the form of one electronic board or box. Boxes within the blue shape represent what is part of the space craft bus, while the payload is attached to that. There can be several interactions between the various subsystems. The mechanical subsystem must allow space for the other subsystems including the payload. The thermal subsystem must ensure that no part of the space craft gets too hot or too cold, balancing the thermal budget. The payload will influence the specifications for the Electrical Power System (EPS) and the ADCS. The EPS must ensure that a positive energy budget is maintained throughout operations and put the satellite into power-saving-mode if necessary. Also, the On-Board Computer (OBC) will interact with the payload to control scheduling and operations.

CubeSat Bus Providers

There is a variety of producers and suppliers of CubeSat platforms. Examples of companies are Tyvak [173], Innovative Solutions in Space (ISIS) [174], Gomspace [175], UTIAS-SFL [176], Open Cosmos [177], NanoAvionics [178] and Clyde Space [179]. All of these can deliver integrated platforms to support a custom payload. From some of them, it is possible to buy individual subsystems and build your own platform. Parts from for example ClydeSpace, Pumkin [180], ISIS and others follow a common interface design and can be integrated into a CubeSat platform.

Spacecraft subsystems

Figure 7.2 shows another representation of a space craft architecture, where more of the common and typical components of each subsystem are shown. The boxes with orange text represent more advanced optional features that may be implemented, depending on requirements and capabilities of the space craft bus.

The following briefly lists the satellite subsystems and introduces their main components and functions. Some of the subsystems are named differently in other literature, but their functions will be the same. Several subsystems are discussed in the literature, for example [29, 181]. Depending on the satellite bus, some subsystems can be integrated on the same hardware, and the modularity is realized in software. This may be the case if a satellite is equipped with a powerful processor capable of performing all processing for all other subsystems. A high level of hardware integration is more common for physically small satellite buses.

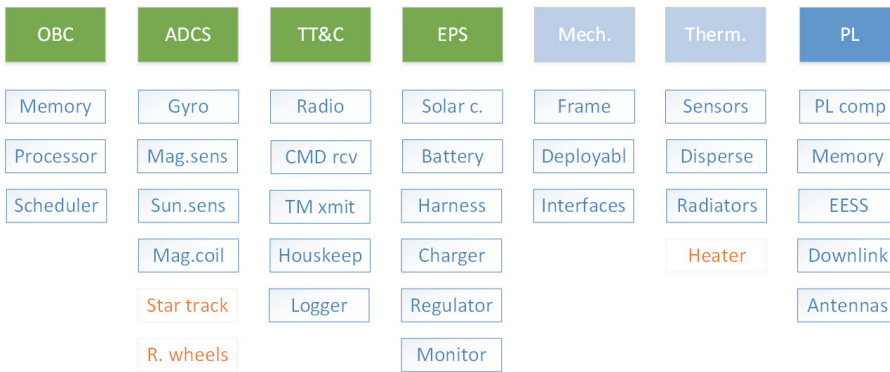| OBC	ADCS	TT&C	EPS	Mech.	Therm.	PL
Memory	Gyro	Radio	Solar c.	Frame	Sensors	PL comp
Processor	Mag.sens	CMD rcv	Battery	Deployabl	Disperse	Memory
Scheduler	Sun.sens	TM xmit	Harness	Interfaces	Radiators	EESS
	Mag.coil	Houskeep	Charger		Heater	Downlink
	Star track	Logger	Regulator			Antennas
	R. wheels		Monitor			

Figure 7.2: Typical conceptual small satellite architecture. Typical optional features are marked by orange text. Some satellites can have a propulsion subsystem.

On-Board Computer (OBC)   The OBC is the brain of the satellite. The main task is to collect, process and organize storing of data. Processor(s), memory and sensor interfaces are typical components. The OBC also provides a data interface connecting the other subsystems with each other. This interface is named "Data and power buses" in Figure 7.1.

Telemetry Tracking and Command (TT&C)   The TT&C is responsible of organizing transfer of house-keeping data to and from the satellite bus. It also maintains the overview of all other systems, and is responsible for logging, scheduling and performing house-keeping tasks. The logged sensor data must be transmitted (named "TM xmit" in Figure 7.2) to the satellite bus operator. Conversely, the TT&C receives commands from the satellite bus operator (named "CMD rcv" in Figure 7.2), interprets and handles or forwards these commands. This system may often be, from a hardware perspective, highly integrated with the On-Board Computer (OBC). Typical components are sensors and processors as well as required radio systems with antennas.

Attitude Determination and Control System (ADCS)   The role of the ADCS is to estimate, maintain and control the satellites orientation in space. For example, pointing antennas or other payload instruments towards their targets. The subsystem will be equipped with a set of sensors for estimation of satellite attitude, as well as actuators in order to point the satellite in a direction. Depending on the pointing requirements and agility of the satellite different types of sensors

and actuators can be required. For coarse pointing magnetic torquers are used as actuators, with sun-sensors, magnetometers and gyros as sensors. If finer control is needed, reaction wheels are used as additional actuators with an accurate star sensor to help attitude estimation. These components are named "R. wheels" and "star track" in Figure 7.2 respectively.

Some satellites can be equipped with a **propulsion system** which can move the satellite from one orbit to another, or that can be used to counteract the impacts of orbital perturbations.

Electrical Power System (EPS) The EPS is the power generator and distributor in the satellite. Typical components are solar cell panels (named "Solar c." in Figure 7.2). for energy harvesting, batteries for storage, and chargers and regulators to make use of and distribute the energy to other subsystems. The EPS must supervise the energy usage of the satellite and always maintain a positive power budget in order not to drain the batteries. This subsystem distributes the energy through a set of power buses every other subsystem must be connected to.

Mechanical The mechanical subsystem keeps the satellite together. It provides mechanical interfaces, a structure and must maintain structural integrity in all the life phases of the satellite; from manufacturing, testing, launch, deployment and operations. The function of any deployable solar panels and antennas also falls under the responsibility of this subsystem.

Thermal The thermal subsystem can, for small satellites, in many cases look "invisible". It is responsible of maintaining a sound temperature balance in the satellite. For small satellites it is usually a passive system, which means that thermal energy is passively distributed through the satellite. For example, potential hot-spots such as power regulators and amplifiers must have good thermal conductivity to other parts of the satellite in order to dump energy, so the components do not overheat. For some components, where temperature balance is especially important, active cooling or heating may be needed. Other typical components of this subsystem are surface coatings for insulating or radiating energy, as well as thermal blankets, heat pipes and so on.

Payload (PL) The payload is the subsystem representing the application of the satellite and is the reason the satellite was made in the first place. The payload or payloads represent the purpose of the satellite. In our case it is a radio system that aggregates messages from sensor nodes, before they are relayed to the GW. Other payloads can be remote sensing instruments such as cameras or radar, or in-situ probes. Typical components are payload computer (named "PL comp" in

Figure 7.2), memory, and specific payload functionality (represented by the EESS-box in Figure 7.2).
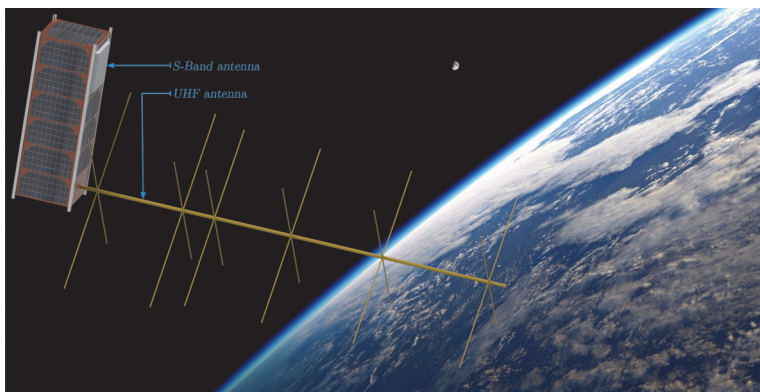
7.1.2 Conceptual Payload Design

Figure 7.3: Artist's impression of a 3U CubeSat with high-gain deployable antenna. Credit: Frida Vestnes.

Figure 7.3 shows a sketch of a 3U CubeSat with a S-Band antenna and a deployable 400 MHz UHF Yagi-antenna mounted on the same face. The gateway and the deployed sensors will most likely be located so they can be reached simultaneously during some passes. Therefore, it makes sense that the antennas are placed on the same panel in order to point in the same direction. It is assumed that there will not be room for mounting both antennas on the ends of the satellite.

Payload Functionality

The payload must be defined with the given system requirements from Table 2.5, and most of these requirements have been discussed and defined through Chapters 4, 5 and 6.

Several of these requirements lead to the need of a payload with a powerful processor capable of decoding all messages from the sensor nodes, to fulfill requirements such as routing, buffering of data and QoS.

The payload functionality is realized by the following components:

1. High-gain UHF antenna
2. Payload processor with a large memory
3. UHF radio for communication with the sensor nodes
4. Integrated (or access to) a high-rate S-Band downlink radio

Multiple Access   As discussed in Section 5.1.5, the satellite should dynamically assign frequency and time-slots for the sensor nodes. As the payload should be both cheap and flexible, but also provide a high throughput, the number of frequency channels must be considered. Given that the full EESS-band can be used for this application over the Arctic area, the theoretical number of possible FDMA-channels is ten. However, at least some guard-bands (to, for example, account for Doppler shift) must be allowed for, so the practical number is lower. Adding multiple channels also increases the complexity of the payload, so this must be a trade-off between complexity and cost vs. increased capacity and utility. This work does not aim to do a detailed analysis of this but assumes that three to five channels are possible.

If needed, these channels can be further divided into time-slots, also discussed in Section 5.1.5. In this application the time-slots may be quite large. Tight spacing of short time-slots is challenging for space applications as sensor nodes at different locations, all within reach of the satellite can have significantly different propagation delay; making timing and synchronization challenging.

Further, the network stack is suggested to be implemented on the payload processor as defined in Section 5.3.

Uplink and Downlink Frequencies   The uplink and downlink will be assigned different frequencies, as shown in Figure 6.1, and listed here:

- Uplink from sensor nodes: 401 – 403 MHz
- Downlink to sensor nodes: 400.15 – 401 MHz
- Uplink from gateway to satellite: 2025 – 2110 MHz
- Downlink to gateway from satellite: 2200 – 2290 MHz

Payload Design Implementation

Figure 7.4 shows one possible high-level design of the payload. The payload consists of and EESS communication unit with an UHF radio for communication with the Sensor nodes. The payload processor takes care of buffering, actions related to QoS if needed, and routing if needed (for example to UVs). The payload design is a *store-and-forward* design, however, if both a sensor node and the gateway are within sight, the payload can relay messages near instantly.

The radio part of the payload consists of a suitable antenna, RX/TX-switch, necessary amplifiers and filters and modulator/demodulator. Coding/decoding and framing/deframing of messages must also be taken care of as described in the Section 5.3 on the proposed network stack.

The S-Band radio may be a part of the CubeSat bus instead of being considered a part of the payload. The command link for the sensor nodes and the signaling

channel will have to go through that radio, but if it should be a part of the bus or of the payload will be subject to trade. The driving factor can be the availability of a suitable standard radio from the bus provider.

The radio(s) may be designed as traditional radios with hardware implementations of every function up to and including the modulator/demodulator. An alternative is to use an SDR implementation. This is a hot topic in the small satellite community, and several designs and implementation alternatives exist, both for the space segment and the ground segment [182].
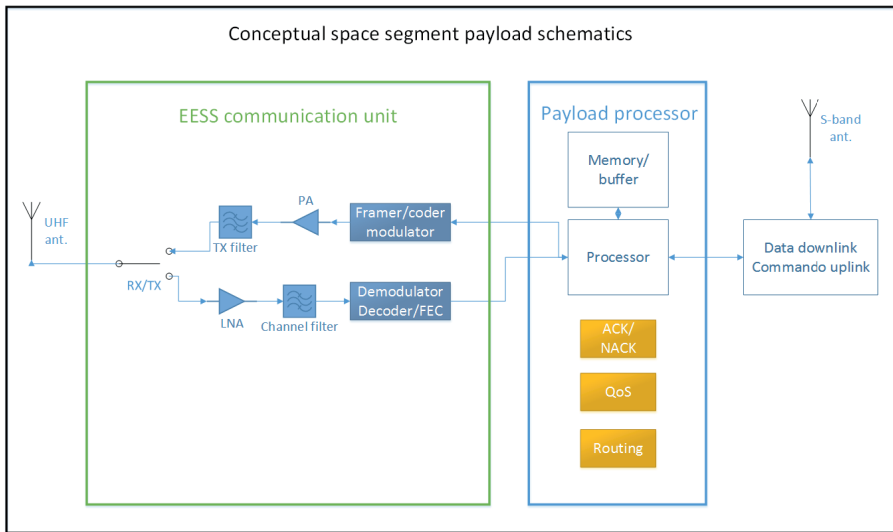

Figure 7.4: Conceptual payload design

7.1.3   System Drivers Linked to the Payload

The choice of payload, and its implementation, will naturally cause some system requirements flowing back to various subsystems in the satellite bus. The most important considerations are presented in the following sections.

On-Board Computer and Telemetry, Tracking and Command

The On-Board Computer (OBC) is responsible for handling the data and running most programs onboard the satellite. Depending on design choices by the Cube-Sat manufacturer, the OBC can physically be a powerful computer that also takes care of computational power for most other subsystems, such as the EPS, TT&C and ADCS. The OBC can also support the payload, either provide computational power as payload processor or also act as a centralized buffer and data storage. For

CubeSats, the OBCs main part often is a powerful processor running Linux, or a System on Chip (SoC) with both processor and a Field Programmable Gate Array (FPGA).

For our space mission, if volume allows, the OBC could be separate from the payload. The OBC will be the link between the satellite operator and the payload, issuing commands and overseeing when the payload can be used. If this solution is chosen, no strong system driver sourcing from the payload is identified.

Power Budget Considerations

The EPS oversees maintaining, regulating and distributing energy within the bus. The satellite must, on average, have a positive link budget, for example, for every orbit or every day. Power available for the payload in a 3U CubeSat can be up to 3 W average. However, given that the satellite will be above the Arctic area for only 10 –20 minutes every pass, the peak power available can be large; up to over 15 W. If the gateway link and the payload links are allocated 2 W on average, the average power consumed during a pass will scale to $90 \min / 20 \min \cdot 2\,\text{W} = 9\,\text{W}$ available during the pass.

The system driver related to the EPS is then the power needed; both peak power during operations as well as total energy consumption during operation. If the energy requirement for the payload is too high for a standard 3U CubeSat, deployable solar panels will be needed. A simple power budget overview is shown in Table 7.1.

Table 7.1: Satellite Payload Power Budget for One Pass

Component	Time on (duty cycle)	Instantaneous [W]	Average [W]
UHF-radio, RX	80%	0.3	0.2
UHF-radio. TX	20%	2.5	0.5
Payload processor	100%	2	2.0
S-Band. RX	30%	3.9	1.2
S-band. TX	70%	4.1	2.9
ACTIVE AVG			**6.8**
Peak Power		**8.6**	
ORBIT AVG	**20%**		**1.4**

From this table we observe that the average energy consumption over a full orbit is on the order of 1.5 W, even if the peak-power reach close to 9 W during a pass. The average power load during a pass should be around 7 W in this case. Values for the UHF-radio and payload processor are estimated. Values for the S-

Band is based on the NanoCom SR2000 from GomSpace [183]. From this, a 3U CubeSat is very likely to provide enough power for payload operations.

If increased use of the satellite system through providing services to other geographical ares is considered, the duty cycle will increase, and the total energy consumption must be carefully considered.

In the design phase, a margin should be added to these numbers. At least 20% is recommended [169].

Attitude Control Considerations

The ADCS has two main tasks; first it has to de-tumble the satellite after deployment and get control over the satellite's attitude. Secondly, the ADCS is responsible for changing and maintaining the pointing direction of the satellite. For this mission, this means the pointing direction of the antennas. The S-Band and UHF-antennas have approximately $7 - 10$ dB gain and require moderate pointing accuracy. This should be possible to achieve by a simple active system based on the classical magnetic torquers, and it should be possible to attain a pointing accuracy on the order of $5°$ [29, Chapter 1]. Advanced components such as reaction wheels and star trackers should not be needed in this application.

The payloads' system driver for ADCS is the pointing requirement, stemming from the antenna gain requirements. Also, if the antennas are mounted on different faces of the satellite, pointing must be performed when changing mode; from data harvesting from the sensor nodes to downlinking the aggregated data. If possible, this should be avoided, and the antennas should be mounted on the same side.

Mechanical and Thermal

The mechanical subsystem takes care of holding the satellite together, providing room for, and integration of, the other subsystems and their components. The system driver is that there must be place for a deployable UHF antenna. The design of the antenna must maximize the probability of successful deployment.

The thermal requirements from the payload should be relaxed. Electronic components with a suitable temperature range should be used, to ensure that the payload can be used both when the satellite is illuminated by the sun and when it is in eclipse. The amplifiers and the payload processor represent hot-spots where thermal energy dissipation must be taken into careful consideration for the components not to overheat. Passive regulation, meaning ensuring good thermal conductivity to ground planes or the main satellite structure, should suffice for this purpose.

Downlink to Gateway

The downlink to the Gateway (GW) must provide a link capacity well above the expected amount of aggregated data between each pass. This is especially important if the gateway is not seen by all satellite passes. The satellite can then have buffered sensor data from several passes that should be downloaded at first opportunity. This downlink must not be a bottleneck in the system.

7.2 Ground Segment - Sensor Nodes

The concept for design of the sensor nodes will be briefly introduced in this section. Figure 7.5 shows the conceptual design of a sensor node. The node consists of a sensor unit, a local processor that is responsible for pre-processing of data (if needed), control and scheduling of the node and preparation of the data to be transmitted to the satellite. The sensor node may also have one or several other radios for communicating with neighboring nodes and/or UVs.
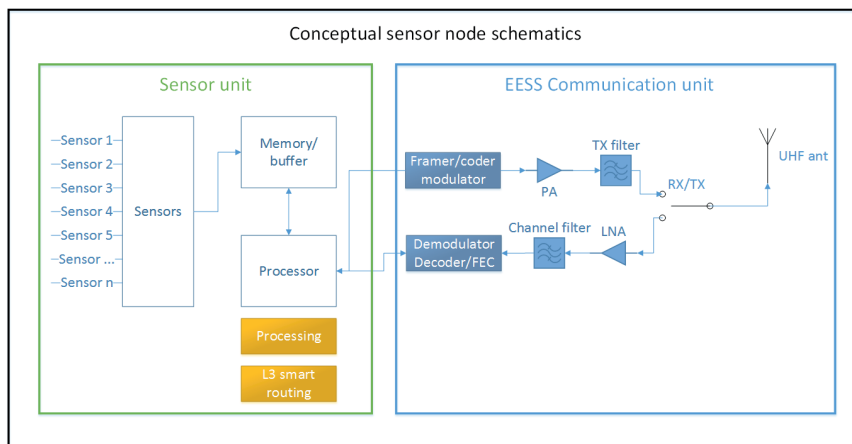

Figure 7.5: Conceptual layout of a sensor node. The left part is the sensor unit, with some functions shown: processing and L3 routing represented by the orange boxes. The right part is the communication unit responsible for communication with the satellite. It is assumed that the software and network stack is running on a shared processor with the sensor node, so that for example layer 3 smart routing could be implemented there.

Depending on the physical size of the node, and the data volume produced, the node may be equipped with a high-gain antenna to increase the throughput. This allows for transfer of a larger data volume, or just transfer the data in a shorter time.

7.3   System Utility Analysis and Results

In this section, the results and contributions from the presented work are summarized. The presented design choices and justifications are evaluated against the *research questions* (c.f. Section 1.3.1), mission- and system requirements (c.f. Section 2.2). Other variations of previously discussed communication systems are also added for comparison. This relates to, for example, the number of satellites in a swarm.

7.3.1   Is There a Gap?

A high-level and important question to answer is if there is a need for a system as proposed in this work. In Section 2.3.1, the communication gap and challenges related to the Arctic are stated. The proposed "very narrowband" IoT constellations as well as broadband solutions such as the Norwegian HEO-project, and the proposed mega-constellations are considered. The first services appear to target the mass market and cheap sensors requiring a very low data rate. The second set of services targets communication for humans more than machine-to-machine (M2M) – services. Sensor networks in the Arctic may not be served by either of the proposed services. Both the technical and financial state of the the mega-constellations remain unknown. Therefore, the conclusion is that the gap exists, and will not be covered in the short-term (c.f Appenix C). The situation is illustrated by Figure 2.6 on page 35.

Current services like the various Iridium options can also be considered. They can be categorized in three service classes, listed in order of low to high data rate and power consumption: The Iridium SDB, Iridium data through dial-up (embedded modem) and Iridium Pilot. SDB is only usable for very short data messages, and for a few transmissions a day. Dial-up can support more data, but only up to 2.4 kbps. Depending on the modems, average power consumption is between 2.3 W and 4 W. Pilot is the "broadband" alternative. The power and installation requirements are higher (over 50 W), so it is not suitable for an embedded system such as the sensor nodes, even if the maximum data rate of 134 kbps is desirable for sensor systems [21, 184].

To conclude, even if the number of potential users in the Arctic is currently low, the need for a data rate higher than planned for in the new IoT-systems, is identified. None of the current available systems provide a viable solution with a reasonable trade-off between data rate and power consumption, and it can be argued that they will not be able to be a part of the network architecture presented in Section 3.1. At least, there is a gap between Iridium and proposed broad systems; in the range between 10 kbps to 200 kbps.

7.3.2 Coverage and Throughput

In this section, aspects about coverage and throughput for variants of the system of small satellites are discussed. In addition to the swarm configurations discussed earlier, a swarm of nine satellites is also considered.

Coverage from Freely Drifting Swarms

As shown in Chapter 4, and in papers [11, 115, 117, 116, 114], swarms of small satellites offer some interesting properties. Their hardware cost and operational cost will be considerably cheaper than satellites with a propulsion system. This saves the cost of the propulsion system itself, and it relaxes the ADCS-requirements. Without a propulsion system or strict ADCS requirements, the space craft size can be reduced and give a lower launch cost.

The drawback of the freely drifting swarm is that the observed distance between the satellite footprints constantly change, and therefore the duration of gaps between satellites (the revisit time) also varies. In addition, satellite footprints will overlap on some occasions. This causes a reduction in system capacity. All satellites are expected to share radio resources and only one of the satellites that overlaps may be used at the time.

Coverage Gaps One figure of merit that can help evaluate the satellite system is the duration of the time between two satellite passes. For a case with a swarm of three satellites, 70% – 80% of the gaps are shorter than the expected gap from a two-satellite constellation [115]. The three-satellite swarm also increases the capacity of the systems and offers more redundancy (see Section 4.3.3). The average gap duration is reduced by adding more satellites to the swarm. However, the maximum coverage gap that can be experienced will depend on the amount of satellite overlap and the location of the GW and sensor nodes.

Responsiveness Responsiveness, or response time, is another figure of merit used to evaluate how a system performs [29, Chapter 7.2.3]. In a communication system like this, this relates to the time between a request is issued (for example a GW requesting data from a sensor node) until the response is received. From the emulation results presented in Section 5.5.4 and in [116], we find that this value varies a lot. When both the GW and sensor node are covered by a satellite, this time can be close to zero. When either the sensor node and/or the GW is placed so that they are not covered by every satellite pass, this time can be up to nine or ten hours. From the results presented, it is found that the satellite swarm with three satellites performs better than a two-satellite constellation in most cases.

As shown through network emulations (c.f Section 5.5.4), the initial system design with satellites in only one plane fail to meet the responsiveness requirement of maximum 6 hours, according to *SR-006*. The suggestion following the discussion in Section 5.6, is to relax the requirement, in order not to drive the cost of the system. The new requirement can be 8 hours for architectures using Svalbard ground station, and 12 hours using only Vardø ground station.

Even if the response time may be several hours for the satellite system, it is much shorter compared to a situation where UAVs, airplanes or even manned expeditions are used to collect the sensor data.

Overlapping Satellites

For the three-satellite swarm, with satellites as defined by Case 3 in Table 4.2, simulations with STK show that more than two satellites overlap 11.6% of the time, with all three satellites overlapping only 2.8% of time. Different combinations of satellites in the swarm may yield different results.

Figure 7.6 shows how nine drifting satellites perform, when observed from the northern most part of the area of interest. The amount of time when a point in the area of interest is covered by a given number of satellites is shown. From this, we observe that the area of interest is covered by one satellite 76.8% of the time.

Coverage from more than one satellite implies overlap and is not desired. The fraction of time when more than three satellites overlap is small. As seen from Figure 7.6, the amount of time where four or more satellites overlap, accounts for less than 4% of the covered time. The total "penalty" of the swarm, meaning how much of the total capacity may be reduced due to overlaps, is calculated to be 23.2% for nine satellites, see Appendix F for a description of the simulation method.

Considerations on Throughput

The baseline is one single satellite with one frequency channel, with 90% availability. Referring again to the iterative methodology in Section 2.1.1, and the system requirements, the single satellite baseline will not provide the capacity needed to fulfill the requirements and the mission objective. Further design iterations have included adding more satellites with better antennas as well as making better use of the frequency spectrum by proposing to add more frequency channels.

Figures 7.7 and 7.8 show a simple analysis of the theoretical throughput from the proposed satellite system. Figure 7.7 shows the case where we only make use of a simple antenna on the sensor node, with an expected gain of 1 dB (see link budget in Section 6.8.3). The data rate is 19.2 kbps, 90% availability is chosen, and a 7/8-code rate is assumed. The expected yearly data volume, per satellite,
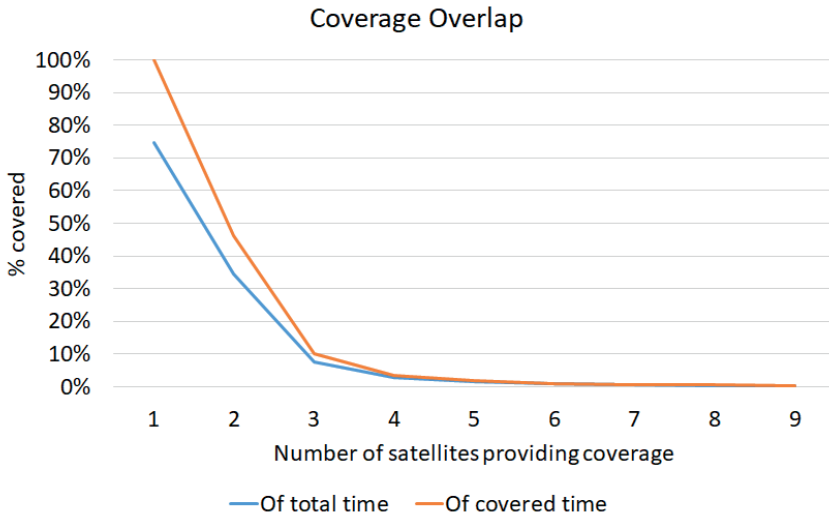
Figure 7.6: Number of satellites providing coverage for the target of interest.

range between 4.2 GB to 6.6 GB, depending on the network stack chosen. The figure includes various orbit configurations.

The orbit variations are two-satellite constellation, three-satellite swarm and a nine-satellite swarm. The capacity will scale with the number of frequency channels. With five channels and nine satellites, the yearly data volume ranges from 148 – 228 GB, depending on network protocol and coding used. This then meets the mission constraint (*MC-002*) of supporting more than 200 GB. More details are included in Appendix E.

Figure 7.8 shows the transferred data volume for a situation where an antenna with 10 dB gain is mounted on the sensor node. The added gain is assumed used to achieve a higher data rate (100 kbps), instead of reducing the transmit power. In this case, we see that the yearly data volume (90% availability) range between 22 GB – 34 GB per satellite. Aside from the data rate, the rest of the variables are like the 19.2 kbps-case. With five channels and nine satellites, the yearly transferred data volume ranges from 770 – 1 192 GB, depending on network protocol and coding. This is well above the throughput requirement *MC-002*.

Both cases scale with the number of satellites in the swarm or constellation, with a factor to adjust for the period when the satellites are overlapping. Simulations show that this corresponds to a 11.6% reduction for three satellites and a 23.2% reduction for nine satellites (see Appendix F).
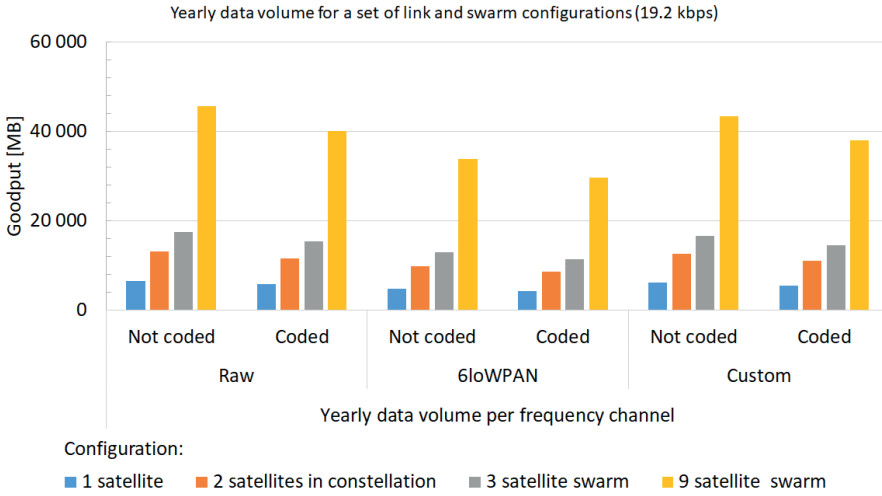
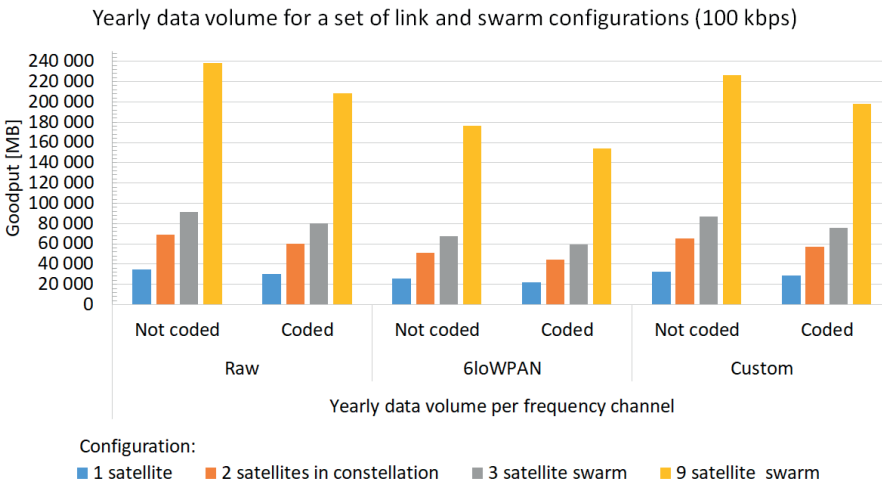Figure 7.7: Potential yearly transferred data volume for a data rate of 19.2 kbps, for one frequency channel.

Figure 7.8: Potential yearly transferred data volume for a data rate of 100 kbps, for one frequency channel.

7.3.3 Relevance for the Use Case

This section presents more details about the use case introduced in Section 2.2.3, and the sensor nodes considered. The utility of the described satellite communication system is then compared to the needs from the use case. Another important factor to consider when looking at the utility of the proposed communication system is if the sensor nodes can host the needed ground terminals. Energy considerations and mechanical considerations are important factors.

Arctic ABC Sensor Nodes

For three satellites in a swarm, a yearly data volume ranging from 296 GB to 457 GB (assuming five frequency channels) can be supported. This may cover the expected data volume from the first or even also second generation Arctic ABC-installation. The system capacity can further be enhanced by employing UVs in tandem with the satellites.

Sensor Node Power Budget

Table 7.2 shows an estimate on power budget for the communications part for a sensor node, with columns for transmit (TX) and receive (RX), respectively. The assumptions for this budget are:

- Transmit power relates to the link-budget in Section 6.8.3
- Approximately 70% of the time is allocated for data transmit (uplink), 30% of the time is allocated for downlink
- Depending on the geographical placement of the node, the budget may be over-estimated since some nodes may not have 14 passes per day
- The power budget is made for communication with one satellite and one frequency channel

At this early design stage, these numbers are very uncertain, and a margin must be added. At least 20% margin should be added according to the ECSS-standard [169].

A yearly energy consumption of close to 1 kWh is significant. However, the sensor nodes are relatively large and will be equipped with a battery capacity of $3 - 5$ kWh, and it meets the battery size mission constraint *MC-003*.

High-Gain Antenna

In the link budget in Section 6.8.3 and from the throughput discussion in Section 7.3.2, we observe that there will be a significant increase in the throughput

Table 7.2: Sensor Node Power Budget for Communications

	TX	RX	
Time active per pass	500	200	[s]
Passes per day	14	14	
Power consumption	1	0.5	[W]
Per pass	0.14	0.03	[Wh]
Per day	1.94	0.39	[Wh]
Per month	58.33	11.67	[Wh]
Per year	710	142	[Wh]
TOTAL		852	[Wh]

if a high-gain antenna is mounted on the sensor node. Following the requirement that there can be no moving parts, nor extruding parts on the sensor node (see Section 2.2.2), the antenna must be inside the node casing. The sensor node concept is depicted in Figure 2.5. This shows that there should be room for an antenna on top of the inner casing within the covering shell.

The design of a high-gain antenna, with a target gain of 10 dB is suggested for future work.

Data Volume and Energy Cost

The maximum expected yearly data volume per satellite, per sensor node is found to be from 22 GB per year for 6LoWPAN at a data rate of 100 kbps (see Figure 7.8), assuming a high-gain antenna on the sensor node. This was calculated for a 600 second pass.

Depending on how the time during a pass is split between uplink and downlink, this capacity will be scaled. If we use the same allocation as for the power budget, the uplink time is 500 s, which then gives a yearly data volume of 18.3 GB.

Incorporating this with the energy budget in Table 7.2, we find that the energy cost is $datavolume/TXenergy = 18.3/.71 = 25.8$ GB/kWh.

For a 19.2 kbps-link, the corresponding numbers are a yearly data volume of 4.2 GB. The energy cost per GB is $4.2/.71 = 5.9$ GB/kWh.

7.3.4   Feasibility of the Communication Payload

This section will discuss some of the findings related to the proposed payload itself, including the link budget, power budget, and proposed network stack.

Regulatory Aspects

The two main regulatory aspects considered here are frequency allocation and space debris mitigation. As stated in Section 6.1, there are frequency bands available to support missions like those discussed here. Regulatory procedures must be followed. This should not pose a challenge.

It is also important to not create space debris. The satellites should be launched in a LEO orbit where the physical orbital lifetime is less than 25 years. This limits the orbital height to around 600 km for satellites without any de-orbit device. For a small satellite LEO communication system, 500 – 600 km is a practical orbital altitude, which is a good compromise between pass duration (higher orbits better) and link budget (lower orbits and shorter distances better).

Space Segment

Detailed technical comparisons between alternative technical implementations of the payload are beyond the scope of this work. However, COTS products that could be used to realize the payload hardware can be acquired through various satellite bus providers, such as GOMSpace. For example, they provide flexible communication products through their SDR platform [183]. This is only named as one possible solution; more detailed design must be carried out and several solutions should be evaluated.

Swarm Launch and Deployment   As argued in Section 4.1.5, a 500 – 600 km orbit is available through ride-share launches. The proposed deployment method presented in Sections 4.2 is assumed to be practical, however, clarifications with launch provider must be ensured. If the required assumptions should not hold, some design changes must be made. The number of satellites in the swarm can be adjusted, and other velocity profiles can be considered, giving different swarm properties compared to the simulations presented here. Another alternative, even if it will increase the cost, is to include a *one go* thruster.

Link Budget   The link budget is presented and discussed in Section 6.9. The most important finding from the link budget is that to provide a link with a usable data rate, both the sensor node and the satellite must have antennas with relatively high gain. For the satellite this is of less concern. It will be a more complicated design compared to a near omi-directional antenna, but similar solutions have flown already on, for example, GOMX-3 and NORSat-2.

For the sensor node, the situation may be more challenging. However, for large sensor node platforms as discussed in Section 2.2.3, it will be possible to integrate a an antenna system with needed dimensions.

For sensor nodes requiring less throughput, or offering less space, a 19.2 kbps link may be feasible.

Power and Energy Budgets   Both power and energy considerations are important for a space craft. The space craft bus must provide enough power during payload operation, and the total energy budget must always be positive. The power budget shown in Section 7.1.3 lists that the maximum power during operation should be close to 9 W. With margins, this should be increased to 11 W.

On the other hand, the average power consumption over one orbit, will be less than 1.5 W. With margins, this will still be less than 2 W, a number that can easily be provided for.

Sensor Nodes

The most important aspects of the ground segment are presented in Section 7.2, in which the conceptual design of a terminal is presented. The power budget is listed in Section 7.3.3. Based on this and the previously discussed mechanical issues related to the high-gain antenna, the concept seems feasible. Further detailed design of the ground segment terminal is outside the scope of this thesis, and is suggested for future work.

7.4   Cost and Resources

At this project stage, detailed cost of the satellite system and other architecture components must be considered rough estimates. Better cost estimates are not possible until completing an Request for Information (RFI) or Request for Proposal (RFP)-process. The background and justifications for cost estimates can be found in Appendix D.

Based on the estimates, an analysis comparing cost between different satellite swarm layouts, UAV and airplane operations is shown in Figure 7.9. The figure shows a comparison of *cost per GB per year* for four different data carriers: The Iridium Pilot system, a combination of a single satellite, three and nine satellites swarms (single satellite up to 110 GB per year, three satellites up to 290 GB per year, and nine satellites above that), UAV, and an airplane.

Iridium Pilot is chosen as a comparison, even if it may not be a direct candidate for the sensor nodes due to requirements for power and installation, as discussed in Section 7.3.1. Dial-up Iridium may be more realistic when it comes to power and installation constraints but will offer a considerably lower data volume throughput.

It is very important to note that all four options represent considerably different properties. Using Iridium may provide near continuous coverage, however at

a higher energy cost (c.f. Section 7.3.1). The UAV and airplane cannot provide an update rate or responsiveness compared to what a satellite solution can. Campaigns making use of UAVs or airplane will be prone to delays and risks due to, for example, weather conditions. The airplane can harvest less data per campaign than the UAV (see Appendix D).

Satellites may provide regular and "risk free" access to data, at a comparable cost of the UAV-campaigns. For the satellite system, the following assumptions are made:

- All satellites cost the same; both for hardware and launch. Development cost comes in addition.
- All practical satellite communication capacity is used all the time. IoT-protocols are used.
- For the satellite system, five frequency channels are used.
- The cost of the satellite system is plotted for three, five, and seven years system lifetime.
- The cost of UAV-operation is scaled by the number of flights (one, six and twelve flights are shown).
- The cost of airplane-operation is scaled by the number of flights (six to 48 flights are shown, with six flights increment).

As expected, deploying a dedicated satellite system is not cost effective unless the full capacity is used. However, even over three years, the satellite system is expected to have a lower cost than the aircraft operations as well as similar to the cost of Iridium Pilot (as mentioned, only shown as a comparison, not as a realistic option). For data volumes over 700 GB per year, the satellite system represents comparable cost to the UAV, for a five and seven years lifetime. The airplane will always be more expensive, except for low data volumes and a short lifetime for the satellite system.

The numbers may have considerable uncertainties. However, even if the cost of the satellite system is doubled, a system with five or seven years lifetime may still be cheaper than Iridium Pilot and the airplane alternative. The UAV-option may become more favorable from a pure cost perspective.

In addition to only comparing the cost per GB, it is important to consider the difference in operations for the options. While satellites offer access to sensor data several times a day, the airplane and the UAV alternatives will have several weeks, or months, delays between each campaign. This must also be factored in, when deciding which main architecture to rely on.

Referring to the iterative methodology presented in Chapter 2, this cost analysis should be used as input for the next design iteration, leading to firmer requirements. A realistic design lifetime for the satellite system should be at least five years.
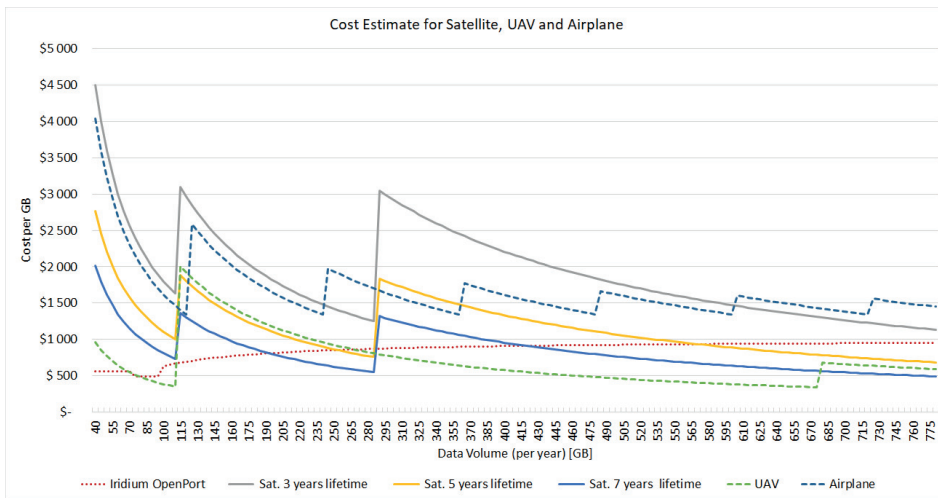
Figure 7.9: For the satellites, the jumps represent transitions from one to three to nine satellites, respectively. For the UAV, each segment represents one, six and twelve deployments over one year. For the airplane, segments correspond to 6, 12, 18, 24, 30, 36, 42 and 48 flights per year. The transition between one segment to the next is put when the yearly capacity is exceeded. The cost of the satellites is spread over a life time of three, five and seven years, respectively.

Even though supplementary uses for this satellite system are not discussed to a large extent (c.f. Section 2.2.6), the cost per Gigabyte may be up to halved if the satellite system can be put into use in other geographic areas, such as the Antarctica.

The cost and utility of other mission architectures based on future satellite systems (see Section 3.3) are not considered due to lack of available information.

7.5   Chapter Conclusions

This chapter joins together topics discussed in previous chapters into one space segment design proposal. First, a conceptual design of a CubeSat capable of supporting the mission is presented. Further, an overview design of a payload is presented, taking into account the requirements discussed in previous chapters. Implications and interactions between the payload and the satellite bus are discussed, such as power budget, pointing requirements and the need for a high-gain antenna.

Then, important figures of merit such as responsiveness and coverage from a swarm of small satellites are discussed. The presented design complies with the initial system requirements, however, the responsiveness requirement (*SR-006*)

was subject to further discussions (c.f Section 5.6). A system with satellites in only one plane fails to comply with this for some nodes. It is recommended to revise and relax this requirement, as keeping it will require expensive solutions.

The throughput and data volume of the various satellite swarms are discussed. A system of three satellites complies with the data volume required by S*R-005*.

Finally, a indicative cost analysis, where costs of using UAVs, satellites and air planes are compared. It is shown that for larger data volumes (implying several satellites with multiple channels) we can provide a system cost comparable with, or lower than the alternatives.

Chapter 8

Conclusions

Through this system engineering thesis, we have found that at the moment, none of the existing satellite communication systems, nor planned ones, seem adequate to meet the communication challenges in the Arctic. Especially not from the perspective of a sensor network requiring a larger data volume to be transported than a few bytes per day. The most likely candidate of the proposed systems is OneWeb. However, neither their technical details, nor financial status, are known. Therefore, we state that establishing a dedicated infrastructure tailored to user needs is the best option. This will be possible within a larger scientific infrastructure project. Such a system will enable daily contact with sensor nodes, and will reduce or eliminate the need for costly expeditions to retrieve sensor data. This will reduce risk both to personnel, and prevent loss of sensor data should a sensor node malfunction during the measurement campaign.

No description of a complete communication architecture, encompassing satellites and UVs, was found in literature. The combination of UVs and satellites for some special applications has been described by several (c.f. Chapter 2). A description of an integrated architecture, based upon standard and open protocols is however missing. Not all required components of such a network are available, so some development and adaptions, especially with respect to the link layer, is needed. Using standard protocols when possible will ease integration of unmanned vehicles into this architecture. The satellites and UVs can complement each other, and the combination is beneficial in many aspects, for example, as shown through the explanation of message passing in Section 5.5.6.

The use of common network protocols results in an overhead cost. By using lean protocols such as 6LoWPAN, this overhead can be reduced extensively compared to full IPv6, from 45.5% to 26.3%. This amount of overhead can be justified because of the benefit of intrinsic interoperability.

By using the new space philosophy and employing network nodes with pro-

cessing capability, both in satellites and in sensor nodes, new functionality such as the forward looking routing procedure, will be enabled. Network emulations shows that this reduces the average end-to-end delays with up to 71 minutes.

The use of uncontrolled satellites looks promising, compared to fixed constellations. According to emulation results, the network performance (for example, the responsiveness) is better for three satellites in a swarm compared to two in a constellation. Also, when comparing to three satellites in a fixed constellation, the performance is similar, and to a lower cost.

A simple cost analysis show that up to nine satellites can be deployed at a comparable cost of using only aircraft or Unmanned Aerial Vehicles (UAV)s to relay the required volume of data from the sensor network.

In conclusion, the proposed architecture and space segment are favorable over existing solutions. This chapter continues with a summary of the space mission architecture, a discussion on the relevance, and answers to each of the research questions. Finally, the thesis will be concluded by identifying the contributions and impact of this work.

8.1 Revised System Requirements and Proposed Space Mission Architecture

Table 8.1 shows the revised system requirements that were introduced and identified in Table 2.5 in Chapter 2. The updated parameters are identified by red text.

Table 8.1: Revised System requirements

ID	System requirement	Value	Explanation	Section
SR-006	Responsiveness for a sensor node	8 hours	Requires ground station at Svalbard	7.3.2
SR-008	The satellite antenna gain	10 dB	Required to close link budget	6.9
SR-009-1	The sensor node antenna gain (powerful node)	10 dB	Required to close link budget and reach required data rate	6.9
SR-009-2	The sensor node antenna gain (simpler node)	2 dB	For relaxed data rate	6.9
SR-010	The number of satellites required	$3-9$	Required to achieve yearly throughput	7.3.2
SR-011	Satellite orbital height	500 km	No change	4.1.5
SR-012	Frequency band	$400-438$ MHz	No change. Compliant with EESS	6.1
SR-013-1	Bit rate (powerful node)	100 kbps	High gain antenna required. C.f. SR-009	6.9
SR-013-2	Bit rate (simpler node)	19.2 kbps	Can use simpler antenna	7.3.2
SR-014	Multiple access scheme	TDMA	Should be dynamic allocations	5.3
SR-015	The network stack to support interoperability	IoT protocols	IoT-protocols can be used, link layer needs adaptions	5.3
SR-016	The BER should be less then	10^{-4}	Achievable, according to link budget	6.8
SR-017	The payload shall adapt to changing link conditions	ACM/VCM	Should be implemented, work remains	6.6
SR-018	Pointing requirement	$10°$	Achievable	7.1.3

The table shows that antenna gains are the parameters subject to the largest changes. The achievable data rate is split in two cases, one (100 kbps) for a larger node with high gain antenna (*SR-009-1*), suitable for the Arctic ABC use case (c.f Section 2.2.3). Smaller nodes with a simpler antenna installation, can benefit from 19.2 kbps data rate (*SR-009-2*). This also couples to the bit rate, which is split into *SR-013-1* for large nodes and *SR-013-2* for smaller nodes.

Further, the data volume can be supported by launching several satellites (c.f. Section 7.3.2). One more parameter must be changed, as the initial responsiveness requirement cannot be met for all nodes with only one orbital plane, c.f. Sections 5.6 and 7.3.2.

In Table 8.2, the mission elements from Section 2.1.2 are repeated, with the specific items of the mission proposal.

Table 8.2: List of space mission elements - Proposal

Element of Mission Architecture	Description	Defined in
Mission concept	Heterogeneous communication architecture	Chapter 3
Subject	Sensor nodes in the Arctic	Section 2.2.3 Section 7.2
Payload	Store-and-forward, network enabled SDR-based radiooperating in UHF.	Section 7.1.2
Spacecraft bus	COTS CubeSat-bus, 3U	Section 7.1.1
Launch system	Ride-share launch to LEO	Section 4.1.5
Orbit	500 km altitude, polar orbit. 1 orbital plane. 1 – 9 satellites per plane	Section 4.1.5
Ground system	Downlink aggregated data through S-band link to GW and distribution through Internet	Section 3.2
Mission operations	Autonomous data transfer operations	Section 3.2

8.2   Conclusions on Research Questions

The focus of the thesis is to show how a satellite communication payload for small satellites, or a swarm of those, can close a communication gap for scientific missions in the Arctic area.

The basis of these discussions is the definition of the mission, with its mission objectives given in Section 2.2.1 and recalled below in Table 8.3, together with the design parameters and constraints from Section 2.2.3.

The communication gap in the Arctic is identified, and none of the existing services nor the proposed services seem adequate to fill this gap. We therefore

Table 8.3: Mission Objectives

ID	Mission Objective	Derived
MO-001	Set up a communication infrastructure that enables interoperability between various types of networks and network nodes in remote areas, for example, the Arctic.	RQ1
MO-002	Reduce or eliminate the need of manned missions, by enabling access to data from sensors in remote locations	RQ1 RQ2
MO-003	Define a satellite payload which provides the required data throughput in order to fulfill scientific mission needs	RQ2 RQ3

conclude that development of a dedicated communication system should be considered.

In the following, a summary of the findings related to the research questions defined in Chapter 1.3.1 is given.

8.2.1 Research Question 1

How can satellite communication payloads and sensor nodes be integrated with other (moving) network nodes into a resilient heterogeneous communication network?

An overall network architecture is described in Section 3.1 and in paper [32]. To ensure interoperability, the use of standard network protocols on higher network layers; Layer 3 and up, should be considered [116, 117]. The gains with respect to reduced development time and the functionality the standard protocols give, speak to their advantage, even when taking into account the overhead. Standard protocols will also ease integration with other NWN, such as UVs. Suitable adaptions must be made to the physical layer and the link layer. The flexibility of the CubeSats allows this network stack to be implemented in the communication payload using COTS electronics and processors.

Due to power constraints, the satellite part of the network will be limited, and must be utilized in the best possible way. Therefore, the implementation of the network stack should also include custom functionality, for example, improvements such as the forward looking routing described in Section 5.1.6. Also, procedures and rules on how to share the load between satellite network nodes and UVs must be implemented (c.f. Section 5.5.6).

8.2.2 Research Question 2

With the emerging possibilities from new space systems and satellite platforms, how can a small satellite mission be designed and used to aid operation in the Arctic area, or in any other remote location?

The satellite part of the system architecture defined in Section 3.1 can be realized through small satellites such as CubeSats. The feasibility of the payload design is discussed in Section 7.1. The link budgets for the radio links enabling this communication are introduced and discussed in Section 6.8.

The link budget shows that a data rate of over 100 kbps can be achieved with adequate antenna design for both the satellites and the sensor nodes. The most important trade-offs are discussed in Section 6.9, where it is shown that up to 16 dB may be added to the link margin by analyzing various design choices.

Other applications can be supported by an integrated network architecture based on IoT technology, where the satellites operate together with other agents such as UVs. This includes missions that need to relay greater data volumes a few times a year.

Challenges do exist. Since both the sensor nodes and the satellite are small and energy limited devices and power for the communication link is a limited resource, this must be carefully considered in the design.

The available technology is maturing and quickly changing, and the time frame of a space project seems to become comparable with a scientific data collection project. From this we conclude that it is feasible to realize a dedicated communication system based on small satellites within the scope of an Arctic science mission.

8.2.3   Research Question 3

Given the flexibility and simplicity of small satellites, how can swarms of small satellites be utilized to make up for a lack of capacity compared to larger satellites?

In Chapter 4 it is shown that uncontrolled swarms are practical and that they yield good results compared to static constellations comprised of more expensive satellites with station keeping capabilities [114, 115, 116]. Deploying a swarm of satellites, where the number of satellites will scale both the throughput and the average delay, can be an attractive solution for realizing the space component of the proposed communication architecture. The gap between passes is directly linked to the number of satellites in a constellation or swarm; which is also a cost driver for the end product.

A main advantage of the small satellites is their high flexibility at a low cost. This enables architectures making use of several space crafts. Basing this architecture on a satellite swarm will reduce the complexity and cost of the system, compared to fixed constellations, since the swarm members do not need to be equipped with thrusters or devices for drag management. An important point is that we do not need a careful orbit estimation/determination with swarms. This

reduces complexity and cost related to operations. According to [65], orbit determination is important when performing station keeping operations with thrusters or drag management.

From the economical point of view, we can conclude that the communication network and the satellites should be designed with as high a data rate as possible, to drive the cost per GB down. This implies that such a satellite system can best fit a sensor network where the sensors can be supplied with large battery packs and some antenna gain. A system with a lower data rate may also be considered if the data is valuable and important, and the sensor nodes fall outside the scope of, for example, the proposed IoT constellations.

From this, we conclude that a dedicated communication system, based on small satellites, is a realistic and attractive alternative within the scope of an Arctic scientific mission.

Challenges   There are issues that must be handled, and assumptions that must be verified, for each specific use case. The main challenges are listed:

- The need for deciding and developing a suitable link layer for the satellite communication, that can be combined with 6LoWPAN. A basic implementation of a stack consisting of the IEEE 802.15.4 link layer, 6LoWPAN and CoAP was, as mentioned, performed by D. Palma [92], and can be a low-effort solution to investigate further.
- Deployment strategies for the satellite swarm must be discussed with a launch provider in order to confirm the viability.
- End users (research organizations, for example), must be made aware of the this opportunity, and deeper cost-benefit analysis for each user case must be carried out by the stakeholders. Specific mission design must be performed.

8.3   Contributions and Impact

The work performed through this thesis consists of the contributions listed in Table 8.4. Relevant links to papers and chapters are included.

We have found that deploying a dedicated satellite system seems promising, both from a technical point of view, and from an economical point of view (c.f Section 7.4). From this perspective, the system can be designed for only one, or a few users. In addition to defining an integrated communications architecture for the Arctic [32], the main part of this study has been on providing coverage using swarms of small satellites [114, 115]. In addition, we have shown how different communication systems can be integrated by basing them on IoT-protocols [116, 117]. The link budget developed in this thesis, shows the viability

Table 8.4: Contributions

Contribution	Papers	Chapters
Identify Arctic communication challenges, the lack of existing systems and definition of a satellite mission for Arctic communication.	A.1, A.2	1, 2
Presenting a system engineering feasibility study on the satellite bus, payload overview and radio link design needed to realize said mission (answers *RQ1 – RQ3*).		3, 4, 5, 6, 7
Presenting a novel architecture comprising small satellites and UVs for enabling a communication system for the Arctic (answers *RQ1*).	A.5	3
Performing a study of un-controlled swarms, showing that the network capacity penalty is not severe, compared to the added redundancy and reduction of both investment and operational costs compared to that of static constellations (answers *RQ2* and *RQ3*).	A.3, A.4	4, 5
Creation of a test-bed with simulators, emulator and hardware for network evaluation and tests.	A.3, A.4, A.5	7, 4, 5
Performing a study of network performance (overhead, re-transmissions and end-to-end delay) in a realistic environment, employing a IoT stack. A novel evaluation of 6LoWPAN and CoAP in this context (answers *RQ1 – RQ3*).	A.6, A.7	5
Presenting methods for enhancing network performance, such as collaborative message passing encompassing satellites and UVs, and a method of smart routing for selecting the best satellite (answers *RQ1 – RQ3*).	A.7	5

of a radio link meeting the requirements from the assumed use case. The space segment can be realized by relying on a standard CubeSat-bus, capable of supporting the communications payload. A definition of the payload is given in Section 7.1.2. This payload can be implemented as an integration of COTS products, for example, implemented as an SDR.

8.3.1 Impact

The research performed through this thesis has a considerable impact on other research activities at NTNU. The focus on *new space* and small satellites has opened up for larger research projects, such as the MASSIVE project, funded by the Norwegian Research Council and AMOS. In addition, the research has been extended through projects funded by the Norwegian Space Centre. This includes feasibility study for an SDR mission, and definition of two new PhD projects, in addition to presenting fundamental requirements and ideas for new research projects, with a focus on maritime, oceanographic and Arctic applications.

The technical discussions and findings in this thesis are applicable for more general applications than just Arctic sensor networks. Cheap CubeSats, and distributed swarms of these, can be used for EO in addition to communication ap-

plications. The use of IoT protocols for ensuring both interoperability between network nodes in a multi-agent system as well as how these protocols ease communication between sensors and satellites, are general topics. The cooperation between UVs and satellites is also of general interest for many applications, such as regular coverage of remote areas and ad-hoc networks for disaster management.

In conclusion, this thesis covers several system engineering problems related to design of both a communication architecture suitable for Arctic applications, as well as the realization of the satellite component of this architecture. Calculations, simulations and emulations show that when taking the limitations (power, coverage, antenna gains) of small satellites in LEO orbit into careful consideration, deploying a service based on CubeSats is feasible and favorable compared to existing and planned commercial satellite systems.

8.3.2   Current and Future Work

Current and future work, based on contributions from this thesis, are:

- Specifications and requirements for a payload radio that can enable the link between sensor nodes and UVs must be defined. This continues as a new PhD-project, with focus on SDR technology.
- Better estimation of a UHF channel model, and practical implementation of ACM and VCM in an SDR is part of a new PhD-project.
- The study of communication systems and architectures for the Arctic continues through the NRC-funded MASSIVE project and as a separate project proposal for an Arctic communication infrastructure, focusing on Arctic IoT.
- Further simulation and emulation of this architecture should be explored, focusing on how to best make use of the various data links available. How can UVs and the satellites best operate together? (c.f. Section 5.5.6).
- Add layer 2 MAC-functionality to the emulator to evaluate different schemes
- Use of multiple satellites in swarms in above-mentioned projects will be continued.
- The design of ground terminals, and especially the sensor node antennas must be carried out, for example, through a set of master theses. One is already initiated and the work is well advanced [185].

Space technology and the new space philosophy are key focus areas for NTNU and other research and industry organizations. The work presented in this thesis serves as a foundation for the continuation and increase in activities at NTNU.

References

[1] Norwegian University of Science and Technology, "Camos webpage," 2014, accessed November 2015. [Online]. Available: http://www.ntnu.edu/ime/camos/

[2] A. Stępień and T. Koivurova, "Arctic Europe: Bringing together the EU Arctic Policy and Nordic cooperation," 2017, Finish Prime Minister´s Office. [Online]. Available: https://tietokayttoon.fi/julkaisu?pubid=17303

[3] A. Raspotnik and A. Stępień, "Analysis: The European Parliament heading towards icy Arctic waters – again," High North News, 2017. [Online]. Available: http://www.highnorthnews. com/analysis-the-european-parliament-heading-towards-icy-arctic-waters-again/

[4] O. R. Young, "The arctic in play: Governance in a time of rapid change," *The International Journal of Marine and Coastal Law*, vol. 24, p. 423–442, 2009.

[5] European Parliament, "Arctic: Meps debate strategy to prevent conflicts over polar region heating up," 2017. [Online]. Available: http://www.europarl.europa.eu/news/en/headlines/world/20170310STO66174/ arctic-meps-debate-strategy-to-prevent-conflicts-over-polar-region-heating-up

[6] European Commission, HIGH REPRESENTATIVE OF THE EUROPEAN UNION FOR FOREIGN AFFAIRS AND SECURITY POLICY, "Developing a european union policy towards the arctic region: progress since 2008 and next steps," June 2013. [Online]. Available: http://eeas.europa.eu/arctic_region/docs/swd_2012_183.pdf

[7] Joseph C. Casas, "Arctic region communications small satellites (arc-sat)," Sep 2012, accessed November 2013. [Online]. Available: http://nix.nasa.gov/search.jsp?R= 20120016896&qs=N%3D4294163423%2B4294957324%2B4294587540

[8] Arctic Council, "TELECOMMUNICATIONS INFRASTRUCTURE IN THE ARCTIC," 2017. [Online]. Available: https://oaarchive.arctic-council.org/bitstream/handle/11374/1924/ 2017-04-28-ACS_Telecoms_REPORT_WEB-2.pdf?sequence=1

[9] G. E. Shephard, K. Dalen, R. Peldszus, S. Aparicio, L. Beumer, R. Birkeland, N. Gkikas, M. Kourantidou, P. Ktenas, P. W. Linde, F. Marazzi, R. B. M. Pincinato, J. Radianti, B. Schartmuller, E. I. Stubner, A. Varnajot, M. Vullierme, and I. Zhilina, "Assessing the added value of the recent declaration on unregulated fishing for sustainable governance of the central arctic ocean," *Marine Policy*, vol. 66, pp. 50 – 57, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0308597X1600018X

[10] Ministry of Foreign Affairs of Denmark, "Historical agreement on fisheries in the arctic to be signed in greenland," 2018. [Online]. Available: http://um.dk/en/news/newsdisplaypage/?newsid=10fd29d5-1968-428f-8963-aeaf9c22b072

[11] R. Birkeland, "Proposal for a satellite communication payload for sensor networks in the arctic area," in *Proceedings of the 65th International Astronautical Congress*, 2014.

[12] ESA, "ESA Artes ARTICOM," 2011, accessed April 2018. [Online]. Available: https://artes.esa.int/projects/arcticom

[13] "Agreement on cooperation on aeronautical and maritime search and rescue in the Arctic," 2011. [Online]. Available: https://oaarchive.arctic-council.org/handle/11374/531

[14] H. Karahalios, "The severity of shipboard communication failures in maritime emergencies: A risk management approach," *International Journal of Disaster Risk Reduction*, vol. 28, pp. 1 – 9, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2212420918301833

[15] A. C. Clarke, "EXTRA-TERRESTRIAL RELAYS - Can Rocket Stations Give World-wide Radio Coverage? ," *Wireless World*, pp. 305–308, 10 1945.

[16] Inmarsat, "Inmarsat webpage," 2013, accessed november 2013. [Online]. Available: http://inmarsat.com

[17] S. Plass, F. Clazzer, and F. Bekkadal, "Current situation and future innovations in arctic communications," in *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, Sept 2015, pp. 1–7.

[18] Orbcomm, "Orbcomm webpage," 2018, accessed August 2018. [Online]. Available: https://www.orbcomm.com/en/networks/satellite

[19] Globalstar, "Globalstar webpage," 2103, accessed nov. 2013. [Online]. Available: https://www.globalstar.com/products

[20] CLS Group, "Argos (webpage)," 2014, accessed March 2014. [Online]. Available: http://www.argos-system.org

[21] Iridium Communications Inc, "Iridium communications," 2014, accessed 15.12.2014. [Online]. Available: https://iridium.com

[22] M. Swartwout, "CubeSat Database," 2017, accessed 08.04.2017. [Online]. Available: https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

[23] M. N. Sweeting, "Modern small satellites-changing the economics of space," *Proceedings of the IEEE*, vol. 106, no. 3, pp. 343–361, March 2018.

[24] H. Helvajian and S. W. Janson, Eds., *Small Satellites: Past, Present, and Future*. The Aerospace Press, 2008.

[25] United Nations, "Sustainable development goals," accessed 08.05.2017. [Online]. Available: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[26] European Commission, "Commission launches new space strategy," pub-lished 25.10.2016. [Online]. Available: https://ec.europa.eu/growth/content/commission-launches-new-space-strategy-1_en

[27] J. Berge, M. Geoffroy, G. Johnsen, F. Cottier, B. Bluhm, and D. Vogedes, "Ice-tethered observational platforms in the arctic ocean pack ice," *IFAC-PapersOnLine*, vol. 49, no. 23, pp. 494 – 499, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2405896316320742

[28] J. Berge, "Mare Incognitum - Arctic ABC project summary," 2017, NFR projects 244319 and 245923. [Online]. Available: http://www.mare-incognitum.no/index.php/arcticabc

[29] James R. Wertz and Wiley J. Larson, Ed., *Space Mission Analysis and Design*, 3rd ed. Microcosm Press and Springer, 1999.

[30] S. A. ASUNDI, "Cubesat system design based on methodologies adopted for developing wireless robotic platform," phdthesis, THE UNIVERSITY OF FLORIDA, 2011.

[31] *ECSS-M-ST-10C Rev.1 - Space project management - Project planning and implementation* , ECSS, 7 2008. [Online]. Available: http://ecss.nl/standard/ecss-m-st-10c-rev-1-project-planning-and-implementation/

[32] R. Birkeland, D. Palma, and A. Zolich, "Integrated smallsats and unmanned vehicles for networking in remote locations," in *Proceedings of The 68th International Astronautical Congress*, 2017.

[33] A. Zolich, D. Palma, R. Birkeland, and Y. Jiang, "A multi-hop intermittent wireless sensor network with unmanned aerial vehicles and satellite links for the arctic," Presentation at Re-CAMP Flagship Workshop, 5 - 6 April 2016, Tromsø, Norway, 2016, abstract available at: http://www.asuf.no/wp-content/uploads/2016/03/ReCAMP2016_AbstractsBook.pdf.

[34] D. Palma, A. Zolich, and R. Birkeland, "Software-defined Intermittent Networking - Reference Scenario and Requirements Definition," October 2016, h2020 grant number 699924. [Online]. Available: https://sinet.item.ntnu.no/wp-content/uploads/2016/10/\D11_Scenario_SINet.pdf

[35] ——, " Software-defined Intermittent Networking - Architecture Specification," October 2016, h2020 grant number 699924. [Online]. Available: https://sinet.item.ntnu.no/wp-content/uploads/2016/10/\D12_Architecture_SINet.pdf

[36] A. Zolich *et al.*, "An ice-tethered buoy for fish and plankton research," in *Proceedings of Oceans 2018*, 2018.

[37] R. Birkeland, "An overview of existing and future satellite systems for arctic communication," in *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[38] Norwegian Space Centre, "Norske satellitter," 2013, accessed Jan 2014. [Online]. Available: http://www.romsenter.no/Bruk-av-rommet/Norske-satellitter

[39] exactAIS, "Vessel monitoring," 2014, accessed April 2014. [Online]. Available: http://www.exactearth.com/applications/vessel-monitoring

[40] Alminde et.al, "Gomx-1 flight experience and air traffic monitoring results," in *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[41] D. L. Porter and K. H. Keller, "Ibuoy: Expendable short time duration wave buoy with satellite data telemetry," in *2012 Oceans*, Oct 2012, pp. 1–4.

[42] . J. Rødseth, B. Kvamstad-Lervold, and T. D. Ho, "In-situ performance analysis of satellite communication in the high north," in *OCEANS 2015 - Genova*, May 2015, pp. 1–6.

[43] ESA Education, "Background on humsat," accessed September 2017. [Online]. Available: http://www.esa.int/Education/Background_on_HumSAT

[44] A. G. C. Guerra *et al.*, "Integrating small satellite communication in an autonomous vehicle network: A case on oceanography," *Aerospace Science and Technology*, 2017.

[45] D. Weeks, A. B. Marley, and J. L. III, "SMDC-ONE: An Army Nanosatellite Technology Demonstration," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC09-X-3*, 2009. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2009/all2009/62/

[46] J. London, M. Ray, D. Weeks, and B. Marley, "The First US Army Satellite in Fifty Years: SMDC-ONE First Flight Results," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC11-III-5*, 2011. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2011/all2011/25/

[47] T. Graff *et al.*, "Ocean systems test and evaluation program - data communications plan," National Oceanic and Atmospheric Administration, Tech. Rep., 2006. [Online]. Available: https://tidesandcurrents.noaa.gov/publications/Data_Communications_Plan_52506.pdf

[48] E. Kulu, "Nanosatellite database by erik," 2018, accessed May 2018. [Online]. Available: http://www.nanosats.eu/index.html#database

[49] D. Mohney, "The 2018 summer of satellite iot – 18 startups, over 1,600 satellites." [Online]. Available: https://www.spaceitbridge.com/the-2018-summer-of-satellite-iot-18-startups-over-1600-satellites.htm

[50] United States Antartic Program, "South pole satellite communications and pass schedules." [Online]. Available: https://www.usap.gov/technology/contentHandler.cfm?id=1935

[51] ——, "Systems architecture description," 2018. [Online]. Available: https://www.usap.gov/technology/documents/Systems_Architecture_Description.pdf

[52] SINTEF, "Getting broadband in the arctic," June 2013. [Online]. Available: http://www.sintef.no/home/Press-Room/Research-News/\Getting-broadband-in-the-Arctic/

[53] OneWeb, "Oneweb homepage," 2015, accessed October 2015. [Online]. Available: http://oneweb.world/

[54] Kepler, "Kepler's first ku-band satellite is in orbit," accessed February 2018. [Online]. Available: http://www.keplercommunications.com/blog/item/first-launch

[55] L. E. Bråten, A. N. Skauen, and A. Yusuf, "Nanosatellites in low earth orbits for satellite communications," Norwegian Defence Research Establishment (FFI), Tech. Rep. FFI -RAPPORT 17/16210, 2018. [Online]. Available: https://www.ffi.no/no/Rapporter/17-16210.pdf

[56] N. A. Dallmann *et al.*, "An Agile Space Paradigm and the Prometheus CubeSat System," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC15-V-4*, 2015. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2015/all2015/33/

[57] G. Liu and S. Zhang, "A survey on formation control of small satellites," *Proceedings of the IEEE*, vol. 106, no. 3, pp. 440–457, March 2018.

[58] N. Crisp, K. Smith, and P. Hollingsworth, "Launch and deployment of distributed small satellite systems," *Acta Astronautica*, vol. 114, pp. 65 – 78, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S009457651500171X

[59] A. W. Koenig and S. D'Amico, "Safe spacecraft swarm deployment and acquisition in perturbed near-circular orbits subject to operational constraints," *Acta Astronautica*, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0094576517311062

[60] A. E. Turner, "Constellation design considerations for smallsats," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC16-P4-18*, 2018. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2016/Poster4/8/

[61] H. Sanchez *et al.*, "Starling1: Swarm Technology Demonstration," *Proceedings of the AIAA/USU Conference on Small Satellites, SSC18-VII-08*, 2018. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2018/all2018/299/

[62] A. da Silva Curiel, M. Meerman, D. Liddle, S. Schwartz, and M. Sweeting, "Frisbee – a platform for a small satellite science swarms," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC03-IX-6*, 2003. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2003/All2003/66/

[63] A. Dono, L. Plice, J. Mueting, T. Conn, and M. Ho, "Propulsion trade studies for spacecraft swarm mission design," NASA, Tech. Rep., 2018. [Online]. Available: https://ntrs.nasa.gov/search.jsp?R=20180001729

[64] C. Jiang, Z. Wang, and Y. Zhang, "Development of the new approach of formation initialization using spring separation mechanism considering j2 perturbation," *Advances in Space Research*, vol. 55, no. 11, pp. 2616 – 2627, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0273117715001301

[65] R. Zimmerman, D. Doan, L. Leung, J. Mason, N. Parsons, and K. Shahid, "Commissioning the World's Largest Satellite Constellation," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC17-X-03*, 2017. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2017/all2017/138/

[66] T. Conn, L. Plice, A. D. Perez, and M. Ho, "Operating Small Sat Swarms as a Single Entity: Introducing SODA," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC17-V-06*, 2006. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2017/all2017/100/

[67] C. Foster, H. Hallam, and J. Mason, "Orbit Determination and Differential-drag Control of Planet Labs Cubesat Constellations," in *Presented at AIAA Astrodynamics Specialist Conference, Vale, CO, August 2015*, 2015. [Online]. Available: https://arxiv.org/abs/1509.03270v1

[68] S. Omar, D. Guglielmo, G. DiMauro, T. Martin, and R. Bevilcqua, "CubeSat Mission to Demonstrate Aerodynamically Controlled Re-Entry using the Drag De-Orbit Device (D3)," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC18-PI-05*, 2018. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2018/all2018/335/

[69] A. Ismail, B. A. Bagula, and E. Tuyishimire, "Internet-of-things in motion: A uav coalition model for remote sensing in smart cities," in *Sensors (Basel, Switzerland)*, 2018. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6068529/

[70] C. Joo and J. Choi, "Low-delay broadband satellite communications with high-altitude unmanned aerial vehicles," *Journal of Communications and Networks*, vol. 20, no. 1, pp. 102–108, Feb 2018.

[71] I. Bekmezci, I. Sen, and E. Erkalkan, "Flying ad hoc networks (fanet) test bed implementation," in *2015 7th International Conference on Recent Advances in Space Technologies (RAST)*, June 2015, pp. 665–668.

[72] I. Dalmasso, I. Galletti, R. Giuliano, and F. Mazzenga, "Wimax networks for emergency management based on uavs," in *2012 IEEE First AESS European Conference on Satellite Telecommunications (ESTEL)*, Oct 2012, pp. 1–6.

[73] H. Skinnemoen, "Uav amp; satellite communications live mission-critical visual data," in *2014 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology*, Nov 2014, pp. 12–19.

[74] M. Bacco, M. Colucci, A. Gotta, C. Kourogiorgas, and A. D. Panagopoulos, "Reliable m2m/iot data delivery from fanets via satellite," *International Journal of Satellite Communications and Networking*, vol. 0, no. 0, 2018. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/sat.1274

[75] M. Bacco, P. Cassarà, M. Colucci, and A. Gotta, "Modeling reliable m2m/iot traffic over random access satellite links in non-saturated conditions," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 5, pp. 1042–1051, May 2018.

[76] E. Tuyishimire, A. Bagula, S. Rekhis, and N. Boudriga, "Cooperative data muling from ground sensors to base stations using uavs," in *2017 IEEE Symposium on Computers and Communications (ISCC)*, July 2017, pp. 35–41.

[77] D. Palma, A. Zolich, Y. Jiang, and T. A. Johansen, "Unmanned aerial vehicles as data mules: An experimental assessment," *IEEE Access*, vol. 5, pp. 24 716–24 726, 2017.

[78] Airbus, "Zephyr - pioneering the stratosphere," 2018. [Online]. Available: https://www.airbus.com/defence/uav/zephyr.html

[79] Thales Group, "Stratobus: Why this stratospheric airship is already being called a "Swiss knife" in the sky," 2018. [Online]. Available: https://www.thalesgroup.com/en/worldwide/space/magazine/stratobus-why-stratospheric-airship-already-being-called-swiss-knife-sky

[80] Loon, "Connect people everywhere," 2018. [Online]. Available: https://loon.co/

[81] O. Kara, R. Birkeland, L. L. Zhang, and U. Kaytaz, "Future cubesat swarms pose signifcant communications challenges," *ROOM - The Space Journal*, pp. 18–24, 2018.

[82] L. Bacsardi, R. Birkeland, A. Hornig, M. Shar, B. Morrison, and Y. Tsodikovich, "Present and the future of space internet: The space generation perspective," *New Space*, vol. 5, no. 4, pp. 257–267, 2017.

[83] M. D. Sanctis, E. Cianca, G. Araniti, I. Bisio, and R. Prasad, "Satellite communications supporting internet of remote things," *IEEE Internet of Things Journal*, vol. 3, no. 1, pp. 113–123, Feb 2016.

[84] N. Celandroni, E. Ferro, A. Gotta, G. Oligeri, C. Roseti, M. Luglio, I. Bisio, M. Cello, F. Davoli, A. D. Panagopoulos, M. Poulakis, S. Vassaki, T. De Cola, M. A. Marchitti, Y. F. Hu, P. Pillai, S. Verma, K. Xu, and G. Acar, "A survey of architectures and scenarios in satellite-based wireless sensor networks: system design aspects," *International Journal of Satellite Communications and Networking*, vol. 31, no. 1, pp. 1–38, 2013. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/sat.1019

[85] K. Schilling, "Networked distributed pico-satellite systems for earth observation and telecommunication applications," in *Plenary Paper in Proceedings of IFAC Workshop Aerospace Guidance,Navigation and Flight Control, Samara, Russia, IFAC*, 2009.

[86] P. Yoo, D. Obukhov, and A. Mrocze, "Integrated Communication Extension Capability (ICE-Cap)," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC15-III-7*, 2015. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2015/all2015/19/

[87] Y. F. Wong, O. Kegege, S. H. Schaire, G. Bussey, and S. Atlunc, "An Optimum Space-to-Ground Communication Concept for CubeSat Platform Utilizing NASA Space Network and Near Earth Network," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC16-IX-04*, 2016. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2016/TS9GroundSystems/4/

[88] S. Houlihan, "The Internet of Satellites: a C&DH Software Framework for Small Satellites Built on Open Internet Standards and Software," in *Proceedings of the AIAA/USU Conference on Small Satellites*, 2016. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2015/all2015/19/

[89] J. Wilmot, "Using CCSDS Standards to Reduce Mission Costs," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC-XII-02*, 2017. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2017/all2017/119/

[90] B. Chandler, "A Novel IP-Centric Approach to LEO Communications," in *Proceedings of the AIAA/USU Conference on Small Satellites, SSC18-X-09*, 2018. [Online]. Available: https://digitalcommons.usu.edu/smallsat/2018/all2018/318/

[91] S. Nazir, G. Fairhurst, F. Verdicchio, R. Van Der Wal, and S. Newey, "Resource monitoring with wireless sensor networks and satellite," in *Fourth Annual Digital Economy All Hands Meeting-DE2013*, 11 2013.

[92] D. Palma, "Enabling the maritime internet of things: Coap and 6lowpan performance over vhf links," *IEEE Internet of Things Journal*, pp. 1–1, 2018.

[93] J. Hui, D. Culler, and S. Chakrabarti, "6lowpan: Incorporating ieee 802.15.4 into the ip architecture," Internet Protocol for Smart Objects (IPSO) Alliance, Tech. Rep., 2009.

[94] D. Giotti, L. Lamorte, R. Soua, M. R. Palattella, and T. Engel, "Performance analysis of coap under satellite link disruption," in *2018 25th International Conference on Telecommunications (ICT)*, June 2018, pp. 623–628.

[95] GobySoft, "Quality software for autonomous marine systems," accessed November 2017. [Online]. Available: http://gobysoft.org/

[96] Massachusetts Institute of Technology, "MOOS-IvP home page," 2017, (Accessed April 2017). [Online]. Available: http://oceanai.mit.edu/moos-ivp

[97] ØMQ, "ØMQ - Distributed Messaging," accessed November 2017. [Online]. Available: http://zeromq.org/

[98] Google Developers, "Protocol buffers," accessed November 2017. [Online]. Available: https://developers.google.com/protocol-buffers/

[99] A. S. Huang, E. Olson, and D. C. Moore, "Lcm: Lightweight communications and marshalling," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct 2010, pp. 4057–4062.

[100] COSMOS Project, "Comprehensive open-architecture solution for mission operations systems," accessed November 2017. [Online]. Available: http://cosmos-project.org/

[101] J. P. Macker, C. Bormann, M. J. Handley, and B. Adamson, "NACK-Oriented Reliable Multicast (NORM) Transport Protocol," RFC 5740, Nov. 2009. [Online]. Available: https://rfc-editor.org/rfc/rfc5740.txt

[102] J. Pinto, P. S. Dias, R. Martins, J. Fortuna, E. Marques, and J. Sousa, "The LSTS toolchain for networked vehicle systems," in *OCEANS - Bergen, 2013 MTS/IEEE*, June 2013, pp. 1–9.

[103] W3C, "Efficient xml interchange (exi) format 1.0 (second edition)," accessed November 2017. [Online]. Available: https://www.w3.org/TR/exi/

[104] Z. Shelby, "Constrained RESTful Environments (CoRE) Link Format," RFC 6690, Aug. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6690.txt

[105] A. P. Castellani, S. Loreto, A. Rahman, T. Fossati, and E. Dijk, "Guidelines for Mapping Implementations: HTTP to the Constrained Application Protocol (CoAP)," RFC 8075, Feb. 2017. [Online]. Available: https://rfc-editor.org/rfc/rfc8075.txt

[106] A. Rahman and E. Dijk, "Group Communication for the Constrained Application Protocol (CoAP)," RFC 7390, Oct. 2014. [Online]. Available: https://rfc-editor.org/rfc/rfc7390.txt

[107] IETF, "Ipv6 over networks of resource-constrained nodes (6lo)," accessed November 2017. [Online]. Available: https://datatracker.ietf.org/wg/6lo/

[108] D. T. Narten, T. Jinmei, and D. S. Thomson, "IPv6 Stateless Address Autoconfiguration," RFC 4862, Oct. 2015. [Online]. Available: https://rfc-editor.org/rfc/rfc4862.txt

[109] Analytical Graphics, "STK," 2016, accessed April 2016. [Online]. Available: http://www.agi.com/products/stk/

[110] B. Rhodes, "Pyephem home page," 2015, accessed October 2015. [Online]. Available: http://rhodesmill.org/pyephem/

[111] J. D. Hunter, "Matplotlib: A 2d graphics environment," *Computing In Science & Engineering*, vol. 9, no. 3, pp. 90–95, 2007.

[112] A. Zolich, T. A. Johansen, K. Cisek, and K. Klausen, "Unmanned aerial system architecture for maritime missions. design hardware description," in *2015 Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS)*, Nov 2015, pp. 342–350.

[113] M. Ludvigsen, P. S. Dias, S. Ferreira, T. O. Fossum, V. Hovstein, T. A. Johansen, T. R. Krogstad, Ø. Midtgaard, J. S. P. Norgren, Ø. Sture, E. Vågsholm, and A. Zolich, "Autonomous network of heterogeneous vehicles for marine research and management," in *IEEE Oceans 2016 – Monterey, CA*, September 2016.

[114] R. Birkeland and A. Hornig, "On how a cubesat swarm can improve the coverage for an arctic ground based sensor network," in *Proceedings of ESA Small Satellites Systems and Services 2016*, 2016.

[115] R. Birkeland, "Freely drifting cubesat constellations for improving coverage for arctic sensor networks," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/7997293

[116] R. Birkeland and D. Palma, "Freely drifting small-satellite swarms for sensor networks in the arctic," in *Third International Congress on Information and Communication Technology*, X.-S. Yang, S. Sherratt, N. Dey, and A. Joshi, Eds. Singapore: Springer Singapore, 2019, pp. 175–190. [Online]. Available: https://link.springer.com/chapter/10.1007/978-981-13-1165-9_16

[117] D. Palma and R. Birkeland, "Enabling the internet of arctic things with freely-drifting small-satellite swarms," *IEEE Access*, vol. 6, pp. 71 435–71 443, 2018.

[118] N. Beauchamp, "Return of the intrepid wave glider," 2014, [Accessed 13-July-2016]. [Online]. Available: http://oceantrackingnetwork.org/return-of-the-intrepid-wave-glider/

[119] A. Zolich, J. A. Alfredsen, T. A. Johansen, and K. R. Skøien, "A communication bridge between underwater sensors and unmanned vehicles using a surface wireless sensor network - design and validation," in *OCEANS 2016 – Shanghai*, April 2016, pp. 1–9.

[120] I. Vasilescu, K. Kotay, D. Rus, M. Dunbabin, and P. Corke, "Data collection, storage, and retrieval with an underwater sensor network," in *In Proceedings of the International Conference on Embedded Networked Sensor Systems (ACM SenSys 2005*, 2005.

[121] T. A. Johansen, A. Zolich, T. Hansen, and A. J. Sørensen, "Unmanned aerial vehicle as communication relay for autonomous underwater vehicle - field tests," in *IEEE Globecom Workshop - Wireless Networking and Control for Unmanned Autonomous Vehicles, Austin, TX*, 2014.

[122] *Recommendation ITU-R M.2092-0 - Technical characteristics for a VHF data exchange system in the VHF maritime mobile band*, ITU, 2015. [Online]. Available: https://www.itu.int/rec/R-REC-M.2092

[123] H. D. Curtis, *Orbital Mechanics for Engineering Students*. Elsevier, 2005.

[124] Wikipedia, 2007, visited June 2016. [Online]. Available: https://en.wikipedia.org/wiki/Kepler_orbit#/media/File:Orbit1.svg

[125] D. T. Kelso, "Frequently asked questions: Two-line element set format," 1998, available at https://celestrak.com/columns/v04n03/.

[126] G. Maral and M. Bousquet, *Satellite Communication Systems*, 5th ed. Wiley, 2009.

[127] Lars Løge, "Arctic communications system utilizing satellites in highly elliptical orbits," Ph.D. dissertation, Norwegian University of Science and Technology, 2013.

[128] Analytical Graphics, "STK programming help - Two-Body, J2 Perturbation & J4 Perturbation Propagators," accessed February 2018. [Online]. Available: http://help.agi.com/stk/index.htm#stk/vehSat_orbitProp_2bodyJ2J4.htm

[129] D. A. Vallado, P. Crawford, and T. S. Kelso, "Revisiting spacetrack report #3: Rev 2," 2006. [Online]. Available: http://celestrak.com/publications/AIAA/2006-6753/AIAA-2006-6753-Rev2.pdf

[130] International Organization for Standardization, "ISO 19683: Space systems - Design qualification and acceptance tests of small spacecraft and units," 07 2017.

[131] O. Kara, B. Yaglioglu, M. Brunner, D. Schor, R. Birkeland, T. Smith, and A. Hornig, "Communication Architecture and International Policy Recommentations Enabling the Development of Global CubeSat Space Networks," in *Proceedings of the 66th International Astronautical Congress*, International Astronautical Federation. IAF, 2015.

[132] G. G. Zohar, "Ad-hoc regional coverage constellations of cubesats using secondary launches," Master's thesis, Faculty of California Polytechnic State University, San Luis Obispo, 2013.

[133] C. F. et.al, "Small spacecraft technology state of the art," Mission Design Division - NASA Ames Research Center , Tech. Rep., 2015.

[134] D. Krejci and P. Lozano, "Space propulsion technology for small spacecraft," *Proceedings of the IEEE*, vol. 106, no. 3, pp. 362–378, March 2018.

[135] P. E. Skanke and R. Birkeland, "Cubesat propulsion – expanding the possibilities of the affordable space platform," in *Proceedings of ESA Small Satellites Systems and Services*, 2018.

[136] J. Puig-Suari, G. Zohar, and K. Leveque, "Deployment of CubeSat Constellations Utilizing Current Launch Oppertunities," in *27th Annual AIAA/USU Conference on Small Satellites*, 2013.

[137] A. Hornig *et al.*, "From ground to space: prototype development and evaluation of the tracking system for small satellites with the Distributed Ground Station Network," in *Proceedings of the 65th International Astronautical Congress*, ser. Proceedings of the 65th International Astronautical Congress, International Astronautical Federation. IAF, 2014.

[138] A. Hornig and D. Fritsch, "New space operations in the internet of things era - anywhere, anytime, anything!" in *Proceedings of the 66 th International Astronautical Congress*, 2016.

[139] M. Enoch *et al.*, "Optical Tracking Telemetry and Commanding (TT&C) For Small Satellites," in *Proceedings of the 13th AIAA/USU Conference on Small Satellites*, 1999. [Online]. Available: https://www.researchgate.net/publication/228690027_Optical_Tracking_Telemetry_and_Commanding_TTC_For_Small_Satellites

[140] G. Maral, J.-J. de Ridder, B. G. Evans, and M. Richharia, "Low earth orbit satellite systems for communications," *International Journal of Satellite Communications*, vol. 9, no. 4, pp. 209–225, 1991. [Online]. Available: http://dx.doi.org/10.1002/sat.4600090403

[141] G. Giambene and S. Kota, "Cross-layer protocol optimization for satellite communications networks: a survey," *International Journal of Satellite Communications and Networking*, vol. 24, no. 5, pp. 323–341, 2006. [Online]. Available: http://dx.doi.org/10.1002/sat.853

[142] P. Barsocchi *et al.*, "Radio resource management across multiple protocol layers in satellite networks: a tutorial overview," *International Journal of Satellite Communications and Networking*, vol. 23, no. 5, pp. 265–305, 2005. [Online]. Available: http://dx.doi.org/10.1002/sat.820

[143] R. De Gaudenzi, O. Del Rio Herrero, G. Gallinaro, S. Cioni, and P.-D. Arapoglou, "Random access schemes for satellite networks, from vsat to m2m: a survey," *International Journal of Satellite Communications and Networking*, pp. n/a–n/a, 2016, sat.1204. [Online]. Available: http://dx.doi.org/10.1002/sat.1204

[144] M. Allman, D. Glover, and L. Sanchez, "RFC 2488 - Enhancing TCP Over Satellite Channels using Standard Mechanisms," January 1999. [Online]. Available: https://tools.ietf.org/html/rfc2488

[145] N. Kuhn, E. Lochin, J. Lacan, R. Boreli, and L. Clarac, "On the impact of link layer retransmission schemes on tcp over 4g satellite links," *International Journal of Satellite Communications and Networking*, vol. 33, no. 1, pp. 19–42, 2015. [Online]. Available: http://dx.doi.org/10.1002/sat.1064

[146] International Organization for Standardization, "ISO/IEC 7498-1:1994 Information technology - Open Systems Interconnection – Basic Reference Model: The Basic Model," November 1994. [Online]. Available: https://www.ecma-international.org/activities/Communications/TG11/s020269e.pdf

[147] A. Meloni and M. Murroni, "Random access in dvb-rcs2: Design and dynamic control for congestion avoidance," *IEEE Transactions on Broadcasting*, vol. 60, no. 1, pp. 16–28, March 2014.

[148] O. D. R. Herrero and R. D. Gaudenzi, "High efficiency satellite multiple access scheme for machine-to-machine communications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 48, no. 4, pp. 2961–2989, October 2012.

[149] H. C. Bui, J. Lacan, and M. L. Boucheret, "An enhanced multiple random access scheme for satellite communications," in *Wireless Telecommunications Symposium 2012*, April 2012, pp. 1–6.

[150] C. Kissling and A. M. Dlr, "On the integration of random access and dama channels for the return link of satellite networks," in *2013 IEEE International Conference on Communications (ICC)*, June 2013, pp. 4282–4287.

[151] D. Merkel, "Docker: Lightweight linux containers for consistent development and deployment," *Linux J.*, vol. 2014, no. 239, Mar. 2014. [Online]. Available: http://dl.acm.org/citation.cfm?id=2600239.2600241

[152] D. Salopek, V. Vasić, M. Zec, M. Mikuc, M. Vašarević, and V. Končar, "A network testbed for commercial telecommunications product testing," in *2014 22nd International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, Sept 2014, pp. 372–377.

[153] G. Tanganelli, C. Vallati, and E. Mingozzi, "Coapthon: Easy development of coap-based iot applications with python," in *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, Dec 2015, pp. 63–68.

[154] Z. Shelby, K. Hartke, and C. Bormann, "The Constrained Application Protocol (CoAP)," RFC 7252, Jun. 2014. [Online]. Available: https://tools.ietf.org/html/rfc7252#page-36

[155] K. Scott and S. Burleigh, "Rfc5050 - bundle protocol specification," 2007, accessed May 2018. [Online]. Available: https://tools.ietf.org/html/rfc5050

[156] J. P. Skagmo, "Ngham radio packet protocol - rev. b," 2015, accessed: 28.05.2015. [Online]. Available: https://github.com/skagmo/ngham/blob/master/documentation/ngham_manual.pdf

[157] *ITU-R Volume 1 - Articles - Radio Regulations Articles*, ITU, 2016. [Online]. Available: http://search.itu.int/history/HistoryDigitalCollectionDocLibrary/1.43.48.en.101.pdf

[158] *Earth Exploration–Satellite Service Handbook*, ITU, 2011. [Online]. Available: https://www.itu.int/pub/R-HDB-56-2011

[159] J. E. Allnut, *Satellite-to-Ground Radiowave Propagation*, 2nd ed. The Institution of Engineering and Technology, 2011, iSBN 978-1-84919-118-0.

[160] *Recommendation ITU-R P.618-12 - Propagation data and prediction methods required for the design of Earth-space telecommunication systems*, ITU, 07 2015. [Online]. Available: https://www.itu.int/rec/R-REC-P.618/en

[161] *Recommendation ITU-R P.531-12 - Ionospheric propagation data and prediction methods required for the design of satellite services and systems*, ITU, 09 2013. [Online]. Available: https://www.itu.int/rec/R-REC-P.531/en

[162] P. M. K. jr, T. Humphreys, and J. Hinks, "GNSS and Ionospheric Scintillation - How to survive the next solar maximum," *Inside GNSS*, 2009.

[163] B. H. Briggs and I. A. Parkin, "On the variation of radio star and satellite scintillations with zenith angle," *Journal of Atmospheric and Terrestrial Physics*, vol. 25, pp. pp 339–365, 1963.

[164] S. R. Saunders and A. Aragón-Zavala, *Antennas and Propagation for Wireless Communication Systems*, 2nd ed. Wiley, 2007.

[165] *Recommendation ITU-R P.372-13 - Radio noise*, ITU, 09 2016. [Online]. Available: https://www.itu.int/rec/R-REC-P.372/en

[166] Louis J. Ippolito Jr., *Radiowave Propagation in Satellite Communication*. Van Nostrand Reinhold Company, 1986, ISBN 978-94-011-7027-7.

[167] E. Grayver, A. Chin, J. Hsu, S. Stanev, D. Kun, and A. Parower, "Software defined radio for small satellites," in *2015 IEEE Aerospace Conference*, March 2015, pp. 1–9.

[168] P. Frenger, S. Parkvall, and E. Dahlman, "Performance comparison of harq with chase combining and incremental redundancy for hsdpa," in *IEEE 54th Vehicular Technology Conference. VTC Fall 2001. Proceedings (Cat. No.01CH37211)*, vol. 3, 2001, pp. 1829–1833 vol.3.

[169] *ECSS-E-TM-E-10-25A - Space engineering Engineering design model data exchange (CDF)* , ECSS, 10 2010. [Online]. Available: http://ecss.nl/hbstms/ecss-e-tm-10-25a-engineering-design-model-data-exchange-cdf-20-october-2010/

[170] California Polytechnic State University, "CubeSat Design Specification Rev 13," 2015. [Online]. Available: https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/56e9b62337013b6c063a655a/1458157095454/cds_rev13_final2.pdf

[171] Gunter's Space Page, "Ardusat 1, x," accessed March 2018. [Online]. Available: http://space.skyrocket.de/doc_sdat/ardusat-1.htm

[172] "NASA's Raspberry Pi-based Pi-Sat Cubesat," 2016, accessed March 2018. [Online]. Available: http://spaceref.com/nasa-hack-space/nasas-raspberry-pi-based-pi-sat-cubesat.html

[173] Tyvak.com, 2015, accessed October 2015. [Online]. Available: http://tyvak.com/

[174] Innovative Solutions in Space, "Satellite products," 2015, accessed October 2015. [Online]. Available: http://www.isispace.nl/cms/

[175] GOMSpace, "Gomx-platform," 2015, accessed October 2015. [Online]. Available: http://gomspace.com/index.php?p=products-platforms

[176] UTIAS-SFL, "Products & services: Satellite platforms," 2015, accessed October 2015. [Online]. Available: http://utias-sfl.net/?page_id=89

[177] Open Cosmos, "Open cosmos webpage," 2018, accessed March 2018. [Online]. Available: https://open-cosmos.com/

[178] NanoAvionics, "Nanoavionics webpage," 2018. [Online]. Available: https://n-avionics.com/

[179] Clydespace, "Cubesat lab," 2015, accessed October 2015. [Online]. Available: http://www.clyde-space.com/cubesat_shop

[180] Pumkin, "Begin your cubesat mission with the cubesat kit," 2015, accessed October 2015. [Online]. Available: http://www.cubesatkit.com/

[181] M. Macdonald and V. Badescu, Eds., *The International Handbook of Space Tecnology*. Springer, 2014.

[182] G. Quintana-Díaz and R. Birkeland, "Software-defined radios in satellite communications," in *Proceedings of ESA Small Satellites Systems and Services*, 2018.

[183] GOMspace, "Space qualified Software Defined Radio (SDR) Platform for Sensing and Communication Applications using powerful and advanced FPGA Technology," 2017. [Online]. Available: https://gomspace.com/Shop/payloads/software-defined-radio.aspx

[184] ThalesGroup, "Thales MissionLINK™." [Online]. Available: https://www.thalesgroup.com/sites/default/files/database/document/2018-10/MissionLINK_Data%20Sheet_03092018.pdf

[185] E. Udnæs, "High-gain antenna for Arctic ABC," Project thesis at NTNU, 2018.

[186] *Recommendation ITU-R M.1371-5 - Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band*, ITU, 02 2014. [Online]. Available: https://www.itu.int/rec/R-REC-M.1371-5-201402-I/en

[187] Delovski et.al, "Ads-b over satellite the world's first ads-b receiver in space," in *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[188] Alliance for Telecommunications Industry Solutions, "ATIS telecom glossary 2000 : T1.523-2001," 2001, accessed February 2018. [Online]. Available: http://www.atis.org/glossary/

[189] *ECSS-Q-ST-60-15C - Space product assurance - Radiation hardness assurance EEE components*, ECSS, 10 2012. [Online]. Available: http://ecss.nl/standard/ecss-q-st-60-15c-radiation-hardness-assurance-eee-components-1-october-2012/

Appendix A

Included Papers

The following papers are results of the work carried out in this PhD-thesis, and were written during the process. These papers present some of the main contributions with respect to the communication network architecture specification and the application and properties of satellite swarms.

The series of papers starts with presenting the communication gap in the Arctic, and the challenges for an Arctic communication system in Paper A (Section A.1) and Paper B (Section A.2). Then, swarms of small satellites, and how they can be designed to best provide coverage, are introduced in Paper C (Section A.3) and Paper D (Section A.4) respectively. A full communication architecture proposal encompassing satellites and other unmanned vehicles is presented in Paper E (Section A.5). Paper F (Section A.6) focuses on simulation and emulation evaluation parts of the architecture introduced in Paper E. Paper F presents results on coverage and end-to-end delay for different swarm configurations, sensor node and gateway placements. Finally, Paper G (Section A.7) presents a deeper analysis of how real IoT protocols may perform in this architecture. Suggestions on how to reduce delays by employing a forward-looking routing method is also presented.

A.1   Paper A

R. Birkeland, "An overview of existing and future satellite systems for Arctic communication," in *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

In this paper a survey on satellite communication systems covering the Arctic is presented. Section 2.3.1 is partially based on this paper. The author presented the paper at the conference.

An Overview of Existing and Future Satellite Systems for Arctic Communication

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Abstract

For users and systems located in the high north, communication is a difficult task. This is due to a challenging climate, missing land-based infrastructure and also a lack of suitable satellite systems. For example, operation of remote sensors and sensor networks in this area is more challenging compared to operation in areas with better infrastructure. A growing interest in the Arctic for economic reasons, and the recent developing changes in climate, cause many parties to see a greater use of the Arctic area in the future and an increasing need for infrastructure.

In this paper we will present some existing satellite communication systems and some proposed communication systems that could serve as an example of systems to relay information from a sensor network located in the Arctic area. By looking at the existing systems, a gap in service coverage for users in the Arctic area is revealed. The lack of coverage in the Arctic area is widely recognized, but there are only a few proposed systems to mitigate this situation.

For many systems and services a high bandwidth system will be needed, or is at least preferable. For other systems and networks, a narrow band system can be sufficient. In the CAMOS (Coastal and Marine Operations and Surveillance) project at NTNU (Norwegian University of Science and Technology), we are studying sensor networks with relatively low bandwidth requirements. We aim to propose a satellite system employing small satellites that can be used as a network node in a sensor network operating in areas outside coverage area for traditional communication systems.

The cost of introducing a new satellite system will be significant, but the benefit compared to existing systems can be less complex and more rugged ground terminals, lower energy consumption and a more tailor made system well fitted for sensor networks. Using small satellites, it will be possible to launch a series of payloads with increasing functionality to a manageable cost. The Norwegian AISSat-1, a small satellite project, has been carried out to a cost of approximately €2.4 million EUR. A sensor network satellite payload can perhaps be of similar type and costs. However, it is envisioned that a payload for sensor networks can be a part of a satellite mission consisting of multiple payloads, thus reducing the cost for this project.

1 Introduction

1.1 The CAMOS project

In the CAMOS (Coastal and Marine Operations and Surveillance) project at NTNU (Norwegian University of Science and Technology), we will research different aspects of operation and communication in the arctic area. The project is divided into three activities. The first activity will look at the use of robust and efficient networking in dynamic heterogeneous environments. The second activity will address mission and path planning for mobile sensor in a sensor network. The third activity, on focus in this paper, will aim to propose a micro satellite component that can be used as a network node in a sensor network operating in areas outside coverage area for traditional communication systems [25].

While the CAMOS project will aim to find general solutions useful for several purposes, the main user case in the project is how to monitor the area between Svalbard and Greenland and between Svalbard and Franz Joseph land. The area of interest is shown in Figure 1. We envision a sensor network consisting of sensor nodes making a barrier east and west of Svalbard. The bathymetry on each side of Svalbard is very different; the east side is quite shallow with depths of some hundred meters, the west side is a deep trench. This will call for different types of sensor nodes. However, the make of these sensors will not be further discussed here. We will assume that they share some common features. There will be gateway nodes responsible of collecting data from child nodes and signaling other nodes through various types of communication channels. We envision that the gateway nodes will have direct satellite communication as well as being part of a "terrestrial" network together with other surface nodes, Unmanned Aerial Vehicles (UAVs) and ships.

The scope of this paper is to make a short survey of existing and proposed satellite communication technologies that may be used together with such a sensor network. However, it will be shown that the excising systems have limitations which are hard to overcome.
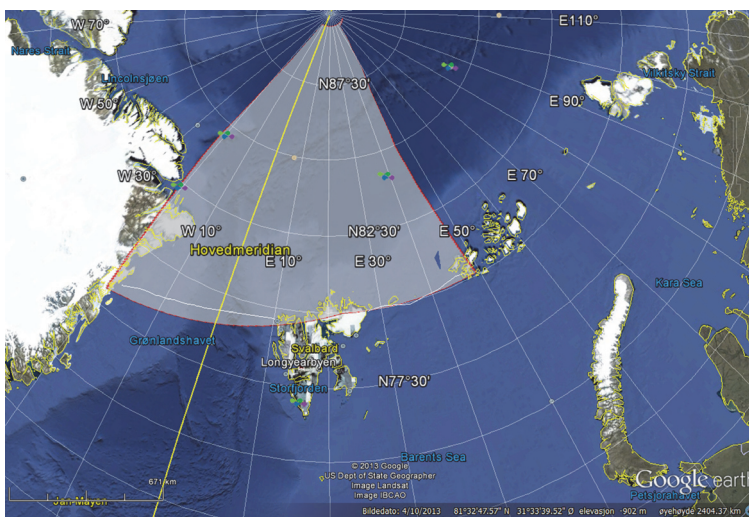

Figure 1: The area defined as area of interest for CAMOS

1.2 Focus on the Arctic

In this paper, we will generally define "the Arctic" as the area from 70° N to the North pole. This area is shown in Figure 2. In addition to the above mentioned sensor network on focus in the
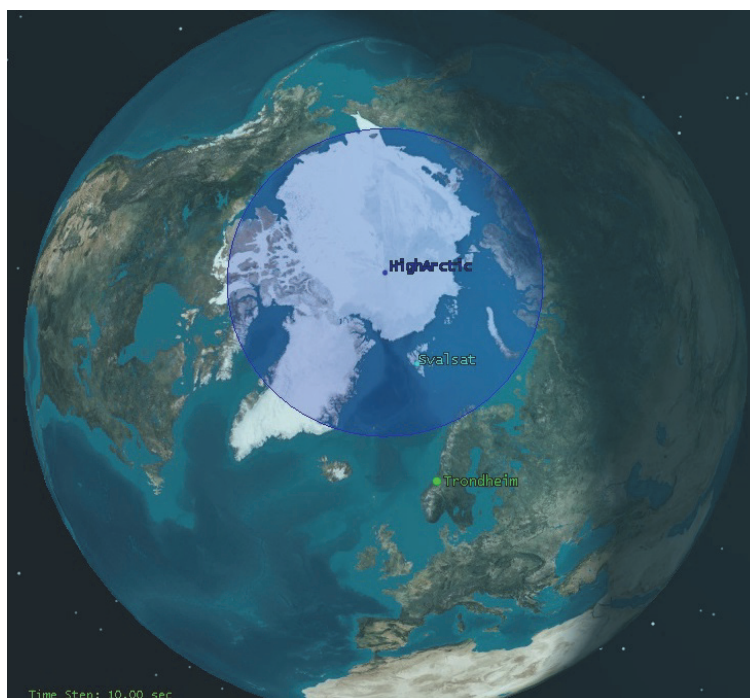
Figure 2: Our definition of the Arctic area

CAMOS project, the Arctic is an area of overall increasing interest. Several parties foresee more utilization of the Arctic area in both near and distant future [11, 19]. This can relate to research, tourism, fisheries, resource exploitation, national presence and protection of national interests and then needed search-and-rescue (SAR). Private, public, governmental and military stakeholders all share an interest in the use of the Arctic area. All these groups will need other means of communication than what is available at the present moment.

The needs for communication services between these users will however be different. The oil industry and military might both have a need for high bandwidth communication links which are non-existing north of around 80° latitude.

Redundancy might be needed and a satellite link could provide such services. Military operations might have a high bandwidth requirement. This kind of users are often mobile (vessels, aircrafts; manned or un-manned), and for such users satellite communication is the only viable solution for high rate data communications. This level of data communications services must be offered by a service comparable to the GEO satellite systems.

Other users, such as shipping, fishing and tourism, could also benefit from a high data-rate link. Depending on the level of service, a lower rate datalink could be sufficient to cover the most important services, such as access to weather forecasts, ice forecasts, general communication and distress messages. Such a communications system could be realized using smaller satellites in low Earth orbit. Some of these needs are already covered by use of Iridium services.

Data from and for scientific users might also benefit from a low-to-medium rate communications system. Remote sensors and network, both "permanent" and more mobile systems measuring slowly varying parameters are generating a small amount of data. If it is not urgent to transmit this data, the system could benefit from a LEO communications system. Much of the user needs may be covered by employing a system that not necessarily has 100% access time; for example one satellite returning to the Arctic area every 90 minutes. One satellite will only give around

10 minutes of access time for each pass, and this can support only a limited number of users, depending on the capacity of the communications payload.

With a European focus, ESA has conducted a study to identify gaps in present and future communication system in the Arctic [10]. An article in the Norwegian Research magazine GEMINI from 2011 presents some of the challenges of operating in the Arctic, with focus on the maritime sector. It also includes the lack of proper communication in the northern areas [13]. Most of the challenges are related to weather and climate in addition to the general lack of infrastructure. In combination, these facts can result in more severe consequences if an accident of some sort occurs.

The climatic conditions also lead to more technical challenges, equipment that placed outside in the arctic environment must endure icing, harsh winds, no sun during the winter, the ice moving and equipment may be crushed due to ice breakage.

2 Existing Systems

The following sections briefly present a few existing LEO and GEO satellite communications systems. Even if the GEO systems, and some LEO systems, do not provide coverage in the Arctic, they are good examples of the level of service one would need and expect from an Arctic communications system. The different systems all have different properties and commercial availability, ranging from systems accessible for public users to more or less closed/private systems. A more thorough description of some of these systems (OrbComm, Globalstar, Iridium) can be found in a study of Arctic communication [22, Appendix C]. Generally, one could divide the communication systems into two groups; the messaging systems (one-way) and the two way communication systems.

2.1 LEO Tele-and Data Communication

2.1.1 Gonets

Gonets (Messenger) is a Russian system composed of 12 satellites in an 1400 km orbit at 82.5° inclination [15]. The data rate available is between 2.4 kbps to 64 kbps. Offered services are tracking and monitoring of remote equipment and relay of telemetry data from sensors. The constellation is not yet fully populated, more launches are planned for 2014 [16]. The frequency used is between 200 MHz and 400 MHz. The deployment of the full system is planned for 2015. The Gonets installation will then consist of 18 satellites in total, of two different kinds [27]. The satellites will be placed in six orbital planes with eight satellites in each plane.

A new satellite system called KOSMONET is under investigation, and the plan is to launch 24 satellites by 2016 and 48 satellites by 2020, at a total cost of 20 billion rubles [27]. The goal of the system is to provide a mobile internet system.

2.1.2 Iridium

Iridium Communications LLC is a company offering several planet-wide satellite communications services spanning from voice to low-rate data transfer. Through Iridium it is possible to transfer both one-way sensor/tracking data through the Short Data Burst service as well as higher two-way data rates from 2.4 kbps to 132 kbps in today's system. Iridium plans to launch a new range of satellites from 2015. This new constellation will be called Iridium NEXT, and is planned to be operational from 2017 [18]. A short comparison over the legacy Iridium services and the new services is shown in Table 1.

Today, Iridium is the only open, planet-wide communications solution enabling voice and data services in the Arctic area.

The Iridium NEXT-service will support new services compared to today's Iridium-services.

Service	Iridium	Iridium NEXT
Voice	2.4 kbps	2.4 kbps
Circuit Switched Data	2.4 kbps	9.6 - 64 kpbs
Short Burst Data	low	on demand
OpenPort®	132 kpbs	128 - 512 kbps
OpenPort Aero	132 kbps	128 - 512 kbps
L-Band High Speed	N/A	512 kbps up - 1.5 Mbps down
Broadcast	N/A	64 Mbps

Table 1: An overview of Iridium-services. Data from Iridium homepage [18].

2.2 Systems for Messaging

In this category we find systems for only one-way communication, mainly for tracking objects. These systems are quite tailor made and usually only support one type of service, though the applications vary.

2.2.1 OrbComm

OrbComm is a US company providing machine-to-machine communications. With their constellation of 29 LEO satellites, at 775 km orbit height, they provide services for tracking moving equipment. Their satellites are small, only about 50 kg. A new constellation with bigger satellites is planned [26]. OrbComm provides no continuous coverage, the latency can be up to 20 minutes, but they have some arctic coverage. The system uses VHF and UHF frequencies.

2.2.2 ARGOS

ARGOS is a messaging/tracking system used to track sea wildlife amongst other things. This system enables one-way transmission of small messages from 32 to 256 bits directly from the tag to the satellite. The receiving payload is flown on meteorological satellites and data is downloaded at several locations around the world. ARGOS is using a UHF frequency [8, 6].

2.2.3 Satellite based AIS

During the last years several satellite based Automatic Identification Systems (AIS)-receivers have been placed in orbit. One example is the Norwegian AISSat-1 mission, enabling global AIS-coverage [24]. The Canadian company excatEarth is an example of a commercial operator of satellite based AIS [12].

2.3 GEO Communication Systems and Systems with No Arctic Coverage

Finally, there are also several satellite systems such as Inmarsat and Globalstar which do not provide any coverage in the Arctic area. Other VSAT-systems based on GEO systems also exist. None of these systems will provide any service in the Arctic.

Globalstar is a US system offering voice and 9.6 kbps data and internet services. The system is a bent-pipe system with a constellation of 24 satellites in 55° inclination at 1400 km height. The new fleet of satellites was completed in 2013. Due to the low inclination and the lack of ground stations in the Arctic, the system does not provide any coverage in the Arctic [3, 14, 22].

Inmarsat is an international GEO system for communications between ship and shore and ship - ship. This includes both narrow band, broadband and distress services [17]. There is no service above and below ± 75° - 80° North and South latitude respectively.

3   Summary of Available Solutions

System	Freq.band	Capacity	Con't coverage	Arctic
Gonets	UHF	2.4 - 64 kbps	planned	yes
OrbComm	VHF	low	no	some
Iridium	L	2.4 kpbs	yes	yes
Globalstar	L	9.6 kbps	yes	no
Inmarsat	L	20 kpbs	yes	no

Table 2: Proposed systems for the Arctic areas

As shown, there are some existing systems covering the Arctic area, but gaps have been identified by bodies like EU and NASA [11, 19]. Of the systems listed in Table 2, Iridium is the only operational service capable of providing 24/7 coverage to users in the Arctic. This system, is "modem and voice oriented" and can only provide limited bandwidth. None of the above systems, will fit a sensor network where e.g. a gateway buoy or a vessel transmits sensor data regularly on a limited power budget. Of the proposed systems, Arktika may be the only system, besides Iridium NEXT which can provide continuous coverage. Depending on the sensor and sensor data, 24/7 coverage might not be needed to provide sufficient service for the user.

4   New Missions Towards the Arctic

Since there is an increasing interest for activities in the Arctic, several parties have plans for missions aiming to fill the communication gap identified by bodies like ESA. From the ESA study *Future Arctic Communications Needs* we can read: "demand for broadband communications could extend over 100 Mbps in 2020. Maritime activities are considered one of the main drivers of the demand. The supply is virtually non-existent, i.e. there is an considerable capability gap." [11]. For Europe, it is also an important fact that the operational/planned systems for Arctic coverage so far are non-European projects.

The following sections present a sum-up of planned systems. The exact status for each project is not easily accounted for, but they serve as examples on envisioned systems.

4.1   Antarctic Broadband

Even if this proposed system has Antarctica in mind, one could easily see it as relevant for the Arctic as well. The project is an Australian proposed system to use a small satellite (the UTIAS Generic Nanosatellite Bus) in a LEO orbit to demonstrate a Ka broadband link to the Antarctic area. The system is now in a pilot phase [9, 5, 4], and the plan is to launch two or three satellites to complete the service.

4.2   ARC-Sat

Arctic Region Communications Small Satellites (ARC-Sat) is a demonstrator system proposed by NASA Marshall Space Flight Center [19]. This project envisions one small satellite as a demonstrator on how to fill the gap between the excising low rate systems and a system capable

of providing a 3 Mbps link. The presentation [19] also outlines reasons why such a system is important, such as the interest of increasing maritime domain awareness in the polar areas, relay data from remote sensors and more.

4.3 Polar Communications and Weather

The Polar Communications and Weather (PCW) Project is a Canadian proposed constellation of satellites with a multitude of capabilities. This spans from wideband and UHF communications for military users, meteorological imaging, space weather system and other payloads. The number of satellites is yet to be determined, as well as the launch date. The system will probably use a high elliptical orbit. The Canadien government issued an Request-For-Information late 2013 [1].

4.4 Arktika

Arktika is a proposed Russian satellite system composed of ten satellites in four different constellations for communications, meteorology and surveillance. The launch of the first satellite in this system is planned to be in 2015 [29]. Different orbits will be used, as shown in Figure 3. Most of the satellites will be in high elliptical orbits to increase the coverage time above the areas of interest.
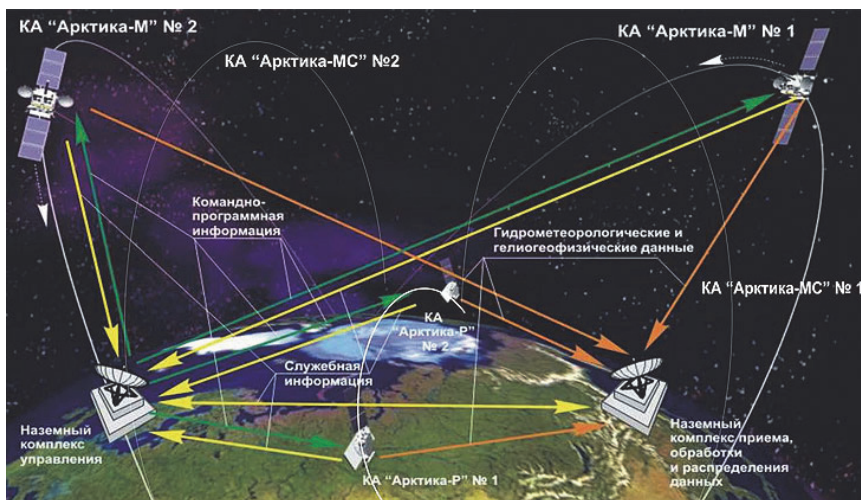
Figure 3: The Arktika system. Credit: NPO Lavochkin. From [29].

4.5 CASSIOPE/Cascade

Cascade is the secondary payload for the Canadian CASSIOPE mission. This is a technology demonstrator for a store-and-forward payload capable of transferring data chunks of several GB [2, 23]. This satellite is a cooperation between Canadian industry (MacDonald, Dettwiler and Associates Ltd. (MDA), Magellan and ComDEV) and several Canadian Universities. The satellite is built upon Magellan Aerospace MAC-200 which is bigger than the UTIAS Nanosatellite bus, measuring 180 by 120 cm. The satellite was launched in September 2013 [7]. The status of the experiment is not known at time of writing.

4.6 Norwegian Polar Broadband Initiative

SINTEF Marintek, Telenor and the Norwegian Space Centre has conducted a study of how to provide broad band access to the Arctic [28]. The aim is to use HEO satellites to provide network services comparable to GEO systems. However, this system will require much time and resources and its future is uncertain [20].

5 Summary of Proposed Communication Solutions

The six proposed systems in Section 4 are quite different. The Antarctic broadband, the ARC-Sat proposals and Cascade pin-point the use of small satellites, first as technology demonstrators. This means that the systems will not deliver continuous coverage of the area of interest. Depending on the chosen orbit, some of the Arctic area will be covered for every pass. Given a polar LEO satellite, one can assume about 90 minutes orbital period with around 10 minutes of coverage for every pass. The amount of data throughput in the system will then strongly depend on the frequency and communications payload of the satellite. A low frequency system, such as ARC-sat will only be capable of relaying a small amount of data for each pass. The proposed Antarctic broadband and the Norwegian Broadband Initiative would be able to serve more data to several users. Table 3 sums up the proposed services. From a sensor network perspective, none of the listed systems will provide a suitable service. The broad band systems will probably require too large ground terminals to be used on sensor nodes, PCW is a closed system and the status of Arktika is not know.

System	Freq.band	Capacity	Con't coverage	Arctic
Ant. B.band	Ka	TBD	no	not known
ARC-Sat	S, X, UHF	3 Mbps	no	yes
PCW	TBD, UHF	TBD	no?	yes
Arktika		Mobile	maybe	yes
Cascade		Gbit	no	yes
Telenor HEO		Broadband	yes	yes

Table 3: Proposed satellite communications systems

6 Other Missions With an Arctic Target

In addition to the above mentioned communications missions, there are different monitoring missions both planned and in operation. Many of these consider AIS and ship traffic surveillance systems. The European Sentinel satellites, CryoSat and the MyOcean project are examples of this [11]. These projects will be monitoring only, but missions like the PCW and ARC-Sat include both monitoring and surveying as well as communications. The Norwegian AIS-Sat family and the future NORSAT-1 satellite will provide AIS monitoring along with other measurements [24, 21].

Several of the proposed missions, both for communications and monitoring, are built around small satellites. Antaric Broadband, AIS-Sat and NORSAT all use, or will use, different versions of the UTIAS Generic Nanosatellite bus.

7 Conclusions

This paper presents a brief summary of existing and some proposed systems for satellite communications in the Arctic area. However, few of them could be used for sensor network operations. The systems mentioned lacking Arctic coverage, are included to give examples of what one could want and expect from a satellite communication system.

Several of the new technology demonstrators build their projects around small satellites. Small satellite platforms have through several missions, such as the Norwegian AIS-Sat mission, shown how to use a small satellite to do a big job. The AIS-Sat1 shows how much information only one sensor satellite can collect and relay during its mission. The satellite has mapped ship traffic in areas far from land all over the globe. For Norway, the use of this data has enabled a much better control over the Norwegian Economic Zone and illegal fisheries.

In the CAMOS project, a scenario for environmental surveying is designed. The focus area in this user case will be the areas between Greenland and Svalbard and Svalbard and Franz Joseph Land. It is envisioned that this area can be monitored by an array of sensors. To convey sensor data from this network back to the end user, a satellite link will be required. As discussed above, the selection of satellite communications is limited. From the existing systems there are two likely alternatives; the ARGOS system can provide one way trickle data and Iridium can provide one or two way close to real time data. A system like Iridium will be capable of transmitting much more data than ARGOS, but also to a higher cost with respect to needed power in the sensor node. Of the proposed systems, none of them seems as likely candidates to be used together with a sensor network.

Through the CAMOS project we will focus on develop a communication system with requirements and capabilities between ARGOS and Iridium to support operations like the proposed sensor network.

References

[1] Marc Boucher, SpaceRef. Polar communications and weather satellite project one step closer to reality, November 2013. URL http://spaceref.ca/missions-and-programs/canadian-space-agency/polar-communication-and-weather-mission/polar-communications-and-weather-satellite-project-one-step-closer-to-reality.html. Accessed November 2013.

[2] Canadian Space Agency. CASSIOPE: Observing Space Weather with a Hybrid Satellite, 2014. URL http://www.asc-csa.gc.ca/eng/satellites/cassiope.asp. Accessed April 2014.

[3] Arianespace. Arianespace/starsem completes the deployment of globalstar's constellation with a soyuz mission from baikonur cosmodrome, Feb 2013. URL http://www.arianespace.com/news-mission-update/2013/1017.asp.

[4] Australian Government Space Portal. Antarctic broadband: Definition and capability development, 2013. URL http://www.space.gov.au/AustralianSpaceResearchProgram/ProjectFactsheetspage/Pages/AntarcticBroadbandDefinitionandCapabilityDevelopment.aspx.

[5] Antarctic Broadband. Antarctic broadband the project, 2011. URL http://antarcticbroadband.com/projects/. Accessed November 2013.

[6] CLS Group. Argos (webpage), 2014. URL http://www.argos-system.org. Accessed March 2014.

[7] CNW. Magellan aerospace-built mac-200 bus successfully launched on cassiope, 2013. URL
http://www.newswire.ca/en/story/1233785/
magellan-aerospace-built-mac-200-bus-successfully-launched-on-cassiope. Accessed
April 2014.

[8] Environmental Studies. About argos, argos services for wildlife tracking, 2014. URL
http://www.environmental-studies.de/Argos/Argos-System/A-1.html. Accessed March
2014.

[9] eoPortal. Antarctic broadband nanosatellite demonstration mission, 2013. URL
https://directory.eoportal.org/web/eoportal/satellite-missions/a/antarctic-broadband.
Accessed November 2013.

[10] ESA. ESA ARTES webpage, December 2011. URL
http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=30581. Accessed
November 2013.

[11] European Commission, HIGH REPRESENTATIVE OF THE EUROPEAN UNION FOR
FOREIGN AFFAIRS AND SECURITY POLICY. Developing a european union pol-
icy towards the arctic region: progress since 2008 and next steps, June 2013. URL
http://eeas.europa.eu/arctic_region/docs/swd_2012_183.pdf.

[12] exactAIS. Vessel monitoring, 2014. URL http://www.exactearth.com/applications/vessel-monitoring.
Accessed April 2014.

[13] GEMINI. Safety in the north: Polar perils, October 2012. URL
http://www.ntnu.no/gemini/2012_autumn/34-41.htm.

[14] Globalstar. Globalstar webpage, 2103. URL http://eu.globalstar.com/en/. Accessed nov.
2013.

[15] Gonets Leosat System. Gonets.ru webpage, 2013. URL http://gonets.ru. Accessed Nov. 2013.

[16] Gunter's Space Page. Gonets-m, 2013. URL http://space.skyrocket.de/doc_sdat/gonets-m.htm.

[17] Inmarsat. Inmarsat webpage, 2013. URL http://inmarsat.com. Accessed november 2013.

[18] Iridium Communications Inc. Iridium next: Advanced technology, 2013. URL
http://www.iridium.com/About/IridiumNEXT/Technology.aspx. Iridium NEXT: Advanced
Technology.

[19] Joseph C. Casas. Arctic region communications small satellites (arc-sat), Sep 2012. URL
http://nix.nasa.gov/search.jsp?R=20120016896&qs=N%3D4294163423%2B4294957324%2B4294587540.
Accessed November 2013.

[20] The Wall Street Journal. Northern arctic could have long wait for reliable broadband, January 2014.
URL http://online.wsj.com/news/articles/SB10001424052702303947904579338123242192890.
Accessed April 2014.

[21] UTIAS Space Flight Laboratory. Norwegian space centre awards norsat-1 contract to sfl!, 2013. URL
http://www.utias-sfl.net/RecentNews/news-20130614.html. Accessed January 2014.

[22] Lars Løge. *Arctic Communications System Utilizing Satellites in Highly Elliptical Orbits*. PhD thesis,
Norwegian University of Science and Technology, 2013.

[23] MDA Information Systems. Cassiope, 2014. URL
http://is.mdacorporation.com/mdais_canada/Programs/Programs_Cassiope.aspx. Ac-
cessed April 2014.

[24] Norwegian Space Centre. Norske satellitter, 2013. URL
http://www.romsenter.no/Bruk-av-rommet/Norske-satellitter. Accessed Jan 2014.

[25] Norwegian University of Science and Technology, 2014. URL http://www.ntnu.edu/web/camos/. Accessed January 2014.

[26] Orbcomm. Orbcomm webpage, 2013. URL http://www.orbcomm.com/services-overview.htm. Accessed Nov 2013.

[27] Russian space web, 2013. URL http://www.russianspaceweb.com/gonets.html. Accessed Nov 2013.

[28] SINTEF. Getting broadband in the arctic, June 2013. URL http://www.sintef.no/home/Press-Room/Research-News/Getting-broadband-in-the-Arctic/.

[29] Russian space web. Russia to build arctic satellite network, 2013. URL http://www.russianspaceweb.com/arktika.html. Accessed Nov 2013.

A.2 Paper B

R. Birkeland, "Proposal for a satellite communication payload for sensor networks in the Arctic area," in *Proceedings of the 65th International Astronautical Congress*, 2014.

Background, challenges and potential users as described in Chapter 1 are presented in this paper. The author presented the paper at the conference.

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PROPOSAL FOR A SATELLITE COMMUNICATION PAYLOAD FOR SENSOR NETWORKS IN THE ARCTIC AREA

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For users and systems located in the high north, communication is a difficult task. This is due to a challenging climate, missing land-based infrastructure and a lack of suitable satellite systems. For example, operation of remote sensors and sensor networks in this area is more challenging compared to operation in areas with better infrastructure. A growing interest in the Arctic for economic reasons and the recent developing changes in climate causes many parties to see a greater use of the Arctic area in the future and an increasing need for infrastructure. In this paper, we will discuss and present how a small satellite with a suitable payload can be used as node in a sensor network.

For many systems and services, a high bandwidth system is needed or at least preferable. For other systems and networks, a narrow band system can be sufficient. In the CAMOS (Coastal and Marine Operations and Surveillance) project at NTNU (Norwegian University of Science and Technology), we are studying sensor networks with relatively low bandwidth requirements. We aim to propose a satellite system employing small satellites that can be used as a network node in a sensor network operating in areas outside coverage area for traditional communication systems. Using a small satellite can reduce cost. In Norway, several small satellites are planned in the near future. These satellites will employ different versions of the UTIAS small satellite bus. Our goal is to propose a payload to fly on one of these satellites. Then the payload will share the cost of the satellite bus and the launch with the other payloads and projects. Another option will be to fly the payload on its own platform, such as a CubeSat. However, a CubeSat will add more constraints to the project on available power, pointing accuracy, available volume, reduced options for deployable antennas and more.

I. INTRODUCTION

In the CAMOS (Coastal and Marine Operations and Surveillance) project at NTNU (Norwegian University of Science and Technology), we will research different aspects of operation and communication in the Arctic area. The project is divided into three activities. The first activity will look at the use of robust and efficient networking in dynamic heterogeneous environments. The second activity will address mission and path planning for mobile sensors in a sensor network. The third activity, on focus in this paper, will aim to propose a micro satellite component that can be used as a network node in a sensor network operating in areas outside coverage area for traditional communication systems [1]. While the CAMOS project will aim to find general solutions useful for several purposes, the main user case in the project is how to monitor the area between Svalbard and Greenland in addition to the area between Svalbard and Franz Joseph land. The area of interest is shown in Figure 1. We envision a sensor network consisting of sensor nodes making a barrier east and west of Svalbard. The bathymetry on each side of Svalbard is very different; the east side is quite shallow with depths of some hundred meters, the west side is a deep trench. This will call for different types of sensor nodes. However, the make of these sensors will not be further discussed here. We will assume that they share some common features and can communicate with the satellite in the same manner. There will be gateway nodes responsible for collecting data from child nodes

Fig. 1: The intended area of interest in the CAMOS scenario.

and signalling other nodes through various types of communication channels. We envision that the gateway nodes will have direct satellite communication as well as being part of a "terrestrial" network together with other surface nodes, Unmanned Aerial Vehicles (UAVs) and ships. The scope of this paper is to make a short presentation on the envisioned CAMOS system and overall idea for a feasible payload.

I.I Focus on the Arctic

In this paper, we will define "the Arctic" as the area from 70° N to the North Pole, shown in Figure 2. mentioned sensor network on focus in the CAMOS project, the Arctic is an area of increasing interest. In addition to the above mentioned sensor network on
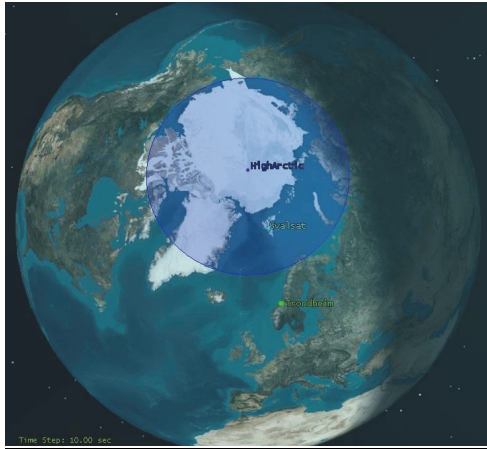
Fig. 2: Our definition of the Arctic area.
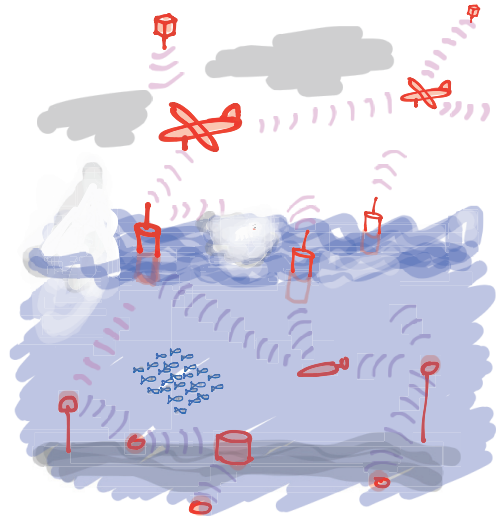

Fig. 3: The CAMOS network. The network could consist of satellites, UAVs, floating and submerged sensors and AUVs.

focus in the CAMOS project, the Arctic is an area of increasing interest. Several parties foresee more utilization of the Arctic area in both near and distant future [2, 3]. This can relate to research, tourism, fisheries, resource exploitation, national presence and protection of national interests and then needed search-and-rescue (SAR). Private, public, governmental and military stakeholders all share an interest in the use of the Arctic area. All these groups will need other means of communication than what is available at the present. The needs for communication services between these users will however be different. The oil industry and military might both have a need for high bandwidth communication links, which are non-existing north of around 80° latitude. For other uses, narrow band systems as discussed here can suffice.

II. THE GAP IN THE SERVICE

As shown in [4], several parties such as EU and ESA [5, 6] have identified a gap in satellite services in the Arctic, both for general cases and especially for shipping. None of the excising and proposed new systems listed in [4] will completely fulfil the role as service network for a sensor network such as the proposed CAMOS network. GEO based systems cannot be used far north, and requires big and steerable antennas, impractical to use for small nodes. ARGOS cannot be used for larger amounts of data and lacks a return channel. Iridium could be used, but might require more power at the sensor compared to a tailor made radio in addition to be expensive in use.

III. USER CASE

Figure 3 shows a sketch of the intended network. When deciding on the systems specification for the

scenario described in Section I, some assumptions are made. First, we propose a polled system, meaning that the satellite knows which sensors are deployed where and polls all sensor nodes in turn. All nodes are treated alike and it is assumed that their generated data also have equal priority. We assume that the nodes sample the environmental data at a low rate. Wind at 1-minute interval, temperatures, humidity and pressure at 10 minutes intervals and precipitation are registered every hour. All parameters are allocated 8 bits of storage. This gives 1020 bits of data for each 1.5 hours, which will be the approximate interval between passes. We must add some protocol overhead as well as take into account a kind of error-correcting coding. If we use a code with an efficient rate, we can expect little code loss with respect to capacity. To choose a suitable code, we must consider the whole link budget and its calculated link margin.

Assume that the final package to be transmitted from one sensor node every pass consists of 1500 bits. Assuming a bit rate of 500 bps, each transmission will take around 3 seconds. Adding 1 second for link setup for each node, this will give us throughput to serve more than 350 nodes for every pass. This is assuming the satellite knows which of the nodes should be polled when, according to their place along-track. Capacity to serve 350 nodes is more than we need in the first phase of the project. An alternative solution would be to let the sensor node send its data to a gateway node with a more powerful transmitter, like an UAV, allowing for

higher bit rates and again enabling us to serve even more users.

Assuming we have all 350 nodes, this corresponds to around 525 kbit of user data collected in the satellite node that must be downlinked after every pass. Given that we use a ground station at Svalbard, the measurements can be downloaded almost instantaneously, since the satellite will see sensors and the ground station at the same time, at least for some passes.

IV. SYSTEM PROPOSAL

In the simple scenario discussed here, we propose polling to solve our multi user access. We suppose that all nodes have something equally important to tell at each pass. Other multiple access schemes should also be investigated. For a demo system with only one satellite a polled system can make sense. For a system with several satellites and with nodes generating data of different priorities, we must assume that their data transfer frequency is not uniform anymore. The nodes should also be able to initiate an assert or alarm into the system, and a polled system will not allow for this. This depends on the type of data the nodes collect and the importance and real-time need of this data. Further discussion of such topics must be carried out.

Similar payloads to what we are discussing here are the AIS and ADS-B payloads. Such payloads have been flown on both CubeSats [7, 8] and bigger small-satellites [9, 10]. A payload being used for the CAMOS project could be of similar type. The missions are similar since all AIS and ADS-B also aim to record data from different types of sensors, ships and airplanes respectively. Of other similar proposed systems, an Australian project has investigated how to build both sensor terminals and satellite payload for a sensor network employing a very large number of deployed sensors that can communicate without much synchronization [11]. Their main focus is not the Arctic, but their findings may be useful for other similar systems also.

It is envisioned that a payload similar to the AIS-payload developed by Kongsberg Seatex can be used for the CAMOS network. Some adaptations must however be made; the payload must have a downlink for polling sensors in addition to the receiver. Since we foresee a polled system for the demonstration payload, the receiver end of the payload can be simpler since it only will communicate with one node at the time.

It will be recommended to build a Software Defined Radio (SDR) payload, as this will give the most flexible solution. A SDR payload can be configured in-flight, allowing test of different modulations, waveforms and data protocols in an easy manner. This way, it can be possible to test very different configurations and evolutions of the payload without requiring the launch of a new satellite.

IV.I Satellite Bus and Orbit Requirements

To be able to support bigger antennas and leave a more flexible power budget, the payload should be targeted for a satellite bigger than a CubeSat. However, the payload does not require a special platform. The Generic Nanosatellite Bus from UTIAS, as used for the AIS-Sat1 and AIS-Sat2 is an example of a bus platform that can be used. We could also have a shared mission together with an AIS receiver, given that the satellites power budget allows for this. The payload can also be considered as a hosted payload on board a bigger satellite with another primary mission e.g NORSat.

Since the area to be served is far north, any LEO polar orbit could be used. There will be no need of a solar synchronous orbit or other special orbits. Since we do not have any special orbit requirements, we will have more launches to choose from.

IV.II The Nodes

In addition to the payload, the sensor nodes must be addressed. It is outside the scope of this paper to thoroughly describe the make of the nodes, but a few important parameters will be mentioned.

Nodes and Power Requirements

Depending on how the nodes are deployed, the node communication system can be in a low power mode most of the pass, and only active when the satellite is over an area of interest. The downlink will only be used for very short command messages to nodes, such as polling requests and other messages.

The nodes should be deployed for a year or more. Due to the short duty cycle of the uplink, the lifetime limiting factor will be the power consumed by node housekeeping and sensors. A crude calculations shows that if we assume an output power of 50 mW at 50% efficiency and around 4 seconds per transmission for each pass for 14 passes a day, the node radio system will only consume around 0.6 Wh a year. If the rest of the node continuously consumes 2 W, total consumption over one year is more than 17.5 kWh. From this, it is seen that the sensors will stand for most of the energy consumption, not the transmitting radio. This also could allow us to increase the transmit power if needed to improve our link budget margin.

Of course, we must also room for communications between the nodes, the UAV and such, but the clue is that the satellite link itself does not account for a huge amount of energy consumption. In addition to the power

considerations, local climatic factors must be addressed when designing the nodes. This can be icing and snow covering of antennas, low temperatures, stability at sea, expected average sea state and more.

It is expected that such a system will use the UHF band, which will generally mean that antennas will be around 40 cm long (for a half wave dipole or monopole). The sensor antenna should not be very directional, since we cannot control the antenna pointing. The sensor might move due to waves and the satellite can pass over the sensor in any direction. Depending on the size of the node and the height of the antenna over the sea, the antenna ca also be totally drowned or waves can block the line of sight between the node and the satellite. Such events must be considered and the system design must mitigate the effects still ensuring that the node is able to deliver its message to the satellite.

IV.III Link budgets

As mentioned above, 50 mW transmission power from the sensors to the satellite should close the link budget for a 500 bps link with a margin, assuming good weather conditions. Further analysis must be made with respect to capacity, coding and weather conditions.

V. FEASIBILITY AND DISCUSSION

We have mentioned that ARGOS and Iridium are the only current services capable of serving remote sensors in the Arctic. ARGOS lack a return channel, and Iridium might be expensive to use and require too much power at the node. On the other hand, it will of course be a high initial cost to initiate a service with a dedicated satellite for this purpose. If we draw lines from the flight proven AIS and ADS-B missions, we anticipate that small satellites can carry small payloads ready for store-and-forward of sensor data.

There are two main differences between the CAMOS payload and the AIS and ADS-B systems. The first is that the latter two are only a sensor-to-satellite link. Still, the systems are multi-user networks that causes problems due to interference and packet collisions. The CAMOS network is intended to be a heterogeneous network comprising several links, and the final payload must be able to support all of these. The second difference is that the AIS and ADS-B systems do not have a return channel. The CAMOS system must have a return channel for control and command of the nodes.

This payload will be proposed for the next Norwegian NORSat mission. This mission will fly a micro satellite, possibly of the SFL NEMO class.

REFERENCES

[1] Norwegian University of Science and Technology, 2014. URL http://www.ntnu.edu/web/camos. Accessed January 2014.

[2] European Commission, HIGH REPRESENTATIVE OF THE EUROPEAN UNION FOR FOREIGN AFFAIRS AND SECURITY POLICY. Developing a European union policy towards the arctic region: progress since 2008 and next steps, June 2013. URL http://eeas.europa.eu/arctic_region/docs/swd_2012_183.pdf.

[3] Joseph C. Casas. Arctic region communications small satellites (arc-sat), Sep 2012. URL http://nix.nasa.gov/search.jsp?R=20120016896&qs=N%3D4294163423%2B4294957324%2B4294587540. Accessed November 2013.

[4] Roger Birkeland. An overview of existing and future satellite systems for arctic communication. In *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[5] ESA. ESA ARTES webpage, December 2011. URL http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=30581. Accessed November 2013.

[6] GEMINI. Safety in the north: Polar perils, October 2012. URL http://www.ntnu.no/gemini/2012_autumn/34-41.htm.

[7] Aalborg University. AAUSAT3, September 2014. URL http://www.space.aau.dk/aausat3/. Online.

[8] Almindeet.al. Gomx-1 flight experience and airtraffic monitoring results. In *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[9] Norwegian Space Centre. Norske satellitter, 2013. URL http://www.romsenter.no/Bruk-av-rommet/Norske-satellitter. Accessed Jan 2014.

[10] Delovski et.al. Ads-b over satellite the world's first ADS-B receiver in space. In *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[11] David Hayley et.al. Enabling technologies for a microsatellite-based global sensor network. In *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

A.3 Paper C

R. Birkeland and A. Hornig, "On how a CubeSat swarm can improve the coverage for an Arctic ground based sensor network," in *Proceedings of ESA Small Satellites Systems and Services 2016*, 2016.

The first results from small satellite swarm simulations from Chapter 4 are presented in this paper. The author's contribution is the main idea, simulations and writing most of the paper save for Section 1.2. The author presented the paper at the conference.

On how a CubeSat swarm can improve the coverage for an Arctic ground based sensor network

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Abstract

In recent years, CubeSats have evolved from mere toys and technology demonstrators into real tools for remote sensing, communications and other services. Since the satellites' lifetimes are short by design, they must constantly be replenished in order to maintain a continuous service. CubeSats are traditionally built with COTS components, which reduces the development time and hardware cost. This makes the satellites well suited for replenishment. CubeSats are often power- or data-throughput limited. It can therefore be beneficial to launch several CubeSats together. The desired service can then be based on a CubeSat swarm where the load is shared between the swarm members.

The CubeSats are generally launched without any station keeping capabilities, as it increases cost and complexity in the production phase and the operational phase. Without station keeping, the swarm satellites will drift relative to each other. This means that the level of coverage and service will change with time. The governing parameter of the drift is the relative velocity difference received at the time of deployment. This work focuses on a swarm of CubeSats with payloads providing a communication infrastructure for an Arctic sensor network. Central issues for the space- as well as the ground-segment are presented.

The space segment shows the properties related to deploying and operating a swarm of CubeSats in polar orbit, covering the high Arctic area. For the ground segment, fundamental operation aspects are discussed, as well as the degree of expected service improvement compared to using only one satellite or a well-designed constellation with station keeping. A key element of this mission scenario is the orbit determination of the drifting CubeSats. For this, solutions based on services like NORAD's CelesTrak and a Distributed Ground Station Network (DGSN) are discussed as possible solutions. All solutions are compared with respect to the requirements of availability of service, including scalability and load-sharing. The focus here will be on a dedicated service controlled and operated by the CubeSat mission itself and a crowd-sourced citizen science approach based on the "Internet of Things" (IoT).

1   Introduction and Background

In light of an increasing interest for the Arctic environment, with respect to for example mapping environmental changes, resource extraction, tourism and national sovereignty, there is an increasing need for various types of data from the Arctic area. Through the project Coastal and Maritime Operations and Systems (CAMOS) at the Norwegian University of Science and Technology (NTNU) topics on communication technologies and heterogeneous network operation are addressed. In this paper we aim to discuss how a constellation - more proper - a swarm of Cube-Sats can improve satellite coverage in the Arctic area. A CubeSat is a much used type of small satellites, with a base unit dimension of 10 x 10 x 10 cm^3. Up to 3 base units can be stacked on-top of each other to make up a 2U or 3U satellite.

Several parties, such as the European Union (EU) and European Space Agency (ESA) [2, 6] have identified a gap in the satellite communication services for the Arctic region, this is also discussed in [1]. It is limited or no service at all for broad-band services from satellites geostationary orbit (GEO) above 70-80° North. As for narrow band services, the only public available option that supports two-way communication is Iridium [10]. There are several projects aiming to bridge this gap in different ways, such as the Norwegian HEO broadband project [14, 18] or the satellite extension to the narrow band VHF Data Exchange System (VDES) [9], primarily intended for maritime communications and e-navigation aids.

Definition   *When we speak of a* `node` *in the CAMOS-context, we refer to a sensor node and a data-source in the CAMOS network.*

1.1   CubeSats in the CAMOS Proposal

The CAMOS project aims to bridge the gap by providing an integrated delay-tolerant network (DTN), capable of transporting data over several carriers; using the carriers that are available at any given point in time [15, 4].

As shown in Figure 1 one central component in the CAMOS network will be the satellite link. In order to provide a cheap and simple satellite service, the use of CubeSats[1] are explored.

CubeSats and other small satellites have become more popular during the past few years. The services they can provide, have grown from technology demonstrators into commercial applications. Examples of this is Planet Labs [12] global imaging service (CubeSats) and the AIS-service for Norwegian authorities (small satellite) [13]. The Planet labs satellites are also an example of CubeSats operating "together", in a swarm or constellation. The purpose of this paper is to outline some possibilities, and limitations, for a CubeSat swarm used in a communications system for the Arctic area.

1.2   Satellite Positioning and Tracking

Most CubeSats have to deal with several issues that have major influences on their operational orbits' parameters. One is the method in how they are injected into their orbit and the other is the lack of thruster controlled orbit maneuvering.

Depending on whether or not they are launched piggyback / secondary payload or by the Nanoracks catapult on board the ISS, the precision of the injection method varies. This can lead to several kilometers of difference in the semi-major axis and thus all Keplerian elements. For the inaugural phase, this unknown injection orbit can lead to several days of not being able to contact the CubeSat during the automatic booting phase. From the operational point of view, this can lead to mission critical difficulties. Furthermore, when the CubeSat is operational and under mission operation control, the long-term drift of orbit parameters need to be determined. This drift is due

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[1]The discussions in this paper are valid for other types of small satellites, as well.
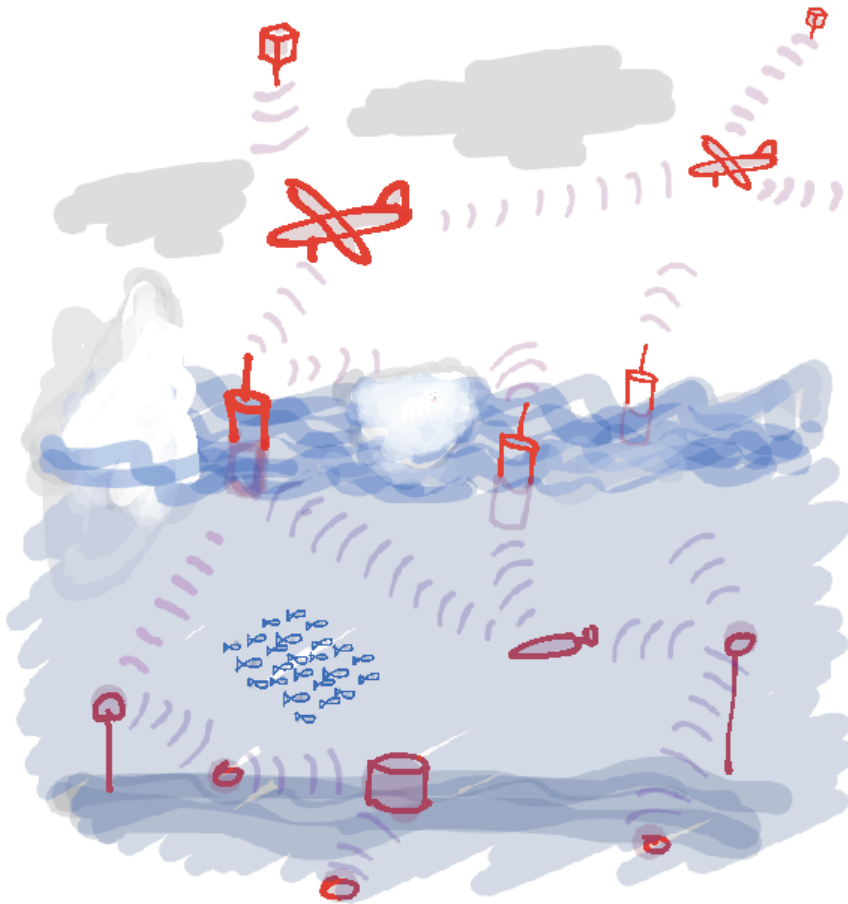
Figure 1: The CAMOS proposal. Credit: T. Ekman

to the fact of atomic and molecular atmosphere is inducing a drag on the CubeSat in typical Low Earth Orbits. This drag the leads to a change of orbit parameters. Knowledge about this, and the ability to adjust this is essential for CubeSat swarms in order to keep the form of the constellation.

The knowledge about orbit position is normally acquired by Two-Line Elements (TLE) [11] provided by NORAD, the North American Aerospace Defense Command in the USA. NORAD updates their TLE database every two weeks with all known satellites. For new satellites, this can lead for several days of waiting until the first TLE for this mission is publicly released. For the swarm constellation, it means that the precision information of the position within the swarm will decrease during those 14 days until the next update will provide the new data, which is within 100 meters of the real position. When several satellites are deployed close to each-other, identifying individual satellites within the cluster also takes time.

The proposed Distributed Ground Station Network (DGSN) [3] is meant as an addition to position data from NORAD. It will be its own tracking and control network for the CubeSat operator. It consists of a grid of ground stations trilatering the position of beacon signals or passive radar reflexions of satellites. The method is shown in Figure 2. The network consists of small ground station nodes equipped with Software Defined Radio hard- and software, a processing unit, simple antennas for several radio-frequency bands and an Internet connection.
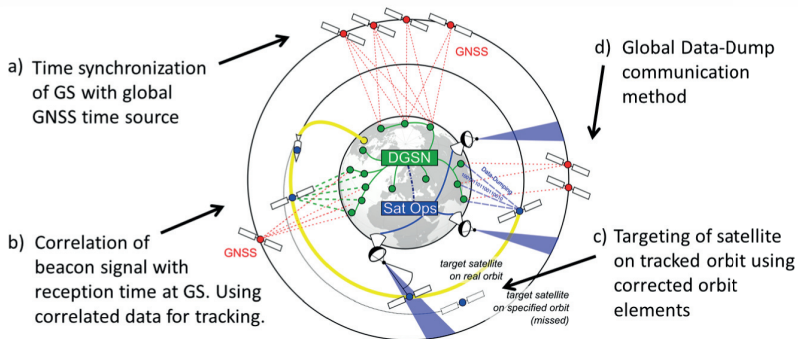
Figure 2: The DGSN infrastructure.

Definition *When we speak of a `node` in the DGSN-context, this is a station receiving a satellite signal and it is contributing to find the satellite's position. DGSN-station will be used.*

The DGSN-stations send the time-of-arrival information to the central server in the Internet where the position of the received signal is analysed and computed. It allows a permanent monitoring of the RF-bands and thus tracking of CubeSat. With this system, intermediate positioning can be achieved during the 14 days of NORAD's update cycle. The simulation analysis done in [3] showed, that positioning of CubeSat within a 1000 kilometer box can be achieved for typical LEOs.

Due to the small and simple approach of DGSN, the DGSN-stations can be placed on land, and in addition also placed on ships with an Internet connection for near real-time data-transfer, or with a regular data collection at harbors. This allows a finer grid in the northern areas where the infrastructure of existing satellite ground stations is limited, but the availability of cellphone towers is still high, like in the Scandinavian area. Furthermore there are ship routes in the Atlantic ocean and Arctic sea whose ships can be equipped with a DGSN station. This makes DGSN very interesting for an Arctic mission like the proposed mission.

2 CubeSat Swarms

Arguments for deploying a CubeSat swarm can range from adding redundant capacity to a flock of satellites such as the Planet Lab case (where some of the cheap satellites might fail, but service is maintained due to a high number of satellites) or in order to improve service quality by for example reduce coverage gaps. Another scenario can be the deployment of satellite clusters for communication, and for example link the smaller satellites to a larger "mother satellite" for downlink purpose. This scenario is discussed in [5]. However, none of these cases discusses how to deploy or control the swarm.

How to describe and evaluate the swarm from deployment until the operational phase is discussed for example discussed in a masters thesis from CalPoly [19].

2.1 Orbit Considerations

Free-flying satellites, such as CubeSats without any propulsion system, should not be called a constellation, but rather a freely drifting swarm. The CubeSats, if deployed from a common launch, will likely be released in arbitrary directions due to for example 3rd stage spin and arbitrary placement of the deployment pods on the upper stage. This will give them slightly different velocity leading to different orbit parameters, and therefore cause them to drift relative to each other. The spacing between the satellites will change over time. Therefore, we cannot rely on a uniform distribution to decrease coverage gaps. Every sensor-node will be covered more frequently, but the gaps will not be uniformly reduced. This means that a gap duration comparable to that of a single satellite will occur once in a while, and over periods of consecutive days or weeks. The satellites motion is predictable over a moderate period of time so the network utilization can be planned and scheduled according to the current coverage pattern.

2.2 Orbit Perturbations

The satellites will experience drag due to the very thin, but still present, remaining atmosphere in LEO. This drag will reduce the velocity and inevitably bring the satellite back to Earth if the orbit is low enough. This drag is a function of the satellite's mass/weight ratio, sun activity, orbit, angle-of-attack and other parameters. In order to let the drag be of little importance with respect to how the constellation is developing, all satellites in the swarm should be of the same make and size in order to experience similar drag.

2.3 Controlling the Swarm

Even if the size of the CubeSats is quite limited, leading to limited power and volume, for example for thrusters, there are emerging technologies that can provide propulsion for CubeSats. There are a few ways we can imagine to control the swarm:

Define/control deployment times and/or directions   As the authors of [19] and [16] argue, one way to control the constellation buildup will be to control timing and direction when the satellites are deployed from their upper stage. If the satellites are deployed in the same angle relative to the main direction of motion, for example directly aft, the satellites will have very little relative velocity related to each other. The constellation can then be built up by precise control of the deployment time, for example in order to deploy a uniform constellation. The drawback is that this system has no feedback, so if for some reason, the timing was a bit wrong or if the satellites were deployed in an angle relative to the direction of motion, they will slowly start to drift and the constellation will break down. The time this takes will depend on the relative velocity. If the velocity difference is small, and the constellation breakdown will be slowly happening. If the planned lifetime of the system is short, this might not impact the service.

One-go Thruster   As an expansion of the above scenario, we can imagine that the satellites are either deployed at the best effort or in a closer cluster. Then a one-go thruster could be used for two purposes. For the first purpose, assuming the satellites are deployed in a close group, we can imagine the satellites being equipped with varying amount of ΔV in order to create a uncontrolled swarm as discussed in the examples in this paper. The second option could be to fire the one-go thruster to give the satellite a a precise ΔV in order to build up, or lock, the constellation. This will need careful measurements of the satellites orbit parameters.

The satellite tracking measurements must be precise in order to be useful. The measurements can be presented to the satellite operator on the form of TLEs [11] or other measurements from the operator's own ground terminal together with the proposed DGS-Network [3].

This approach increases the scan possibilities and thus leading to measurements that will be accessible on an early stage commissioning stage, in order to not waste satellite lifetime.

After the correct satellite relative positions are derived, the satellite thrusters can be fired in order to give them the zero relative velocity, and therefore lock in the constellation. This implies that the constellation is allowed to naturally drift into its full build-up first, before the satellites are moved.

Controllable and re-friable thruster   If the satellite lifetime is long, so long that the constellations created either by timely deployment or an one-go thruster will break down before end of satellite life, one can envision that the satellites are employed with thrusters that can be fired in an controllable manner several times, in order to re-shape the constellation if required. This is the most flexible, but also most expensive solution.

Both solutions involving a thruster will need a very capable Attitude Determination and Control System (ADCS), in order to control the direction of the thruster firing.

2.4   Managing the Swarm

If the satellites in the swarm are viewed upon as only individual satellites, and used as such, operation might be fairly easy. However, as the layout of the swarm is constantly changing, the network topology will also change. Depending on the number of satellites, load sharing and other smart techniques for better scheduling and resource allocation must be implemented. Management and operation of swarms, swarms-of-swarms and large constellations are important topics to address, due to the increasing number of small satellites (individual satellites could communicate across a swarm), swarms such as Planet Labs Doves and potential massive constellations for global connectivity. Allocation of radio frequencies will be an important and challenging issue. For individual CubeSats and small swarms, the paper [5] points at some issues and propose recommendations on how to for example ease frequency coordination and registration. In addition, the concept of communication between satellites within a swarm and across swarms is discussed. One solution could be to have larger satellites with station keeping capabilities[2] act as communication relays and gateways for the other satellites in the swarm, thus remove the need for all satellites to communicate directly to the ground. This concept is the "reverse" of a sensor network with a gateway node with a satellite link that other sensor in the network can relay data through. For our case, we would need all satellites in the swarm to be able to communicate directly with the sensor nodes, but perhaps the downlink data could be relayed through a "mother" satellite. This could also extend the downlink availability in some cases as the bigger satellite might be visible both from the ground station and the data collecting CubeSat, but the CubeSat might not be visible directly from the ground station.

By deploying satellites in a particular manner as discussed in [19] or by use of emerging technologies as micro thrusters, the free flying swarm can be better controlled and the possibility to have a more defined constellation exists. These topics are identified as some of the more interesting themes for further work within the CAMOS project.

Tracking of CubeSats is essential for swarms and their operations and management. To allow an adequate availability of their position and knowledge about their states, a combined approach of an operator controlled main terminal, the existing services like NORAD and new services like DGSN with Internet of Things capability should provide this. It is a cost optimizing strategy for a small mission like the proposed one and a starting point for further missions of the same organisation but also for further users. This can be achieved by synergistic effects and open standards. The proposed mission is a matching candidate for demonstrations.

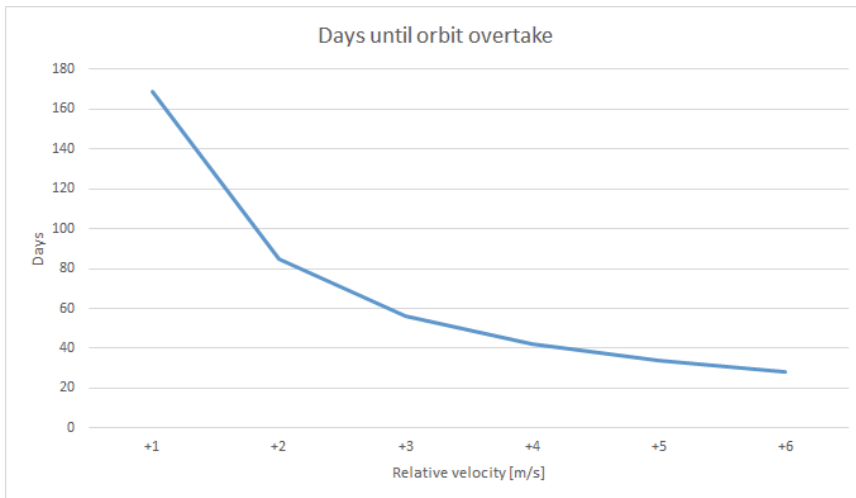[2]Station keeping is not mentioned nor assumed in [5].

Figure 3: Days until one satellite overtakes another vs. relative velocity

3 Example Cases of CubeSat Swarm Deployment

The following cases show examples on how deploying an uncontrolled swarm increases the coverage and level of service for an Arctic communication system. Simulations are performed for a single satellite as well as "swarms" of two, three and four satellites, and two locations, namely Longyearbyen, Svalbard and Trondheim, mainland Norway. The locations used in the simulations are selected to match area-of-interest of the CAMOS project. Longyearbyen is located so far north that all satellite passes of a polar orbiting satellite are visible. This is then compared with communication nodes placed further south, in Trondheim. The simulation shows how the "constellation" of satellites forms (evenly spread satellites), break downs (clustered satellites) and and re-shapes in a deterministic pattern. Modified TLE data[3] are used as input for the orbit propagator. The simulation is run over an extended period of time, so the validity of the TLEs are pushed. In addition, other orbit perturbations than a pre-defined drag parameter are not accounted for. The relative velocity between the satellites are set as an example value, realistic and achievable values must be derived in the future.

The parameter used to evaluate the level of service is the duration of the gap between two consecutive satellite passes.

The initial assumptions are that we can control the deployment from the pod[4] in a way that gives each CubeSat 3 m/s[5] exit speed at angles that give us 2 m/s relative velocity between the satellites as shown in Table 1. Since different velocities lead to different orbit heights due to Kepler's laws, the spacing between the satellites will vary over time. They will separate until they are fully separated by 180° , then they will cluster up until they overlap and the cycle will start over again. The time it takes for one satellite to overtake another as a function of relative velocity is shown in Figure 3. These numbers are representative for circular orbits with altitudes between 600 and 800 km.

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[3]The TLE-data used is AAUSat-3 with epoch 13 Feb 2014 12:35:42.657. The TLE source is STK [7].

[4]The box (or adepter) housing the satellites during launch is called a "pod". Different suppliers have slightly different specifications.

[5]This maybe a too high value, the expectations is between 1 m/s and 3 m/s, however 3 m/s is used as an example in this paper.

3.1 Simulation and Results

The simulation is using Python with `matplotlib` [8] and the `pyephem` library [17] for astronomical calculations. This shows that on average the gap time is greatly reduced, but we are not able to remove the tail of the gap distribution; the very long gaps will occur at some point. This is especially visible in the case of four satellites, as shown in Figure 4d. The figure shows the distribution of gaps between two passes for a sensor node at Longyearbyen from a swarm of four satellites at approximately 780 km altitude and 98 degrees inclination. The satellites have the initial values as shown in Table 1.

Table 1: Initial values for the satellite swarm simulation

Satellite	Velocity [m/s]	Altitude [km]	Period [min]	Periods/day
Sat1	7461	787.3	100.6	14.3
Sat2	7463	783.4	100.5	14.3
Sat3	7465	779.6	100.4	14.3
Sat4	7467	775.8	100.3	14.4

The base satellite (Sat1) is based upon the TLE of AAUSat-3 with epoch 2014/02/13, and the other satellites have their orbit-per-day value in the TLE adjusted. The simulation is run for a period over a few months. This means that we are pushing the validity of the TLEs, but it shows the general behavior. The used library takes drag into account while running the simulation.

3.2 The Swarm Seen from Longyearbyen

Figure 5 shows how the gap times varies along the simulation period. The figure shows the case for two satellites with 2 m/s relative velocity seen from Longyearbyen. At deployment, both satellites are near each other, and we only have long coverage gaps[6]. As time increases, we see that we will have interchangeably long and short gaps (area A in the figure) until the satellites are separated by 180° and we have the best utilization of our two satellites, as indicated by C. Area B indicates the period where we only have long (and negative) gaps. The cycle starts over after around 60 days (3500 passes / 14 passes/satellite/day / 4 satellites)

The three other cases produce similar results. If we only have two satellites, but increase the relative velocity to 6 m/s, we get three times as many periods of long gaps, but then their duration will be shorter. This might be an advantage and help network utilization planning. In the case of three and four satellites, the periods of long gaps are comparable to the first two-satellite case, but the average gap time in the "good" periods are shorter.

Figure 4 shows the gap distribution for the Longyearbyen case. As seen from the figure, we get a wide range of coverage gap durations. For one satellite, the gaps would last for about 80 to 90 minutes. For two satellites, the distribution is near uniform, with approximately 50% of the gaps lasting longer than 40 minutes. We clearly see that, that adding a third satellite will change the gap distribution so that only around 20% of the gaps having a duration of more than 40 minutes. Adding a forth satellite changes this to 16% of the gaps having a duration of more than 40 minutes.

When the satellites coverage areas are overlapping, a long gap will be followed by a short (negative gap), meaning that the sensor node could potentially see more than one satellite at the

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[6]Since the ground node can see both satellites at the same time, we have a "negative" pass also (the time between AOS for the second satellite and LOS for the first satellite). All the negative passes are removed from the simulations since they do not provide any real improvement of service. This minimum time between two passes could have been further increased in order to only include usable passes in the simulations.

time. In these simulations, overlapping passes are removed and all "negative gaps" are left out of the calculations.
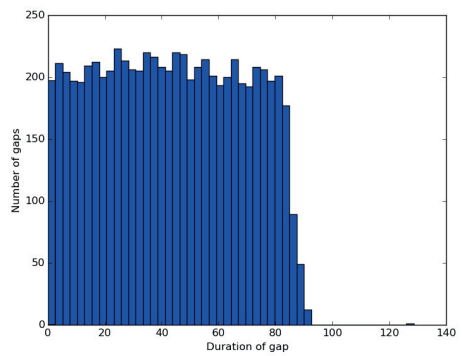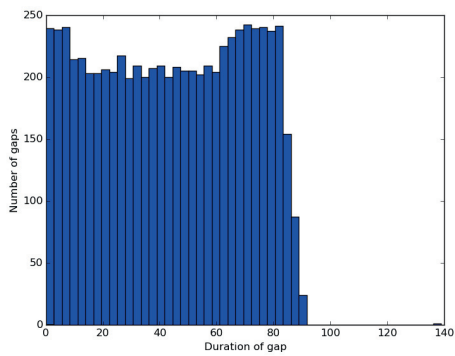
(a) Coverage gap distribution for two satellites seen from Longyearbyen. 2 m/s relative velocity.
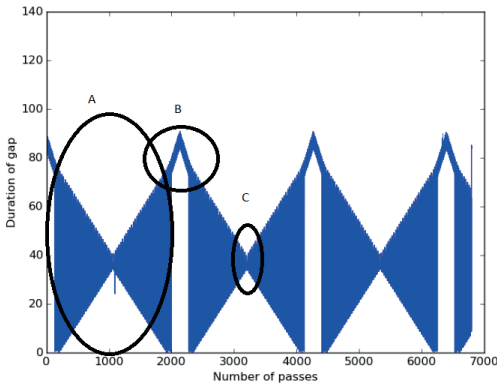

(b) Coverage gap distribution for two satellites seen from Longyearbyen. 6 m/s relative velocity.
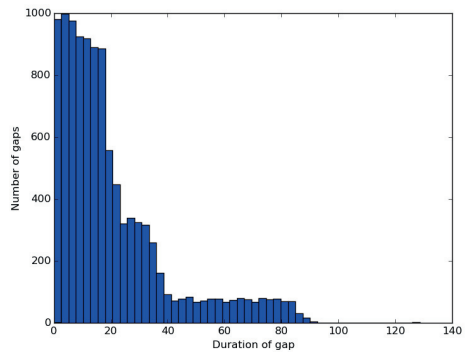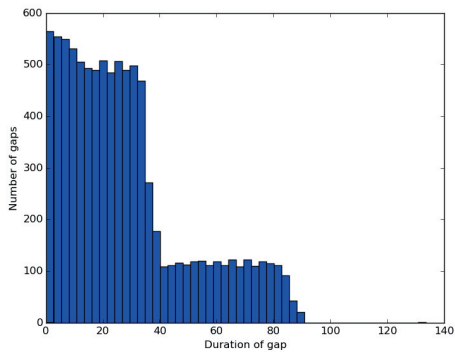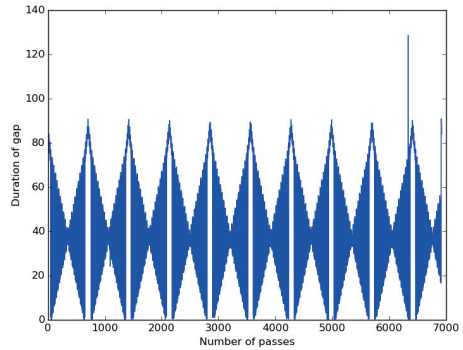

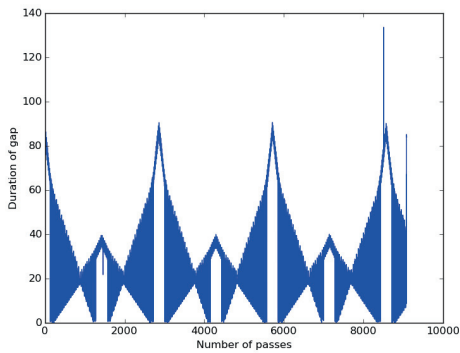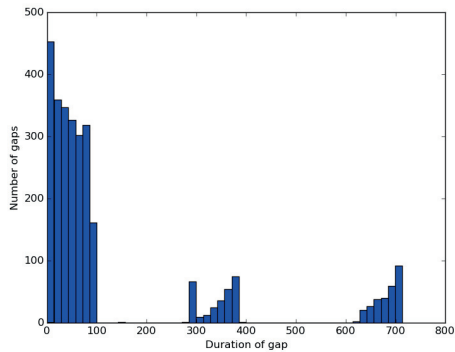**(c)** Coverage gap distribution for three satellites seen from Longyearbyen. 2 m/s, 4 m/s relative velocity.

(d) Coverage gap distribution for four satellites seen from Longyearbyen. 2 m/s, 4 m/s, 6 m/s relative velocity.

Figure 4: Gap distributions seen from Longyearbyen.

(a) Constellation development for two satellites seen from Longyearbyen. 2 m/s relative velocity.

(b) Constellation development for two satellites seen from Longyearbyen. 6 m/s relative velocity.

(c) Constellation development for three satellites seen from Longyearbyen. 2 m/s, 4 m/s relative velocity.
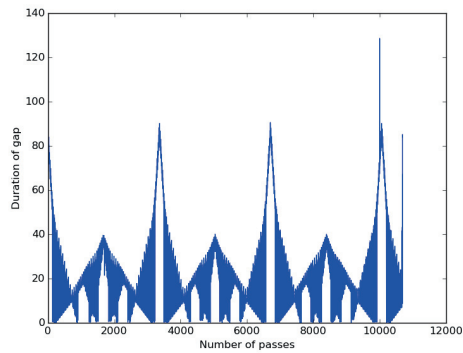
(d) Constellation development for four satellites seen from Longyearbyen. 2 m/s, 4 m/s, 6 m/s relative velocity.

Figure 5: Constellation development seen from Longyearbyen.

3.3 The Swarm Seen from Trondheim

In Figure 6 the distributions of coverage gaps are shown for the same constellation (two cases with two satellites, three and four satellites). From the figures it is seen that changing the relative velocity between the two satellites does not change the distribution, but obviously the timing of when the two satellites are visible will change.

Due to the fact that the satellites are deployed in only one plane, there will be several orbits where the satellites are not visible from Trondheim, hence the periods of very long gaps (300-400 minutes and 600-700 minutes). Adding more satellites to the constellation does not help this situation, it will only compress the mean gap time when the orbit plane is oriented so the satellites are seen from the ground station. Therefore, we can state that adding more satellites to a single plane will not improve the coverage situation to the same degree as for the northern case.
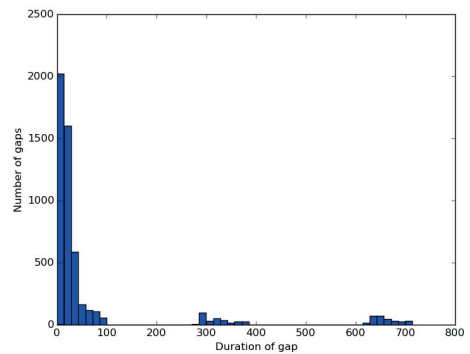
(a) Coverage gap distribution for two satellites seen from Trondheim. 2 m/s relative velocity.
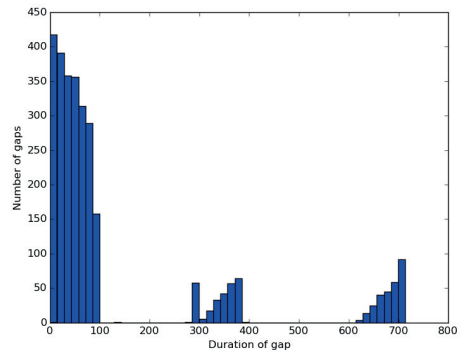
(b) Coverage gap distribution for two satellites seen from Trondheim. 6 m/s relative velocity.
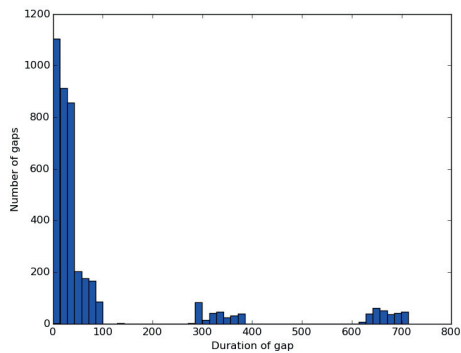
(c) Coverage gap distribution for three satellites seen from Trondheim. 2 m/s, 4 m/s relative velocity.

(d) Coverage gap distribution for four satellites seen from Trondheim. 2 m/s, 4 m/s, 6 m/s relative velocity.

Figure 6: Gap distributions seen from Trondheim.

4 Conclusion

Deploying an uncontrolled swarm of satellites in the same plane will increase the level of service for a network such as CAMOS if the nodes are located so far north that all passes are observed. However, the shape of the constellation will have a cyclic behaviour, and when the constellation breaks down, i.e. the satellites' coverage areas are overlapping, long gaps will occur for several days in sequence.

In the case presented, it is shown that adding a third satellite will change the gap distribution from approximately 50% of the gaps having a duration of more than 40 minutes to that around 20% of the gaps having a duration of more than 40 minutes. Adding a forth satellite changes this to 16% of the gaps having a duration of more than 40 minutes.

If the node cannot see all passes, such as in the Trondheim case, there will still be a lot of long gaps, and the duration of the gap periods will vary greatly. Adding more satellite planes will improve this situation, but that is more costly.

Such a system will also greatly benefit from more rapid updated position data from for example a ground station network as DGSN. This will be even more important if the swarm is to be controlled and managed.

Acknowledgements

References

[1] Roger Birkeland. An overview of existing and future satellite systems for arctic communication. In *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[2] ESA. ESA ARTES webpage, December 2011. URL \http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=30581. Accessed November 2013.

[3] Andreas Hornig et.al. From ground to space: prototype development and evaluation of the tracking system for small satellites with the Distributed Ground Station Network. In *Proceedings of the 65th International Astronautical Congress*, Proceedings of the 65th International Astronautical Congress. International Astronautical Federation, IAF, 2014.

[4] Artur Zolich et.al. A multi-hop intermittent wireless sensor network with unmanned aerial vehicles and satellite links for the arctic. Presentation at ReCAMP Flagship Workshop, 5 – 6 April 2016, Tromsø, Norway, 2016. Abstract available at: http://www.asuf.no/wp-content/uploads/2016/03/ReCAMP2016_AbstractsBook.pdf.

[5] Ozan Kara et.al. Communication Architecture and International Policy Recommentations Enabling the Development of Global CubeSat Space Networks. In *Proceedings of the 66th International Astronautical Congress*, Proceedings of the 66th International Astronautical Congress. International Astronautical Federation, IAF, 2015.

[6] GEMINI. Safety in the north: Polar perils, October 2012. URL http://www.ntnu.no/gemini/2012_autumn/34-41.htm.

[7] Analytical Graphics. Stk. Online, 2016. URL http://www.agi.com/products/stk/. Accessed April 2016.

[8] J. D. Hunter. Matplotlib: A 2d graphics environment. *Computing In Science & Engineering*, 9(3): 90–95, 2007.

[9] International Association of Marine Aids to Navigation and Lighthouse Authorities. Iala proposals for itu-r m vdes, May 2015.

[10] Iridium Communications Inc. Iridium communications, 2014. URL https://iridium.com/ProductList.aspx?productCategoryID=9. Accessed 15.12.2014.

[11] Dr. T.S. Kelso. Frequently asked questions: Two-line element set format, 1998. Available at https://celestrak.com/columns/v04n03/.

[12] Planet Labs. Planet labs webpage. online, 2016. URL www.planet.com. Accessed April 2016.

[13] Norwegian Space Centre. Norske satellitter, 2013. URL http://www.romsenter.no/Bruk-av-rommet/Norske-satellitter. Accessed Jan 2014.

[14] Norwegian Space Centre. Satkom i arktis (ask). Online, 2015. URL http://www.romsenter.no/Fagomraader/Satellittkommunikasjon/Satkom-i-Arktis-ASK. Accessed June 2015.

[15] Norwegian University of Science and Technology. Camos webpage, 2014. URL http://www.ntnu.edu/ime/camos/. Accessed November 2015.

[16] Jordi Puig-Suari, Guy Zohar, and Kyle Leveque. Deployment of CubeSat Constellations Utilizing Current Launch Oppertunities. In *27th Annual AIAA/USU Conference on Small Satellites*, 2013.

[17] Brandon Rhodes. Pyephem home page, 2015. URL http://rhodesmill.org/pyephem/. Accessed October 2015.

[18] SINTEF. Getting broadband in the arctic, June 2013. URL http://www.sintef.no/home/Press-Room/Research-News/Getting-broadband-in-the-Arctic/.

[19] Guy G. Zohar. Ad-hoc regional coverage constellations of cubesats using secondary launches. Master's thesis, Faculty of California Polytechnic State University, San Luis Obispo, 2013.

A.4   Paper D

R. Birkeland, "Freely drifting CubeSat constellations for improving coverage for arctic sensor networks," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

This paper resulted from the work presented in Chapter 4. The author presented the paper at the conference.

Freely Drifting CubeSat Constellations for Improving Coverage for Arctic Sensor Networks

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Abstract—In recent years, the interest for the Arctic area has been increasing. Harvesting of scientific data and environmental monitoring are key activities. The Arctic has poor communication infrastructure, both by terrestrial and satellite systems. Launching a free-flying constellation of small Cube-Sats is one proposal to help mitigate this service gap. CubeSats are traditionally built with industrial-grade components, which reduces the development time and hardware cost. Since the cost of one satellite is low, it is possible to launch several together. The CubeSats are generally launched without any station keeping capabilities, as this increases cost and complexity in both the production and operational phase. Without station keeping, the swarm satellites will drift relatively to each other. The governing parameter of the drift is the velocity difference of the satellites at the time of deployment. This paper shows how a freely drifting swarm can improve the coverage for sensor networks in the Arctic, when an effort is made to optimize this velocity difference at deployment. E.g., a free-flying constellation of three satellites will have better coverage properties than a fixed two-satellite constellation for more than 80% of the time.

1. Introduction and Background

In light of an increasing interest for the Arctic environment, with respect to mapping environmental changes, resource extraction, tourism and national sovereignty, there is an increasing need for various types of data from the Arctic area. Several parties, such as the European Union (EU) and European Space Agency (ESA) have identified a gap in the satellite communication services for the Arctic region[1]. Broad-band services from satellites in geostationary orbit (GEO) above 70-80° North are limited or non-existing. As for narrow band services, the only public available option that supports two-way communication is Iridium.

There are ongoing projects aiming to bridge this gap in different ways [1, 8], such as several newly proposed LEO- and HEO-constellations, as well as the satellite extension to the narrow band VHF Data Exchange System (VDES), primarily intended for maritime communications and e-navigation aids.

Research on satellite communication technologies and heterogeneous network operation are addressed in several activities at the Norwegian University of Science and Technology (NTNU) [1, 14]. In this paper we aim to discuss how a constellation - more proper - a swarm of CubeSats or other small satellites can improve satellite coverage for sensor networks in the Arctic area.
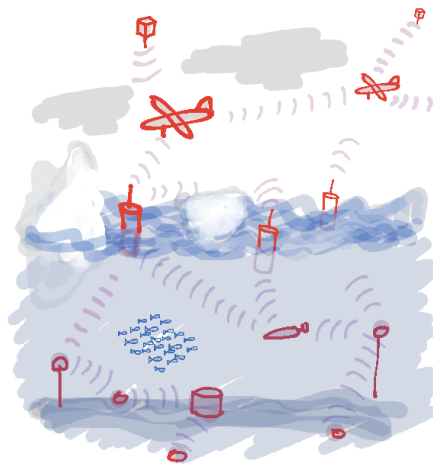

Figure 1: An artist's view of a heterogeneous network consisting of multiple nodes and platforms, communicating over various available network technologies. Courtesy of Torbjörn Ekman.

The premise for this paper is that we envision a set of environmental sensor buoys deployed in the Arctic. In order to transfer data from the sensors in near real-time, a direct link between the sensor nodes and the satellites is desired. This link complements a heterogeneous communication network, as depicted in Figure 1. Temporary nodes such as Unmanned Aerial Vehicles (UAVs) can download larger amounts of data from the sensors when they are near the nodes. However, the satellite link will be usable several times a day, whereas the link from the UAV might only

be available in short intervals, with service gaps spanning weeks or months. Such a network can help bridge the above mentioned gap [13, 4].

Concrete use-cases including types of sensors, how much througput the system should support and a closer look at concrete technology choices, link studies and link budget are part of future research activities.

2. Small Satellite Swarms

In this section we will discuss how a swarm of satellites can be shaped and designed in order to achieve good coverage properties by reducing and adjusting the coverage gaps. In this context, all satellites in the swarm are in the same orbital plane. Arguments for deploying a small satellite swarm can range from adding redundant capacity to a flock of satellites such as the camera satellites by Planet (where some of the cheap satellites might fail, but service is maintained due to a high number of satellites) or deployment of satellite clusters for communication, where the smaller satellites communicate with a larger "mother satellite" for downlink purposes. This scenario is discussed in [9]. None of these cases discuss how to deploy or control the swarm.

Guy Zohar proposed how to evaluate and describe the swarm from deployment until the operational phase in [17]. The term *clusterness* is introduced to describe the form of the constellation. This is a number describing how the satellites are separated.

$$Clusterness = \frac{||\sum(\theta_{max} - \theta_n)||}{(N-1)\theta_{max}}, n = [1...,N-1] \quad (1)$$

θ_N is the separation in true anomaly between two neighboring satellites (N and $N+1$), N is the number of satellites and θ_{max} is the ideal angular distance between N satellites, defined in [17] as $\theta_{max} = \frac{360}{N}$.

When the clusterness is 0, the satellites are evenly separated in the orbital plane, when the clusterness is 1, all satellites are in the same location. Clusterness is only a description of the swarm at a point in time. If the clusterness is calculated over time, we can plot the values and track the development of a swarm as it changes with time. In this paper however, it is the duration of the coverage gap that is chosen as the metric we are investigating.

2.1. Orbit Properties

Free-flying satellites, such as CubeSats without any propulsion system, should not be called a constellation, but rather a freely drifting swarm. The CubeSats, if deployed from a common launch vehicle, will likely be released in arbitrary directions due to 3rd stage spin and arbitrary placement of the deployment pods on the 3rd stage. This will give them slightly different velocity leading to different orbit parameters, and therefore cause them to drift relatively to each other. Due to this, we will not be able to build a uniform distribution. One point on the Earth will be more frequently covered by using more than one satellite, but the

period between two contacts will vary. Due to the continuous drifting of the satellites, long coverage gaps will occur when the *clusterness* close to 1. Depending on the satellites' orbit periods, the time period with successive long gaps will vary. It might be desirable to design the swarm in such a manner so that this time period is as short as possible, or happens infrequently. Some examples are shown in Section 3.1. The satellites' motion is predictable over a moderate period [1] of time so the network utilization can be planned and scheduled according to the current coverage pattern.

In order to create a swarm distribution that helps reduce the gaps between contacts; both averaged over time, and also by limiting the time where the clusterness is near one, several alternatives for the satellites are explored in this paper.

2.2. Orbit Perturbations

All satellites will experience a set of forces causing orbit perturbations. Perturbations are caused by various forces, such as gravitational pull from 3rd bodies and due to the non-spherical earth [10, Chapter 6.2]. For satellites in LEO below 800 km, atmospheric drag will be the dominant force that affects the kinetic energy, and therefore affects true anomaly and orbit height [10, Chapter 6.2.4]. Other perturbation effects will change other orbit parameters rather than the mean anomaly. These effects can actively be used in order to design special orbits, such as Molyna-orbits with zero perigee (ω) drift and sun-synchronous orbits where the drift of the ascending node (RAAN, Ω) is matched to the Earth's movement around the sun in order to keep the angle between the sun and the orbital plane fixed.

For the case studied here, we assume all satellites in one swarm being launched in one operation, therefore they will, on average, experience the same perturbations affecting node and perigee drift.

The drag experienced by the satellites will reduce the orbit height and inevitably bring the satellite back to Earth as the orbit height reduces. This drag is a function of the satellite's mass/volume ratio, sun activity, orbit, angle-of-attack and other parameters. In order to let the drag be of little importance with respect to how the constellation is developing, all satellites in the swarm should be of the same form and size in order to experience similar drag.

Solar radiation will also affect the satellite's orbit, in two ways. First, the solar radiation pressure will assert a force on the satellite itself, in most cases this effect is negligible, if the satellite has a small surface [11, p. 71]. The variation in solar radiation due to the sun cycle will have a greater indirect effect; high solar radiation will cause the atmosphere to expand, hence the drag will increase.

2.3. Deploying the Swarm

In this scenario, we envision a number of similar satellites deployed from the same launcher, into the *same orbital*

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1. By use of Two-line Elements (TLEs) and a common propagator.

plane. They will be deployed with slightly different orbit period, due to a relative velocity change given when deployed from the launcher 3rd stage.

As the authors of [17] and [15] argue, one way to control the constellation buildup will be to control timing and direction when the satellites are deployed from their upper stage. If the satellites are deployed with the same angle relative to the main direction of motion, for example directly aft, the satellites will have very little relative velocity related to each other. The constellation can then be built up by precise control of the deployment time, in order to deploy a uniform constellation. The drawback is that this system has no feedback, so if for some reason, the timing was a bit wrong or if the satellites were deployed in an angle relative to the direction of motion, they will slowly start to drift and the constellation will break down. The time this takes will depend on the relative velocity. If the velocity difference is small (for example less than 1 m/s), the constellation breakdown will take several months. If the planned lifetime of the system is short, this might not impact the service. If the expected system lifetime is longer, the duration with degraded service will also be long, and the service might be heavily degraded.

2.4. Managing and Using the Swarm

If the satellites in the swarm are used as individual satellites, operation might be fairly easy. However, as the layout of the swarm is constantly changing, the network topology will also change. Depending on the number of satellites, load sharing and other smart techniques for better scheduling and resource allocation should be implemented in order to get the most capacity from the swarm at all times.

Management and operation of swarms, swarms-of-swarms and large constellations are important topics to address. There is an increasing number of small satellites (individual satellites could communicate across a swarm), swarms such as Planet Doves and potential massive constellations for global connectivity. Allocation of radio frequencies will be an important and challenging issue. For individual CubeSats and small swarms, the paper [9] points at some issues and proposes recommendations on how to for example ease frequency coordination and registration.

Tracking of CubeSats is essential for swarms and their operation and management. To allow an adequate availability of their position and knowledge about their states, a combined approach of an operator controlled main terminal, the existing services like NORAD and new services like DGSN [3, 6] with Internet of Things capability should provide this.

3. Simulations of Selected CubeSat Swarms Cases

The following cases show examples on how deploying an uncontrolled, or random constellation [12], increase the coverage and level of service for an Arctic communication system. The main case presented is a swarm of three satellites, compared to two satellites in a static constellation, where the two satellites are separated by 180°, meaning the coverage gaps are always approx. 20 minutes. The user is placed in the Arctic, namely Longyearbyen, Svalbard. This location is within the area of interest of the CAMOS project. Longyearbyen is located so far north so all satellite passes of a polar orbiting satellite are visible. The simulations show how the constellation of satellites develops and forms (evenly spread satellites, *clusterness* near 0), break downs (clustered satellites, *clusterness* near 1) and re-shapes in a deterministic pattern. Modified TLE data[2] are used as input for the orbit propagator. The simulation is run over an extended period of time, so the validity of the TLE is pushed. However, this will show the general behavior of the swarm. When planning a concrete mission, simulations with relevant orbit parameters for the given mission must be performed in order to validate/confirm initial plans.

The parameters used to evaluate the level of service are the duration of the gap between two consecutive satellite passes as well as a qualitative discussion on the gap distribution.

As discussed above, we assume that deployment direction (0-360°) as well as deployment velocities in the range of (0 ± 4m/s) can be controlled. In addition, the simulations give the same origin of all satellites. In order to estimate the relationship between relative velocity and orbit period, we can do some calculations based on the orbit equation and the following relationships [2]:

$$r = \frac{h^2}{\mu} \frac{1}{1 + e\ cos(\nu)}, \tag{2}$$

where r is the distance between the satellite and the center of the Earth, h is the relative orbit angular momentum per unit mass, μ is the Earth's gravitational parameter, e is the orbit eccentricity and ν is the true anomaly.

$$e = \frac{r_{apogee} - r_{perigee}}{r_{apogee} + r_{perigee}}, \tag{3}$$

where $r_{perigee}$ and r_{apogee} is the orbital radius at perigee and apogee, respectively.

The relationship between the orbital velocity v and h can be written:

$$v = \frac{h}{r}. \tag{4}$$

By using the equations above, knowledge about the initial apogee and perigee heights as well as the know Earth's radius, we can deduce the orbits' semi-major axis a, and finally find the orbit period T:

$$T = \frac{2\pi}{\sqrt{\mu} a^{\frac{3}{2}}} \tag{5}$$

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2. The TLE-data used is AAUSat-3 with epoch 13 Feb 2014 12:35:42.657. The TLE is retrieved by use of Systems Toolkit (STK) [5].

Table 1 shows an example of orbit periods as a function of relative velocity at deployment. Satellite 5 is based on the TLE of AAUSat-3.

Table 1: Orbit period as function of ΔV. Perigee for all satellites is 768 km.

Sat#	ΔV [m/s]	Apogee [km]	Eccentricity	Period [s]
1	- 4 m/s	771.83	0.00026781	6014.23
2	- 3 m/s	775.66	0.00053565	6016.65
3	- 2 m/s	779.49	0.00080353	6019.07
4	- 1 m/s	783.33	0.00107144	6021.49
5	0 m/s	787.17	0.00133939	6023.92
6	+ 1 m/s	791.01	0.00160738	6026.34
7	+ 2 m/s	794.85	0.00187540	6028.77
8	+ 3 m/s	798.70	0.00214346	6031.20
9	+ 4 m/s	802.55	0.00241155	6033.63

As observed from the Table 1, over a small range of ΔV, the relationship between orbit period and ΔV is nearly linear. At this orbit height, a velocity increase of 1 m/s will extend the orbit period with ≈ 2.4 s. The difference in orbit period between the fastest and the slowest considered satellites is 19.4 s.

3.1. Simulations and Evaluation Methodology

The simulation is using Python with the `pyephem` library [16] for astronomical calculations and `matplotlib` [7] for plotting. `pyephem` takes drag into account while running the simulation.

The location of the user on ground near Longyearbyen, Svalbard at 78° 13" 23' N, 15° 37' 36' E (local horizon is not taken into account). The satellites are modified versions of the TLE for AAUSat-3 with epoch 2014-02-13.

All sets of period differences between the nine satellites in Table 1 were run, and a selection of four interesting cases is selected and presented.

Below are the assumptions made for the orbit calculations and simulations:

- Assume the launcher's 3rd-stage is in circular orbit
- The ΔV is given solely by varying deployment directions (along the velocity vector or in opposite direction) as well as the tension of the springs or similar mechanisms of the CubeSat deployers. Assuming $\pm \approx 4$ m/s is physically feasible.
- The new orbit period is found by simple calculations similar to an orbit maneuver (as an Hohmann-transfer without the final burn).
- The simulations are based on the TLE of AAUSat-3, and then the parameters *orbits per day* and *e* of the satellite object in `pyephem` are changed accordingly.
- The simulations show when the satellite is visible from the ground node. A minimum elevation angle of 5° is defined to be required. This implies that the ground node is placed on a plateau with no obstructions in the horizon. A higher elevation might be needed in practice to assure a good communication link.

- Assuming all satellites are deployed from the same launch, in the same plane.
- Since all satellites are in one plane only, it is fundamental for the analysis that the users are able to see all passes of each satellite. If this is not the case, there will be long gaps due to the fact that the user cannot see any of the satellite in the given plane, for a duration of more than 3 orbits, depending on latitude.
- When two (or more) satellites have overlapping footprints, the pass duration will be adjusted for the overlap. So the total pass duration will assume use of one, and only one, satellite at the time. The gap between passes is then defined to be 0.

3.2. Obtained Results

By varying the combinations of the three selected satellites, different gap distributions are found. Some of the interesting results are presented in this section. This information can be used on how to design a satellite swarm, with a desired set of properties. In this paper, the best result is the one where most of the gaps are shorter than 35 minutes.

Figure 2 shows how the constellation develops over time for the worst-case – where the distribution of long gaps is the greatest. Figure 3 shows a better case and Figures 4 and 5 show two of the best cases. As seen, the gaps vary from 0 to around 90 minutes, and the shape of the constellation development is quite different for the four cases.

Table 2: Selected simulation results

Satellites	Gaps < 35 min	Gaps < 20 min	Gaps < 10 min
Case 1: 1, 2, 4	70.8 %	59.0 %	44.8 %
Case 2: 1, 3, 9	75.1 %	55.1 %	44.0 %
Case 3: 1, 5, 9	80.6 %	55.7 %	39.8 %
Case 4: 1, 4, 7	80.1 %	56.2 %	39.9 %

Table 2 lists some results for the four cases. The table and the figures can be used in order to assess which of the three cases suits a given mission best. If the mission is for communication, as our case is, it is probably beneficial to choose Case 3, for two reasons: This case has, overall, more gaps shorter than 35 minutes, compared to the other cases. In addition, the duration of the period with long gaps is shorter, but occurs more often. The main drawback with Case 1 is that it has a long period in the middle of the simulation period with fairly long gaps. It is also important to note that when in a duration with long gaps, a long gap is followed by a short one (or overlapping pass).

When comparing Case 3 and Case 4, which presents similar statistics wrt. the percentage of long gaps, we can see from Figures 4 and 5 that the main difference is that Case 4 has fewer durations with long gaps, but they last longer. In addition, since the relative velocity between satellite 1 and 7 is less than satellite 1 and 9, Case 4 might be easier to practically achieve.

Figure 6 shows the histogram of gap distributions for Case 3. Since all the overlapping gaps are given the value

of '0', they stand out. The most important point to be made here, is that the vast majority of the gaps, in all cases more than 70%, is shorter than the expected gap between two satellites in an ideal, static constellation.
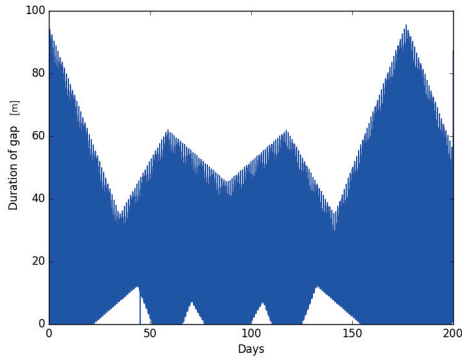

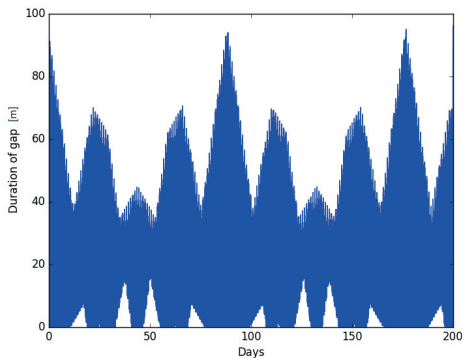Figure 2: Case 1: Largest periods of gaps

Figure 3: Case 2: Medium good distribution of gaps

Figure 4: Case 3: Best distribution of gaps

Figure 5: Case 4: Good distribution of gaps

This shows that instead of launching two satellites in a static constellation, three satellites can be used, and minimum 70% of the gaps will be shorter than what a gap between two fixed satellites is.

In order to deploy a fixed constellation, propulsion will be required. The minimum requirement is enough propulsion to lock the constellation after deployment. The best case will be to have a re-fireable thruster so active station keeping can be maintained. Even if this station keeping does not have to be very accurate for a small satellite, it will heavily influence the cost and complexity of the mission. A propulsion system must be included for each satellite, this will lead to stricter requirements for the Attitude Determination and Control System (ADCS) as well. In addition, the operation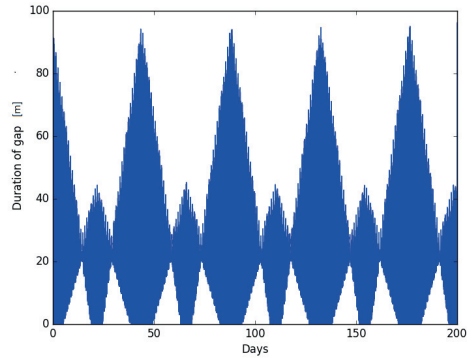 cost and complexity will increase. In sum, this will lead to an increased cost wrt. volume, power and subsystem requirements, and direct costs.
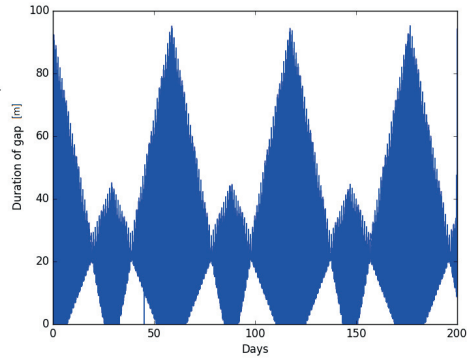
Adding one extra satellite to the swarm (in this example three instead of two) is also costly. Since the satellites can be launched without on-board propulsion, they might be smaller, such as CubeSats. Possibly, the ADCS-system can be made much simpler, and even perhaps removed if the rest of the mission does not require any pointing accuracy.

The satellite orbits are predicable, at least over a modest period of time, it is possible to plan the usage of satellites accordingly. When gaps are overlapping, the user(s) will have longer continuous satellite access (implies handover to next satellite).

One final point to be made is that for small and "cheap" satellites, such as CubeSats, being able to add one more satellite to the mission increases the chance of mission success. If one of three satellites fail, the mission will still be better off than if only one satellite is operational.
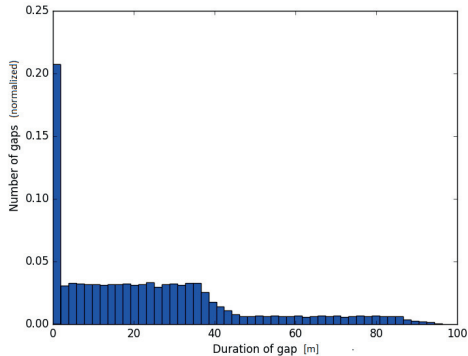
Figure 6: Gap distribution histogram for Case 3

4. Conclusion

By deploying an uncontrolled swarm, consisting of satellites in only one plane, the level of service for a sensor network will be increased when compared to the level of service provided by one or two satellites in fixed orbits and positions. In order to benefit from satellites in one plane, the ground nodes must be placed far enough north to be able to see all passes from all satellites. If this is not the case, there will be very long gap durations when all satellites in the plane are out of view from the ground node.

Due to the cyclic behavior of the constellation shape/reshape, coverage gaps with duration of the order of one orbit will occur when the satellites in the constellation are overlapping. This situation will last for days or weeks, depending on the properties of the swarm. This can be optimized when designing the swarm. A case with a swarm of three satellites has been presented, and it is shown that in this case, 70 - 80 % of the gaps are shorter than the expected gap from a two-satellite constellation. In addition to adding more redundancy and capacity to the system, this helps increase the level of coverage without the need for complex on-board spacecraft systems, such as thrusters and high-yield ADCS.

Acknowledgments

References

[1] Roger Birkeland. An overview of existing and future satellite systems for arctic communication. In *Proceedings of ESA Small Satellites Systems and Services 2014*, 2014.

[2] Howard D. Curtis. *Orbital Mechanics for Engineering Students*. Elsevier, 2005.

[3] Andreas Hornig et.al. From ground to space: prototype development and evaluation of the tracking system for small satellites with the Distributed Ground Station Network. In *Proceedings of the 65th International Astronautical Congress*, Proceedings of the 65th International Astronautical Congress. International Astronautical Federation, IAF, 2014.

[4] Artur Zolich et.al. A multi-hop intermittent wireless sensor network with unmanned aerial vehicles and satellite links for the arctic. Presentation at ReCAMP Flagship Workshop, 5 - 6 April 2016, Tromsø, Norway, 2016. Abstract available at: http://www.asuf.no/wp-content/uploads/2016/03/ReCAMP2016_AbstractsBook.pdf.

[5] Analytical Graphics. Stk. Online, 2016. URL http://www.agi.com/products/stk/. Accessed April 2016.

[6] Andreas Hornig and Dieter Fritsch. New space operations in the internet of things era - anywhere, anytime, anything! In *Proceedings of the 66 th International Astronautical Congress*, 2016.

[7] J. D. Hunter. Matplotlib: A 2d graphics environment. *Computing In Science & Engineering*, 9(3):90–95, 2007.

[8] International Association of Marine Aids to Navigation and Lighthouse Authorities. Iala proposals for itu-r m vdes, May 2015.

[9] *Communication Architecture and International Policy Recommentations Enabling the Development of Global CubeSat Space Networks*, Proceedings of the 66th International Astronautical Congress, 2015. International Astronautical Federation, IAF.

[10] James R. Wertz and Wiley J. Larson, editor. *Space Mission Analysis and Design*. Microcosm Press and Springer, third edition, 1999.

[11] G. Maral and M. Bousquet. *Satellite Communication Systems*. Wiley, 5th edition, 2009.

[12] Gérard Maral, Jean-Jacques de Ridder, Barry G. Evans, and Madhavendra Richharia. Low earth orbit satellite systems for communications. *International Journal of Satellite Communications*, 9(4): 209–225, 1991. ISSN 1099-1247. doi: 10.1002/sat.4600090403. URL http://dx.doi.org/10.1002/sat.4600090403.

[13] Norwegian University of Science and Technology. Camos webpage, 2014. URL http://www.ntnu.edu/ime/camos/. Accessed November 2015.

[14] David Palma. Software-defined Intermittent Networking - Reference Scenario and Requirements Definition. Online, October 2016. URL https://sinet.item.ntnu.no/wp-content/uploads/2016/10/D11_Scenario_SINet.pdf. H2020 grant number 699924.

[15] Jordi Puig-Suari, Guy Zohar, and Kyle Leveque. Deployment of CubeSat Constellations Utilizing Current Launch Oppertunities. In *27th Annual AIAA/USU Conference on Small Satellites*, 2013.

[16] Brandon Rhodes. Pyephem home page, 2015. URL http://rhodesmill.org/pyephem/. Accessed October 2015.

[17] Guy G. Zohar. Ad-hoc regional coverage constellations of cubesats using secondary launches. Master's thesis, Faculty of California Polytechnic State University, San Luis Obispo, 2013.

A.5   Paper E

R. Birkeland, D. Palma, and A. Zolich, "Integrated smallsats and unmanned vehicles for networking in remote locations," in *Proceedings of The 68th International Astronautical Congress*, 2017.

This paper resulted from work presented in Section 3.1. The paper is common work, and the author's contribution is how to integrate the satellites and satellite swarms into the architecture. The author presented the paper at the conference.

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Integrated SmallSats and Unmanned Vehicles for Networking in Remote Locations

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Abstract

The lack of infrastructure in maritime and Arctic regions has a strong impact on many operations, such as the retrieval of scientific data. Nowadays, data logged during these operations must either be collected by manned missions or transmitted over existing satellite links. Unfortunately, both methods face challenges regarding availability, as well as energy and link budget constraints.

When considering the throughput of existing satellite links, the effective amount of data that can be transmitted is limited by the links' throughput, periodicity and economic cost. Consequently, it is a common practice to visit research sites in order to manually collect data recorded over extensive time periods, usually spanning from several months to years. However, manual collection of research data, in particular in harsh maritime environments, poses a risk to crews and also incurs significant costs.

In order to overcome current communication limitations, the use of small satellites and unmanned vehicles for remote and in-situ sensing has been proposed by several authors. This is motivated by the growing availability of small satellite platforms as well as by the foreseen increase in launch availability, enabling the creation of novel dedicated small satellite missions. Constellations or swarms of small satellites, such as CubeSats, can work together with other unmanned vehicles and play a key role in integrated communication systems.

Unmanned vehicles can act as relay nodes or as data mules. The relay node can be used when a vehicle or small satellite is simultaneously in communication-range with research sites and supporting infrastructure, such as other relay nodes. Alternatively, data-mules may also cover regions outside the range of existing infrastructure and reach distant research sites where data is being gathered. In the area of destination, data-mules collect and store data, delivering in when returning to supporting infrastructure.

In this paper, we propose an integrated network, consisting of a combination of dedicated small satellite systems and unmanned vehicles to help in scientific data retrieval in remote locations. The main contribution consists in addressing the communication challenges of heterogeneous unmanned platforms and how they can support different scenarios and experiments. The proposed approach is defined and described in a testbed suitable for a selected set of maritime scenarios.

1 Introduction

Due to the lack of infrastructure in maritime and Arctic regions, operations such as retrieving scientific data become complicated and expensive. It is common that data from remote sensors must be collected by manned missions. To some extent, existing satellite links can be used. Either way there are challenges with respect to availability, energy and link capacity. The creation of an integrated heterogeneous system can help solve these problems. The solution will be an integrated network-of-networks, consisting of terrestrial links between sensor nodes, satellite links and links between sensors and unmanned vehicles (UVs). These communication technologies will not always be available since satellite links are intermittent and UV links may be available only during special data retrieval missions. At a given point in time, individual nodes in the network should utilize the available links best suited to transmit their data.

Maritime operations can be very diversified and lead to a multitude of distinct scenarios. For instance, both dense and sparse deployments of nodes for environmental monitoring may be required. This concerns not only research-oriented activities but also economical or safety operations. An example of a heterogeneous deployment is presented in Figure 1. This figure shows how nodes with different capabilities interact.

The contribution of this paper is to define a state-of-the-art architecture for networking and data exchange in remote locations. We propose cooperation of SmallSats and Unmanned Vehicles (Aerial, Surface, or Underwater) in order to make data retrieval processes more efficient and globally available. We assume that one mission will serve only one or a couple of end users. However, the presented architecture and suggested technologies make use of generic and standardized equipment and communication protocols *when possible.* This will ease integration with

other systems as well as deployment of similar systems and missions later on.

A reference scenario with multiple agents consists of monitoring/sensing nodes, unmanned vehicles, satellite nodes and ground stations (i.e. fixed or mobile stations capable of communication with UVs or satellites). One or more Command and Control (C&C) centres will also be part of this reference scenario, responsible for coordinating operations. This entity is not depicted in Figure 1 as it will likely be connected to existing infrastructure, communicating directly with ground stations.

Figure 1 shows one ground station that represents the edge of available communication infrastructure. In a deployed network, there will usually be several ground stations with various purposes adapted to the vehicle(s) they serve. These will be interconnected using the Internet and will provide a wireless link to the various nodes, for example satellites and UVs. Additionally, in order to reduce the access time of data from sensor nodes, the ground station placement should be tailored and adapted to the scenario. For satellite ground stations, they could be located at the edge of the observation area, e.g. one at the entering point and one of the exit point of the area along the satellite track.

Small satellites, also know as SmallSats, independently deployed or in swarms, are seen as a potential solution for improving communications in maritime environments, where infrastructure currently is lacking. The potential gain of using such swarms is further discussed in [1] and evaluated in [2]. Freely drifting swarms will allow for more frequent visits for nodes within a target area, but still with a limited coverage period and bandwidth. The mean time without coverage is a function of the number of satellites in the swarm.

UVs travelling in the vicinity of the sensor nodes can also be used to collect data, as well as to deliver configuration messages. This approach uses not only autonomous unmanned vehicles for planned visits to sensor nodes [3, 4], but includes also opportunistic interactions with other vehicles (e.g. transport ships) to increase connectivity. Even though unmanned vehicles may act as relay nodes, when sufficiently close to an infrastructure, their primary goal will be to act as data mules. As most maritime operations will likely take place in remote locations, visiting vehicles may have limited resources that constrain their operation, not being able to reach all the nodes in one area. In this case, multi-hop cooperation between the nodes will again be important to guarantee that all sensor nodes are reachable.

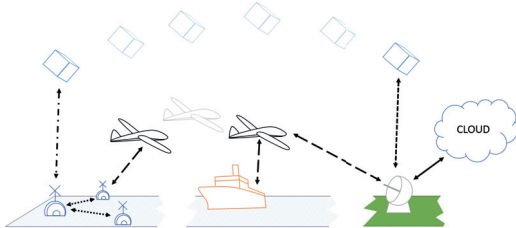This paper reviews state-of-the-art networking

Figure 1: Co-existence of heterogeneous communications and vehicles

technologies and existing unmanned vehicles for maritime operations in Section 2, followed by an identification of existing requirements for such operations (Section 3). Section 4 describes the proposed architecture integrating both SmallSats and Unmanned Vehicles, identifying the role of different nodes in a network, as well as the definition of a preliminary testbed. Finally, concluding thoughts are presented in Section 5.

2 Related Work

Studies on heterogeneous networks integrating terrestrial links and UAVs and/or satellite can be found in existing literature [5, 6, 7]. Typically, unmanned vehicles are used as data mules for sensor networks, being responsible for gathering sensing data and delivering it to supporting infrastructures [8, 3, 9, 10, 4]. Additionally, the use of small satellites and small satellite swarms as a feasible alternative for remote maritime operations has also been studied in the past [11, 1]. Aiming at investigating the performance of network protocols, sensor nodes, swarms of small satellites and corresponding ground stations, an emulation tool has also been proposed [2]. In [12], a comparison between emulation of a scenario and experimental results from a sea trail is presented. These research initiatives include the use of several technologies and various types of vehicles, respectively discussed in Sections 2.1 and 2.2.

2.1 Enabling Network Technologies

Past works have already addressed the challenges of communication and message transfer between nodes with marginal links, having proposed different protocols which are currently used by some systems. However, there is no standard solution integrating the communication between different vehicles in remote locations. Most of them are based on specific hardware and applications, many of them primarily consider messaging over point-to-point links, such as serial links and star networks where there is little need for "true" network protocols.

One example is the Goby Underwater Autonomy Project[1], which defines an autonomous architecture designed for marine robotics focusing on heterogeneous inter-vehicle communication. It was created as a replacement for MOOS [13], while also providing an interface to it. Goby is based on ZeroMQ[2] and supports serializing methods such as Google Proto-

col Buffers (Protobuf)[3] and Lightweight Communications and Marshalling (LCM) [14]. COSMOS[4] is another project that focuses on constrained scenarios, namely small satellites. It resorts to a network architecture that separates the space and ground segments, giving emphasis to space and employing the NACK-Oriented Reliable Multicast (NORM) Transport Protocol [15] and the LCM library. Similar to Goby or MOOS, the LSTS Toolchain [16], from the Underwater Systems and Technology Laboratory, also provides a suite of tools and protocols for autonomous vehicles, employing their own Inter-Module Communication (IMC) protocol.

Despite past efforts in integrating heterogeneous resource-constrained devices, the presented solutions are focused on very specialised environments. For instance, even when resorting to standardised protocols, there is no integration with Internet as we know it today. These proposed systems provide local networks that can be connected to the Internet, but not in a seamless way and disregarding other protocols and formats such as the Efficient XML Interchange (EXI) format[5].

Protocols such as as LCM and ZeroMQ will make use of any form of transport layer, be it a serial link or a TCP/IP like network. However, other solutions, such as NORM, rely on IP, which can be aligned with increasingly popular Internet of Things (IoT). Similarly, another popular solution for constrained environments and the IoT is the Constrained Application Protocol (CoAP), which provides its own link format [17]. It is designed for constrained nodes and networks, supporting secure connections as well as a number extensions such as HTTP mapping [18] and group communication [19]. Moreover, by taking into consideration the developments of the IPv6 over Networks of Resource-constrained Nodes (6lo) working group[6], it can provide optimisation which are ideal for interconnecting heterogeneous networks. In fact, the use of standardised protocols, such 6LoWPAN for interconnecting devices with different capabilities, can also provide a solution for issues such as address attribution [20].

When selecting the appropriate protocol stack for new systems, interoperability, standardization, user base, active use and development must also be considered, in addition to quantitative parameters as network efficiency, throughput, load capacity and so on.

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[1]http://gobysoft.org/
[2]http://www.zeromq.org/

[3]https://developers.google.com/protocol-buffers/
[4]http://cosmos-project.org
[5]https://www.w3.org/TR/exi/
[6]https://datatracker.ietf.org/wg/6lo/

2.2 Capabilities of Various Vehicles

Cooperation between satellites and unmanned vehicles is a great synergy in order to enrich data-transfer options, as well as overall coverage. Various types of unmanned vehicles and satellites are characterized by different capabilities. There are three main categories of autonomous vehicles that can perform advanced operations in the maritime environment as listed in Table 1. Unmanned Aerial Vehicles (UAVs); Unmanned Surface Vehicles (USVs), also referred as Autonomous Surface Vehicles (ASVs); and Autonomous Underwater Vehicles (AUVs). All vehicles can be equipped with communication assets that allow fast data transfer between them and network nodes in their proximity.

UAVs can cover significant distances in a short time thanks to their speed in the air, while being able to fly directly to the area of interest. However, their endurance is limited, usually from some hours to a few days. On the other hand, some types of the USVs, powered by renewable energy, can travel a virtually unlimited period of time and cover great distances. However, their speed will usually be significantly lower when compared to flying vehicles. Last but not least AUVs may be the slowest among all mentioned vehicles. These however, can reach nodes unavailable to other types of vehicles, e.g. under the ice layer.

All vehicles require a certain level of logistics related to their deployment. That can vary from an update of instructions sent to the vehicle, up to a complex operation involving number of crew and complex arrangements, e.g. a vessel cruise, or an airspace reservation. In all cases data collection or data muling is exposed to a variety of uncertainties. Available data-collection using UV depends on multiple factors such as vehicle and crew readiness, economic viability, regulatory framework, traffic in the area or even weather conditions.

Satellite links seem to perfectly fill these gaps when the data mules cannot be used. These links are usually slower and only available for shorter periods of time compared to communication links provided by UVs. However, they are predictable as availability of satellite and their data transfer capabilities are known well in advance. In the end, a network based on a synergy of satellite and unmanned vehicle nodes presents a user with multitude of possible ways to download its data from remote locations. In order to further enhance the network, especially reducing the round trip delay, inter-satellite links can be used to relay data between satellites in order to reach a ground station quicker. In this proposed ar-

chitecture, inter-satellite links are not included due to the increase in the requirements for the on-board power system and to the attitude (pointing) system. This adds both complexity and cost of the satellite platform. In addition, with only a few satellites serving the system, inter-satellite links will be scarce and cannot be used. In a denser constellation or swarm of satellites, inter-satellite links can be of use.

Table 1: Unmanned Vehicles access for Maritime Environments, based on [21].

	UAV		AUV			USV		
	Smaller (< 25 kg)	Larger (>25 kg)	Light AUV	AUV	Gliders	Renew. Energy	Boats	Vessels
Small-scale (0-10 km)	✓		✓	✓			✓	
Medium-scale (10-100 km)		✓		✓	✓	✓	✓	
Large-scale (100-1000 km)		✓			✓	✓		✓
Global-scale (>1000 km)		✓			✓	✓		✓

3 System Requirements

The proposed system shall meet several requirements. First of all, it should *enable interoperability* between different communication technologies, which will be useful to *mitigate network partitioning*. In particular, it will provide multiple degrees of communication coverage and performance.

Maritime operations are characterized by intermittent connectivity, therefore the system shall be *robust and resilient* to these conditions. The system shall include *delay/disruptive tolerant semantics* in the network-substrate, allowing the usage of distributed systems similar to the ones used across the Internet. This means that message acknowledgements must be employed, either on a link-to-link level or on a higher level (end-to-end message transfer verification). The level on which this functionality should be implemented depends on chosen (higher-level) protocols, requirements for timeliness[7] and complexity in implementation.

Communication shall be *accessible to all nodes in a scalable fashion*. Due to the heterogeneity of services and actors, the system shall also provide *distinct levels of communication quality* according to the priority assigned to different data sources.

Although satellite link availability is known well in advance, the use of UVs puts some additional constraints on system operation. Their use is prone to

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[7]Link-to-link verification may reduce the time for end-to-end message verification if communication losses are handled on an early stage
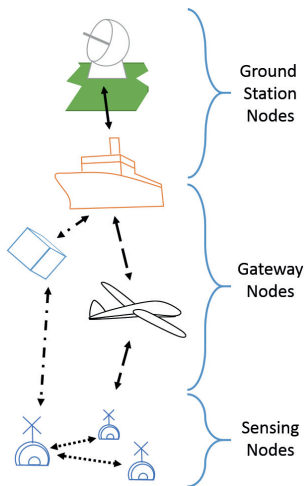
Figure 2: Top-level view of the Network Architecture

additional cost and can be jeopardized by weather conditions, or service-provider availability. For that reason their use must be properly planned, and the system shall allow the user to *select or automatically select, the most efficient data-route* based on a pre-defined metric, e.g. cost-per-bit or delay sensitivity.

The overall solution shall be *extensible in alignment with standards and protocols* developed for the Internet. This will allow maintaining an up-to-date, stable and secure system for current and future developments in maritime operations.

4 Proposed Architecture

In order to enable in-situ sensing in harsh environments it is important to define a clear networking architecture. This architecture must include hierarchical roles for different nodes, ensuring a scalable and organised structure, presented schematically in Figure 2. This architecture consisting of 3 main classes of nodes with distinct roles: **Ground Station Nodes (GS)**, **Gateway Nodes (GW)**, and **Sensing Nodes (S)**. An integrated solution for networking in remote locations must consider multiple communication technologies and interoperable interaction between such nodes. In order to meet the proposed objectives and requirements, chosen components and their configuration should comply with existing standards and be customisable. Additionally, it must support dynamic changes in its topology due to the variability of conditions in, for instance, maritime scenarios (e.g. intermittent links and mobility).

4.1 Network Nodes Types

Ground Station Nodes are considered *root nodes* in the proposed hierarchical network. These have access to a vast amount of resources, such as a large vessel or nodes that are part of an infrastructure, such as a satellite ground station. Additionally, these nodes will be permanently connected to the Internet, which allows them to keep a synchronised perspective of the network, regardless of the distance between them.

Root nodes should also include several communication interfaces, using different technologies, enabling higher levels of connectivity with different vehicles. They will be the main interaction points for unmanned vehicles and satellite nodes, which are GW Nodes, and will be responsible for interfacing the GW nodes and providing connectivity to the Command and Control (C&C) centre.

Ground stations may also be responsible for hosting the C&C centre, however this unit may also operate elsewhere, provided that it has connectivity with all ground stations. The C&C must perform all the required planning and configuration decisions that will improve the system's performance and resource usage. Storage of the collected data must also be handled by the C&C, therefore ground stations will not only serve as a forwarding point for the C&C decisions, but also as a back-haul for all the gathered data.

Gateway Nodes are manned and unmanned vehicles that are integral components of the proposed network architecture. These will serve as *gateway nodes* (GW) between the root nodes and any other nodes in maritime deployments. The focus for the proposed architecture is to exploit different networking options for reaching isolated nodes in remote locations. For example, unmanned vehicles such as Unmanned Aerial Vehicles (UAVs) can be considered as on-demand GWs for high-bitrate transfers, while SmallSats can be used to periodically retrieve or deliver smaller amounts of data (e.g. status information).

UAV gateway nodes can be used to carry or relay data from and to the C&C centre. This should be enabled by at least two different communication technologies, one focused on high bit-rates and another on achieving longer coverage ranges for relaying data. Such heterogeneity will allow GWs to act as data mules for delay tolerant data, or simply as relays for critical data.

Satellites can be an important resource for reaching more isolated sensor nodes, reducing the need for data collection by vehicles. LEO satellites are typ-

ically characterized by periodic coverage, providing approximately 10 minutes of link access every 90 minutes[8]. However, this may be improved by resorting to SmallSat constellations or swarms, combined with well-designed placement of the ground stations. This would allow a satellite to download received data and requests to one ground station, which in turn forwards them to the other station so that it can intercept newly arriving satellites.

The GW nodes, satellites or vehicles, will not only collect data from the sensors, but also deliver any data that may have been requested by the sensor nodes. Additionally, configuration messages from the C&C centre will also be sent throughout the network of nodes. Each vehicle should complement each other, leveraging on their distinct hardware characteristics and specific behaviours or conditions as described in Section 2.2. Since GWs can be hosted on various nodes, the use of standardised protocols will be important for ensuring the interoperability between them, resorting to mechanisms such as Route Advertisements or common addressing based on IPv6.

On some occasions, it is possible for a GW-node to act as a relay node, forwarding all received packets directly to an infrastructure node. An example is a satellite passing over the sensor field while at the same time being in contact with a ground station. However, since a direct link to the ground station infrastructure may be nonexistent or limited in resources (e.g. a long-range low-bitrate link may not be able to relay all the collected data in real-time), GWs must be able to act as data mules, collecting all possible data and delivering it later when closer to the infrastructure. Finally, GW nodes must be capable of acting as proxies of C&C centre, becoming responsible for delivering configuration messages to sensing nodes.

Sensing Nodes are envisaged as quasi-static nodes that aim at collecting scientific data from a given area, though mobile nodes may exist. This area may be covered by a single node or by a cluster, where nodes may be able to communicate with each other. The monitored data is to be relayed through multi-hop links whenever a group of clusters is close to shore.

The sensing nodes are leaf nodes in the presented architecture, which can be deployed in different locations. They will be the main source of data, that should be forwarded towards the C&C. These nodes are typical constrained, with limited energy, processing power and even communication capabilities.

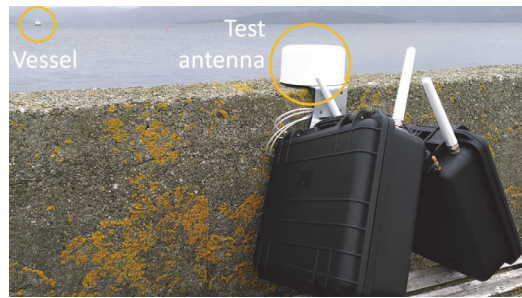[8]Given a node or ground station placement so the satellite can be seen for every pass.

Figure 3: Sea trial of the testbed nodes – communication sea-to-shore
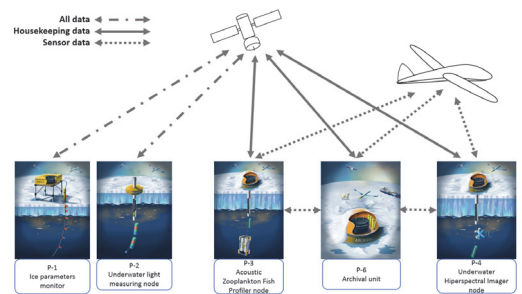

Figure 4: Arctic ABC data collection

However, communication limitations typically result from the lack of energy availability, which can be mitigated by diligently combining different radios. For example, low-power and low-bitrate radios can be used locally between leaf nodes, or for activating more resource-demanding radios when a GW is nearby. The proximity between leaf nodes may allow multi-hop routing so that data can be forwarded to nodes directly connected to a gateway. This can, for example, result either from routing messages sent by a GW acting as a router, or from Software-Defined Networking (SDN) flows installed by the C&C.

4.2 Configurable Testbed

In order to conduct experiments based on the proposed architecture, allowing integration of several networks, a dedicated hardware solution, based on commercial-off-the-shelf testbed has been developed. The testbed consists of four nodes, build into weatherproof, rugged boxes, with a set of 2 radio systems. In the current version, a short-range, high capacity WiFi link and long-range, single channel VHF radio are used. Each node is a complete system with computational power and a battery lifetime of sev-

eral hours and that can be deployed, for example, onboard a research vessel. Using the nodes, it is possible to measure radio link performance as well as to control network behaviour using different protocols (Figure 3).

The first evaluation in a sea trial focused on the cooperation between a UAV and a research vessel [12]. However, the testbed nodes have been designed in order to be able to cooperate with a growing number of assets available for the research activities in the Trondheim area. Some of these assets include fixed-wing UAVs [22], Light Autonomous Underwater Vehicles, a motorboat based USV and a research vessel [8]. The proposed architecture and testbed provide also a feedback to the Arctic ABC-project development [23, 24]. The architecture used by this project is depicted by Figure 4, which resembles the proposed integrated networking scheme. This architecture defines a system consisting of one or a few sensing nodes and gateway nodes based on UAV and a satellite nodes, which complement each other to enhance data collection in the Arctic.

5   Summary and Conclusions

To bring connectivity to the Arctic and enable the Internet of Arctic things, we propose a heterogeneous network architecture interconnecting sensors, relay nodes, data mules and ground stations. In order to ease integration with a wide range of hardware and excising networks, we propose to make use of standardised concepts and protocols suitable for the identified requirements. By building a general network infrastructure encompassing sensor nodes, small satellites and various UVs, the common architecture can support a wide range of missions. Relaying scientific data from environmental sensors is only one example.

The different roles for each node in the network hierarchy and their characteristics are described. This creates different communication opportunities, based on the details of each network node. Interconnection is enabled by resorting to standardised IP-based protocols, suitable for both constrained and high-capacity networks. Multi-hop networking between leaf nodes also allows extending the coverage of GWs and the overall network.

Some leaf nodes may be able to communicate with different types of technologies and GWs, such as aerial vehicles and small satellites. This option is particularly relevant when large amounts of data are to be transmitted, as larger bitrates are expected to be available when nearby GW vehicles exist, saving energy with low-power low-bitrate radios otherwise. Simultaneously, the use of small satellites allows sens-

ing nodes in more isolated areas to periodically deliver their collected data, though at lower bitrates, regardless of the availability of GW vehicles.

Acknowledgment

References

[1] R. Birkeland, "Freely drifting CubeSat constellations for improving coverage for arctic sensor networks," in *IEEE ICC 2017 SAC Symposium Satellite and Space Communications Track (ICC'17 SAC-9 SSC)*, Paris, France, May 2017.

[2] R. Birkeland and D. Palma, "Freely-drifting small-satellite swarms for maritime sensor networks in the arctic," *Submitted for review in IEEE JSAC SatCom'17*, 2017.

[3] N. Beauchamp, "Return of the intrepid wave glider," http://oceantrackingnetwork.org/return-of-the-intrepid-wave-glider/, 2014, [Online; accessed 13-July-2016].

[4] A. Zolich, J. A. Alfredsen, T. A. Johansen, and K. R. Skøien, "A communication bridge between underwater sensors and unmanned vehicles using a surface wireless sensor network - design and validation," in *OCEANS 2016 – Shanghai*, April 2016, pp. 1–9.

[5] D. Palma, "Software-defined Intermittent Networking - Reference Scenario and Requirements Definition," Online, October 2016, h2020 grant number 699924. [Online]. Available: https://sinet.item.ntnu.no/wp-content/uploads/2016/10/\D11_Scenario_SINet.pdf

[6] ——, "Software-defined Intermittent Networking - Architecture Specification,"

Online, October 2016, h2020 grant number 699924. [Online]. Available: https://sinet.item.ntnu.no/wp-content/uploads/2016/10/\\D12_Architecture_SINet.pdf

[7] A. Zolich *et al.*, "A multi-hop intermittent wireless sensor network with unmanned aerial vehicles and satellite links for the arctic," Presentation at ReCAMP Flagship Workshop, 5 - 6 April 2016, Tromsø, Norway, 2016, abstract available at: http://www.asuf.no/wp-content/uploads/2016/03/ReCAMP2016_AbstractsBook.pdf.

[8] M. Ludvigsen, P. S. Dias, S. Ferreira, T. O. Fossum, V. Hovstein, T. A. Johansen, T. R. Krogstad, Ø. Midtgaard, J. S. P. Norgren, Ø. Sture, E. Vågsholm, and A. Zolich, "Autonomous network of heterogeneous vehicles for marine research and management," in *IEEE Oceans 2016 – Monterey, CA*, September 2016.

[9] I. Vasilescu, K. Kotay, D. Rus, M. Dunbabin, and P. Corke, "Data collection, storage, and retrieval with an underwater sensor network," in *In Proceedings of the International Conference on Embedded Networked Sensor Systems (ACM SenSys 2005*, 2005.

[10] T. A. Johansen, A. Zolich, T. Hansen, and A. J. Sørensen, "Unmanned aerial vehicle as communication relay for autonomous underwater vehicle - field tests," in *IEEE Globecom Workshop - Wireless Networking and Control for Unmanned Autonomous Vehicles, Austin, TX*, 2014.

[11] R. Birkeland and A. Hornig, "On how a cubesat swarm can improve the coverage for an arctic ground based sensor network," in *Proceedings of ESA Small Satellites Systems and Services 2016*, 2016.

[12] D. Palma, A. Zolich, Y. Jiang, and T. A. Johansen, "Unmanned aerial vehicles as data mules: An experimental assessment," 2017, submitted for publication.

[13] M. I. of Technology, "MOOS-IvP home page," 2017, (Accessed April 2017). [Online]. Available: http://oceanai.mit.edu/moos-ivp

[14] A. S. Huang, E. Olson, and D. C. Moore, "Lcm: Lightweight communications and marshalling," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct 2010, pp. 4057–4062.

[15] J. P. Macker, C. Bormann, M. J. Handley, and B. Adamson, "NACK-Oriented Reliable Multicast (NORM) Transport Protocol," RFC 5740, Nov. 2009. [Online]. Available: https://rfc-editor.org/rfc/rfc5740.txt

[16] J. Pinto, P. S. Dias, R. Martins, J. Fortuna, E. Marques, and J. Sousa, "The LSTS toolchain for networked vehicle systems," in *OCEANS - Bergen, 2013 MTS/IEEE*, June 2013, pp. 1–9.

[17] Z. Shelby, "Constrained RESTful Environments (CoRE) Link Format," RFC 6690, Aug. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6690.txt

[18] A. P. Castellani, S. Loreto, A. Rahman, T. Fossati, and E. Dijk, "Guidelines for Mapping Implementations: HTTP to the Constrained Application Protocol (CoAP)," RFC 8075, Feb. 2017. [Online]. Available: https://rfc-editor.org/rfc/rfc8075.txt

[19] A. Rahman and E. Dijk, "Group Communication for the Constrained Application Protocol (CoAP)," RFC 7390, Oct. 2014. [Online]. Available: https://rfc-editor.org/rfc/rfc7390.txt

[20] D. T. Narten, T. Jinmei, and D. S. Thomson, "IPv6 Stateless Address Autoconfiguration," RFC 4862, Oct. 2015. [Online]. Available: https://rfc-editor.org/rfc/rfc4862.txt

[21] A. Zolich, D. Palma, K. Kansanen, K. Fjørtoft, J. Sousa, K. H. Johansson, Y. Jiang, H. Dong, and T. A. Johansen, "Survey on communication and networks for autonomous marine systems," 2017, submitted for publication.

[22] A. Zolich, T. A. Johansen, K. Cisek, and K. Klausen, "Unmanned aerial system architecture for maritime missions. design hardware description," in *2015 Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS)*, Nov 2015, pp. 342–350.

[23] J. Berge, "Mare incognitum - arctic abc project summary," online, 2017, nFR projects 244319 and 245923.

[24] J. Berge, M. Geoffroy, G. Johnsen, F. Cottier, B. Bluhm, and D. Vogedes, "Ice-tethered observational platforms in the arctic ocean pack ice," *IFAC-PapersOnLine*, vol. 49, no. 23, pp. 494 – 499, 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2405896316320742

A.6 Paper F

R. Birkeland and D. Palma, "Freely-drifting small-satellite swarms for sensor networks in the Arctic," in *Proceedings of the Third International Congress on Information and Communication Technology*, 2018.

This paper resulted from work presented in Chapter 4; and Chapter 5. The author's contribution is commonly developing the idea behind the paper, simulation of the small satellite swarms, selection of the cases for emulation, providing in-data for the emulation, and interpretation and discussion of the results from simulations and emulations. The author presented the paper at the conference.

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available at https://doi.org/10.1007/978-981-13-1165-9_16

A.7   Paper G

D. Palma and R. Birkeland, "Enabling the internet of arctic things with freely-drifting small-satellite swarms," *IEEE Access*, vol. 6, pp. 1–1, 2018.

This paper resulted from work that extends from Chapter 5; especially Section 5.5. The author's contributions are commonly developing the idea behind the paper, simulation of the small satellite swarms, pass calculations, selection of the cases for emulation, providing input data for the emulation engine, and interpretation and discussion of the results from simulations and emulations. The paper is published in a special section of IEEE Access: *Addressing Economic, Environmental and Humanitarian Challenges in the Polar Regions*.

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Multidisciplinary : Rapid Review : Open Access Journal

Enabling the Internet of Arctic Things With Freely-Drifting Small-Satellite Swarms

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ABSTRACT The widespread deployment of Internet-capable devices, also known as the Internet of Things (IoT), reaches even the most remote areas of the planet, including the Arctic. However, and despite the vast scientific and economic interest in this area, communication infrastructures are scarce. Nowadays, existing options rely on solutions such as Iridium, which can be limited and too costly. This paper proposes and evaluates an alternative to existing solutions, using small satellites deployed as a freely-drifting swarm. By combining these simpler and more affordable satellites with standard protocols, we show how IoT can be supported in the Arctic. Networking protocols and link characteristics are emulated for 3 different satellite orbits and 4 ground nodes. The impact of different protocols and communication conditions is assessed over a period of 49 days and a cross-layer routing approach proposed. The obtained results reveal that a communication overhead bellow 27 % can be achieved and that the implemented satellite-aware route selection allows reducing the end-to-end time of a request up to 93 min on average. This confirms that freely-drifting small-satellite swarms may enable the Internet of Things even in the most remote areas.

INDEX TERMS Satellite communication, Internet of Things, software defined networking, Arctic, small satellites, swarm.

I. INTRODUCTION

Activity in the Arctic region is increasing [1], [2] and several bodies such as the European Union (EU), NASA and the Arctic Council expect this to continue [3]. Activities range across fishing, mining, shipping and securing environmental situation awareness. However, due to the lack of land-based infrastructures and satellite coverage (e.g. satellites in a Geostationary Earth Orbit (GEO) are not reachable north of 81° latitude), information and communication technologies for supporting these activities are scarce.

A project by the European Space Agency (ESA), entitled ArticCOM [4], concluded that there is a communication gap in this area and listed future projects expected to cover parts of non-European Arctic. However, several of these have been cancelled or delayed. This report further acknowledges that no planned systems for the European Arctic existed. Nonetheless, this has changed with projects such as the Norwegian Highly Elliptical Orbit (HEO) initiative, the Canadian Telesat, proposed mega constellations from SpaceX (StarLink) and OneWeb, aiming at providing worldwide broad-band coverage, including in the Arctic.

Science missions currently rely on costly systems such as Iridium [5] or manned missions for collecting nodes and retrieving their data. Alternatively, a hierarchical network could be used with different levels of communication between sensor nodes, unmanned vehicles (UVs) or small satellite nodes [6]. Small Satellites, or smallsats, can be deployed in freely-drifting swarms, which do not require thrusters and allow increasing communication coverage at a reduced cost when compared against traditional satellites [7], [8]. In this work, a freely-drifting swarm is defined as a set of such smallsats in one system, without any station keeping capabilities. This constrasts with a fixed constellation or a swarm of satellites where member satellites perform station keeping and may interact with each-other.

Small satellite constellations are currently under development, however they require more costly equipment and mostly aim at covering densely populated regions of the Earth (e.g. Sky and Space Global [9]). Another limitation is the envisaged throughput of only a few kilobytes per day (e.g. Astrocast [10] and HeliosWire [11]).

The irregular presence of vehicles and the intermittent nature of satellite links requires a robust and flexible IoT setup. This motivated several works to focus on the principles of Delay Tolerant Networking (DTN) [12], [13] or even on the combination of IoT with DTN protocols. For example, the Constrained Application Protocol (CoAP) [14], due to its suitability for IoT constrained nodes, has been combined with the Bundle Protocol (BP) [15] in order to support intermittent connectivity. Moreover, this heterogeneity demands a convergence layer for enabling seamless interoperability between distinct communication technologies.

A cornerstone of the Internet is the Internet Protocol (IP), currently on version 6 (IPv6) [16], which provides a way of identifying nodes and allows data to be sent and received across different networks. IPv6 can be seen as the required convergence layer between different technologies, including satellite-based communications [17], providing seamless interoperability with existing systems. Additionally, the IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) has been considered as an appropriate solution for constrained link-layers [18], as expected in remote locations due to the lack of resources and infrastructures.

This paper takes into account communication needs in the Arctic and evaluates the feasibility of a network solution supported by a smallsat drifting swarm. Specifically, the following contributions are provided:

- Emulation of a smallsat IoT network for the Arctic, combining both IPv6 and 6LoWPAN with CoAP;
- Analysis of the different phases of a 3-satellite freely-drifting swarm and the impact on communications;
- Proposal of a satellite-aware routing approach.

The Internet of Arctic Things (IoAT) is presented in Section II, introducing the envisaged architecture, explaining the inner-workings of a freely-drifting swarm and detailing the proposed network solution. Section III presents the defined evaluation methodology followed by the obtained performance results in Section IV. Finally, Section V provides an overview of the main conclusions of this work.

II. INTERNET OF ARCTIC THINGS WITH SMALLSATS

Smallsats stand out from larger satellites by dint of their simplicity and low-cost design. Multiple satellites can be deployed so that they form a distributed system [19]–[21]. The satellites can be deployed either as a constellation, which implies the use of more sophisticated and expensive platforms with propulsion or drag management for station keeping, or as a freely-drifting swarm using simpler platforms.

By giving the satellites a varying spring load in the deployment pod, they will in turn be deployed with a small velocity difference relative to each other. This results in a varying distribution of the satellites within the swarm throughout time, from now one referred to as swarm phases, leading to variable network coverage and performance. The following subsections discuss these aspects and a possible architecture.

A. ARCHITECTURE OVERVIEW

The Internet of Arctic Things networking proposal presented in this work considers 3 distinct types of nodes:

- **Ground Station (GS):** A gateway to traditional Internet services, located at higher latitudes (e.g. Vardø, Norway);
- **Border Router (BR):** A smallsat acting as relay node or data-mule between a GS and a Sensor Node (SN);
- **Sensor Node (SN):** A resource-constrained Internet-capable device collecting data in the Arctic region.
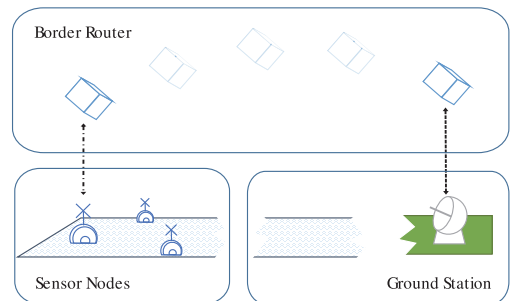

Figure 1. System architecture with different link characteristics between satellites and ground nodes.

Figure 1 shows the system architecture, and how the different network nodes interacts. In order to reduce their complexity, smallsats are not expected to communicate amongst themselves. However, if UVs are to be included, they may also be considered BRs and communicate with smallsats. This could occur when a UV is not in range with a GS and relies on smallsats to act as BRs, even though this is outside the scope of this paper.

Despite being resource-constrained devices, SNs may communicate with other SNs and benefit from data aggregation mechanism to reduce overhead. This is particularly important as the number of SNs increases, further motivating the use of standardised IP-based protocols in order to guarantee interoperability and access to other existing features (e.g. encryption).

B. FREELY-DRIFTING SMALLSATS SWARM

In addition to the lower cost of smallsats when compared to other larger Geostationary Earth Orbit (GEO) satellites, they use a Low Earth Orbit (LEO) which is advantageous when considering low-power communications. This is a direct consequence of the distance between a ground node and a satellite, which can be ten times shorter than when considering GEO satellites. Resorting to GEO satellites would incur much larger propagation losses and delays, requiring higher transmission power and larger antennas. Moreover, GEO satellites are not reachable by ground nodes north of 81° latitude.

The cost of a smallsat node can be kept low due to their simple design and use of commercial-off-the-shelf (COTS) components. In addition, due to their small form-factor smallsats

can be launched as a secondary payload to other missions. This allows a ''ride-sharing'' approach with larger commercial missions, therefore avoiding dedicated launches and further reducing the overall cost of the solution [17]. A limitation of this approach is that the smallsat mission does not control the final orbital parameters, save for choosing which launch to book a ride on. The mission designer must then choose a fitting orbit for the given satellite mission. For example, polar orbits are often used for earth observation missions and by definition they cover the Arctic areas, being therefore suited this kind of mission.

In this paper we consider 3 smallsats deployed from the same upper stage on a common launch, which places them in the same orbital plane. Even without exactly-timed deployments or thrusters, this freely-drifting swarm is able to achieve the same performance as a constellation composed by 2 smallsats [7]. Satellites without station keeping capabilities will be smaller and cheaper, operational requirements become more relaxed and the cost savings can be used to launch more space crafts. Deployment strategies and how to choose reasonable and realistic velocity differences are discussed in [1], [7], [21], and [22].

By giving the 3 satellites small velocity differences, they enter slightly different orbits, with distinct orbital periods. Due to this, the smallsats will drift relatively to each other, resulting in a freely-drifting swarm with varying and evolving phases, as seen in Figure 2. Hence, the properties of a network supported such swarm will constantly change.
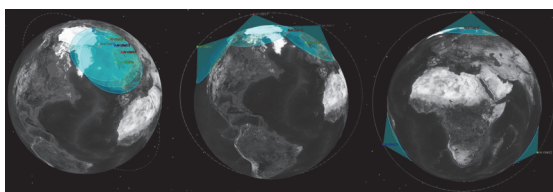

Figure 2. Swarm phases: *overlapping satellites* (left), *trailing* (centre) and *uniform distribution* (right).

The considered freely-drifting swarm with 3 smallsats will transition through 3 different phases as illustrated by Figure 2. The first phase corresponds to 3 *overlapping satellites*, or a variation where only 2 satellites overlap with the third being diametrically opposite to them. Another phase assumes a *trailing* or scattering configuration, where the satellites either diverge or converge towards one of the other phases. Finally, a *uniform distribution* of the satellites around the planet.

Bearing in mind the different possible phases, the best possible coverage with respect to the re-visit time is achieved with a *uniform distribution*, resulting in comparable gaps between each smallsat pass. On the other hand, for the *trailing* phase, short re-visit intervals are followed by a larger one, while for *overlapping satellites* the interval between passes is the greatest, resulting in large periods without coverage.

Nevertheless, when considering the total coverage time for a node placed north of Svalbard (KSAT – 78°13′48.0″N 15°23′24.0″E), our simulations show that *overlapping satellites* only account for 2.8 % of the covered time and that the 2 satellites overlap phase only occurs 10.6 % of the time. It can therefore be argued that the penalty of letting the swarm drift freely is quite small, considering that a satellite with orbit-manoeuvre capabilities (i.e. thrusters) will have a significantly higher cost.

In addition to the variability added by changing phases, it is also important to consider the dynamics between Earth's rotation and the satellites' orbital plane (c.f. Section III-A). The orbital plane is inclined with respect to Earth's rotational axis and Earth rotates within it. This means that the satellites will not pass directly over-head of a given ground node in every orbit revolution. In fact, the satellites' ground track will move along the surface of Earth in each pass, therefore affecting the duration of each pass throughout a day, being less noticeable by nodes at higher latitudes since they are closer to the axis of rotation. For example, ground nodes placed as far north as mainland Svalbard observe all the passes from a polar orbiting satellite, while nodes further south miss some passes in a day.

An IoT network in the Arctic must take into account the dynamics between orbital planes and Earth's rotation, as well as the characteristics of the described freely-drifting swarm, specially when transmitting data between multiple ground nodes that may exist. Since all satellites are capable of eventually reaching all these nodes, a naive networking approach would select the first arriving satellite as a next-hop. However, the desired destination may not be aligned with this satellite's ground track at all given times. Alternatively, selecting a later arriving satellite with a more suitable ground track (i.e. closer to the destination), may provide a shorter delay between the source and destination nodes.
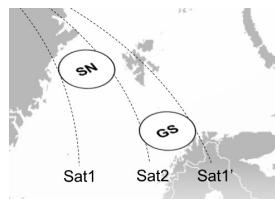
Figure 3. Ground tracks for *Sat*1 and *Sat*2, with $t_{Sat1} < t_{Sat2} < t_{Sat1'}$ (background adapted from Wikimedia Commons / CC BY 3.0).

This is illustrated by Figure 3, where *Sat1* becomes visible to the sensor node *SN* before *Sat2*, but that requires one more orbit revolution until its ground track (*Sat1'*) is aligned with the ground station *GS*. Conversely, while *Sat2* only becomes visible to *SN* later, due to its better track alignment, it is also visible to *GS* in the same revolution. This allows significantly reducing the required time for a message to be relayed from SN to GS.

C. NETWORKING AND COMMUNICATION

Diversity in the IoT increases not only the number of networking possibilities, but also the number of challenges and requirements to be met, such as interoperability. Focusing on the Arctic and maritime operations, different activities may require monitoring of simple weather parameters (e.g. temperature, wind speed), or highly complex data (e.g. hyperspectral images). This leads to several heterogeneous nodes and communication technologies being found in such scenarios [23].

The use of standardised Internet protocols is the best way of guaranteeing interoperability between different nodes and technologies. We rely on IPv6 addressing and on its lightweight version of 6LoWPAN to support this. In particular, we consider the use of full IPv6 addresses for communication technologies and nodes with higher availability of resources, such as the links between GSs and satellites, which will typically have more energy and higher-gain antennas than sensor nodes. Even though 6LoWPAN was developed in the context of IEEE 802.15.4 [24], it has also been considered in the context of other communication technologies [18]. Using it for constrained satellite and sensor-node links would allow benefiting from the existing adaptation layer [25] and compression mechanisms [26], reducing networking overhead.

In order to support other communication links that may exist, even between the same BR and SN, a Software-defined Networking (SDN) solution was used on the satellites. By adding or removing flow rules issued by the Ground Station, our nodes are capable of dynamically changing an IPv6 address into a 6LoWPAN one, from global to unique link-local addresses and by selecting the corresponding network interface. This allows not only the change between communication technologies but also to the establishment of priority between flows, among other features.

Typical satellite-based networking solutions select DTN routing protocols to solve the issue of intermittent connectivity and rely on opportunistic or predictable establishment of communication links (e.g. PRoPHET [27]). However, these solutions typically introduce abstractions such as an overlay of links and networks resulting from the Bundle Protocol or Convergence Layers [28], not considering the specifics of the domain in question and resulting in unnecessary overhead. In our SDN-based approach, routing overhead between nodes is prevented by having routes defined by the GS or by a local controller, which can automatically be added or removed when appropriate. Moreover, these can be updated if new nodes are deployed or if any changes are deemed necessary.

In the Internet many applications follow a client/server representational state transfer (REST) architectural style. Similarly, in IoT and with constrained devices in mind, CoAP was designed to be RESTful while also keeping overhead to a minimum. CoAP messages require a header of only 4 B [14] and the User Datagram Protocol (UDP) is used instead of the Transmission Control Protocol (TCP), with additional mechanisms such as confirmable messages being optional but also possible. The design of CoAP was also conceived so that seamless interoperability with other Internet services could be provided. In particular, CoAP defines the concept of CoAP proxy, where a node can be used to forward request/responses or even to convert Hypertext Transfer Protocol (HTTP) requests into lightweight CoAP messages and vice-versa.

By using CoAP as an application layer protocol responsible for handling data transfers, GSs or SNs can issue requests to any node in the network, specifying BRs as proxy nodes. However, CoAP proxies were not designed to support proxying as typically found in satellite nodes, which can act as DTN-capable nodes. This has already been addressed by previous works in the literature [15] and can be achieved by slightly adapting the protocol without breaking its compatibility with standard implementations (c.f. Section III-B).

Another important networking aspect concerns the selection of the most appropriate next-hop. The simplest approach consists of selecting the first BR available, especially since we consider that each BR is capable of reaching all SNs. If more than one BR is available at a given instant, the typical approach would be to select the one with the lowest hop count to the destination, but they are all equal.

Regardless of having one or more BRs available, as discussed in the previous sub-section, a naive approach can lead to selecting a BR out of alignment with the desired destination node. Bearing that in mind, we propose a smarter approach where, depending on the source and destination ground nodes, where the fastest satellite to reach them both is selected. This exploits knowledge about the domain, namely available satellite orbits and nodes' positions, and can either be pre-calculated or periodically updated by making use of the proposed SDN routing approach.

III. METHODOLOGY

The proposed Internet of Arctic Things architecture, supported by a freely-drifting swarm of smallsats, is depicted in Figure 1. In order to realistically evaluate its feasibility, a combination of simulation and emulation techniques was used. The dynamics of the swarm were simulated, serving as input for the network emulator that ran real networking protocols over emulated links created and destroyed according to the BRs' coverage of each node.

The scope of this paper is to evaluate higher-layer network protocols. Therefore, lower-layer protocols for the radio links and media access strategies are not included. In this setup, the BR is polling each node, hence controlling most of the access to frequency resources. Nonetheless, a suitable media access scheme should be implemented.

The SNs are assumed to be able to run a light-weight operating system (e.g. Linux or Contiki), enabling the use of the IoT network stack. In addition, positioning device shall be available providing also accurate timing. With these capabilities and the knowledge about the satellite's orbits, which can be regularly updated, the SNs can calculate the start time of a pass by use of an orbit propagator. This approach will have

a negligible communication and processing cost and allow nodes to save energy by turning off the radio until the desired satellite pass is near.

A. FREELY-DRIFTING SWARM SIMULATION

The evaluated freely-drifting swarm was based on realistic satellite orbits from the Two-Line-Element (TLE) [29] set of AAUSat-3 [30], with the epoch *13 Feb 2014 12:35:42.657*. The used TLE was retrieved from the Systems Toolkit (STK) [31], and each of the 3 defined satellites had its *orbits-per-day* and eccentricity *e* parameters edited accordingly. An inclination of 98.6235° and a perigee height of 768 km was set to all of them. Their apogee altitudes were 771.83, 787.17 and 802.55 km. These slightly different orbits are responsible for the previously mentioned drift that results in different phases (c.f. Figure 2). For the chosen orbits, one "full cycle" of all the possible satellite phases, from which the same pattern is repeated, lasts for approximately 45 days.

The simulation of the chosen swarm depends on the selected ground nodes, for which a singular coverage perspective must be determined. Focusing on a realistic scenario in the Arctic region, the positioning of the GS chosen for this paper was Vardø, Norway, where one of northernmost mainland ground stations is currently in use. Three other ground nodes were selected, 3 SNs named GR_north, GR_south and Rossøya. Their locations, as seen in Figure 4, were based on a previous research work also addressing the Arctic region [32].

Figure 4. Placement of ground nodes in the Arctic region. Sensor Nodes: **GR_north** (80°52′39.0″N 11°59′53.0″**W**), **GR_south** (75°51′0.0″N 16°52′15.5″**W**) and **Rossøya** (80°49′40.8″N 20°21′0.0″**E**). Ground Station: **Vardø** (70°22′12.0″N 31°6′36.0″**E**).

B. NETWORK EMULATION

The evaluation of the overall networking performance was conducted through emulation, using the simulation details between each satellite and ground node as input for configuring each link. These details concern mostly the delay of each link and its availability, taking into account their ground track and distance to the ground node. The bitrate for links between the GS and BRs was set to 1 Mbit s^{-1}, based on available COTS S-band radios, while for links between BRs and SNs it was set to 20 kbit s^{-1} also based on COTS components with such bitrates already available.[1]

The used emulation tool [33], in addition to the used *qdiscs*, was adapted to mimic the constrained nature of satellite links by using network interfaces based on Linux's *nl802154* physical layer. This means that in addition to controlling the bitrate and delay of each link, the link between BRs and SNs was also limited to a maximum transmission unit of 127 B, fully integrating the links with 6LoWPAN. The entire networking stack was emulated using Ubuntu 16.04 (Linux Kernel 4.14.15-1) containers for each node, using dedicated *network namespaces* for isolating traffic between links.

Network performance was evaluated considering the overhead of the used protocols and from the *user's perspective*. The latter consists of the end-to-end response time, from the instant when a request is issued until its response is received. For this purpose, NON-confirmable CoAP requests were randomly created, following a uniform distribution between 60 s and 180 s. The destination for each request was also selected following a random uniform distribution, so that all SNs were equally used. Finally, a constant payload of 512 B per response was used, based on IoT networking where periodic small-size data transfers are expected. Nonetheless, it is worth noting that several requests and responses may be queued between satellite passes, resulting in data bursts when a new link becomes available.

The chosen CoAP implementation was CoAPthon [34], modified to support the queuing of CoAP messages whenever no route is available. This behaviour allows the support of intermittent connectivity without relying on any additional messages or overhead. Instead, an event-triggered approach was used, resorting to *IPDB-callbacks*[2] for new routes available in the system. This allows CoAP to be completely decoupled from any routing mechanisms being used.

C. SATELLITE-AWARE ROUTING

Regarding the selection of the most appropriate BR as next-hop, Figure 5 shows our satellites' ground track relatively to the used ground nodes. It consists of a combined snapshot of a relay opportunity for two of the satellites (ArcNet1 and ArcNet9) which the first satellite does not observe (ArcNet5). This illustrates one instance when the benefit of smart routing can improve the network performance, considering a request issued from Vardø to GR_north. Specifically, on this occasion, ArcNet5 is the first smallsat to reach the GS at Vardø after several hours without coverage.

A naive approach would select ArcNet5 node as a next-hop since no others would be available at that instant. However, this BR requires one more orbital revolution in order to reach GR_north and complete the communication. Instead, by either waiting for ArcNet1 or ArcNet9 to become visible, 30 min later, requests can be relayed directly to GR_north, reducing the end-to-end time in nearly 60 min.

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[1][Online]. For example: `gomspace.com/Shop/subsystems/communication/nanocom-ax100.aspx`

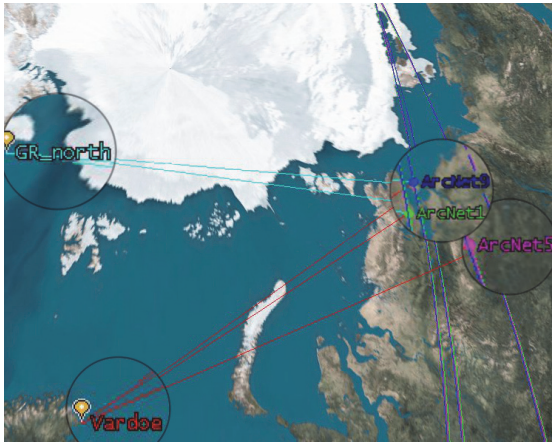[2][Online]. From pyroute2 netlink library. Available: `docs.pyroute2.org`

Figure 5. Example of different ground tracks and coverage: ArcNet5 is the first reaching Vardø but fails to reach GR_north. ArcNet1 and ArcNet9 reach Vardø later but act as relays for GR_north, reaching it simultaneously.

As previously mentioned, the defined network setup allows next-hop selection based on different methods. In addition to the naive approach, routes can be set by the GS or, alternatively, by a local controller in each node that determines the best next-hop based on the desired destination and current time. The *Smart*, or satellite-aware, routing method was implemented using the light-weight *pyephem* library [35], which allows the calculation of upcoming passes for a given node.

The implemented algorithm used the total end-to-end time (i.e. waiting time for a BR in each node) as its main metric, with the best next-hop minimising this value. However, additional path constraints were added, taking into account propagation and processing delays and the duration of each satellite pass. In particular, since some satellite passes may exist but be extremely short, a minimum threshold should be set in order to avoid selecting inadequate paths. In the performed evaluation, 3 flavours of smart-routing were used, *Smart5*, *Smart15* and *Smart30* respectively, with thresholds of 5, 15 and 30 s.

IV. PERFORMANCE EVALUATION

In this section we present the results obtained from emulating and simulating the described network architecture and its respective smallsat swarm. The experiment period was of 49 days, covering more than a "full cycle" of all the possible satellite phases, starting with a *trailing* phase until it returns to its initial state. This resulted in more than 32000 CoAP requests being transmitted through the evaluated network.

A. OVERHEAD
The low communication and computational impact of the chosen IoT protocols, designed to operate in resource-constrained nodes, was one of the main considerations in

TABLE 1. Overhead.

	Full IPv6	6LoWPAN
Ethernet/15.4 (L2) *(%)*	5.803	8.661
IPv6/6Lo (L3) (%)	16.58	10.586
ICMPv6 (L3) (%)	0.95	4.73
UDP (L4) (%)	3.316	0
CoAP (L7) (%)	7.227	2.676
Total Overhead (%)	33.876	26.653

the proposed Internet of Arctic Things. Table 1 presents the overhead registered in the performed experiments, both for full IPv6 addresses and 6LoWPAN compressed (i.e. 16 bit) addresses. Specifically, these results correspond to the links between the GS and BRs (full IPv6) and between BRs and SNs (6LoWPAN).

As expected, the total overhead introduced by using full IPv6 addresses is higher than with 6LoWPAN. For example, due to the used compression mechanisms, 6LoWPAN eliminates UDP overhead by including it in its headers. However, when carefully analysing the sources of overhead for each, some noteworthy results were registered. For example, the percentage of transmitted ICMPv6 messages in 6LoWPAN is more than 4 times greater than IPv6.

By analysing all the captured traffic it was found that this resulted from a characteristic of the *nl802154* driver, which is not namespace-aware and until recently did not support knowledge about connected edges.[3] This resulted in *Neighbor Solicitation and Advertisement* messages being received by multiple nodes simultaneously, even if no link existed. Therefore, in a real scenario this overhead would be lower. Finally, since CoAP requires an extra field for specifying the desired proxy address, the overhead in the link between the GS and BRs was higher.

TABLE 2. Performance comparison – overall.

	Naive	Smart5	Smart15	Smart30
First Satellite (s)	4031	4349	4381	4427
End to end (s)	5853	5060	5113	5401
Same Choice (%)	–	85.7	85.6	85.2
Improvement (s)	–	5636	5381	4281
Total Losses (%)	2.8	5.2	5.0	3.3

B. OVERALL PERFORMANCE
The overall performance of the evaluated experiment is summarised in Table 2, comparing the average end-to-end time for all the created requests and verifying that a low-percentage of losses can be achieved, even without using CoAP confirmable requests. The obtained results also

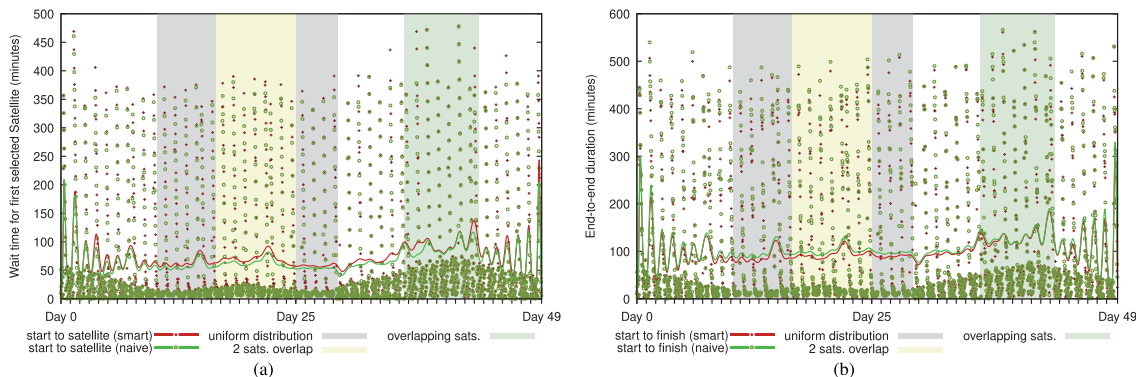[3][Online]. Available: `https://patchwork.kernel.org/patch/10369859/`

Figure 6. Performance of *Naive vs. Smart30* routing approaches. (a) Time taken for a GS request to reach the selected BR. (b) Time taken from request to received reply at the GS.

validate the claim for the need to employ satellite-aware routing mechanisms in nearly 15 % of the routing decisions. By analysing the row *Improvement* it is possible to see that the end-to-end time to retrieve data from a sensor node can be, on average, reduced up to 93 min.

Since a real networking stack was used, unpredictable behaviours due to congestion or delays led to the *Naive* approach being better for some requests. However, these correspond to less than 3 % of the requests and should be considered as outliers and are ignored in this evaluation.

After a careful analysis the registered outliers, they were attributed to a concurrency issue in the used software implementation of CoAP, resulting in a request to miss the expected pass and therefore taking an incorrect route. Moreover, this behaviour of the network stack is confirmed by the number of increasing losses in the less restrictive routing approach (*Smart5*), where selecting a short-lived pass results in some messages timing-out, and not necessarily being lost.

Figure 6 presents a comparison between the *Naive* and the *Smart30* routing approaches, using the green and red colours respectively. Each emulated request corresponds to a point in the plot (i.e. a circle or a cross depending on the used routing approach). Their interpolation is represented by a continuous line of the same colour of the corresponding routing approach.

Figure 6 further illustrates the impact of the different satellite phases. For example, it is possible to see that a majority of the requests takes less time when the swarm follows a *uniform distribution*. This value increases the most with *overlapping satellites* and is subject to higher variation when the swarm has a *trailing* phase (white background).

More concretely, Figure 6a shows the time taken since creating a request at the GS until it reaches the selected BR (i.e. smallsat). It shows that *Smart* routing generally takes longer to communicate with the desired BR, depicted by the red line slightly above the green one, confirming the results

presented in Table 2. However, this is justified by the selection of BRs that are better aligned with the final destination.

Conversely, Figure 6b confirms the resulting improvement from this selection. It shows that the total amount of time from the request being issued until the response is received (end-to-end time) is lower for the *Smart* approach, outperforming the *Naive*. This is seen in the green line constantly being above the red one.

C. GEOGRAPHICAL IMPACT

As previously described, the location of a ground node influences the perceived satellite coverage. However, resorting to a *Smart* routing approach significantly improves performance, regardless of the nodes' positions. This means that the penalty of using a *Naive* approach should also be analysed for each different destination.
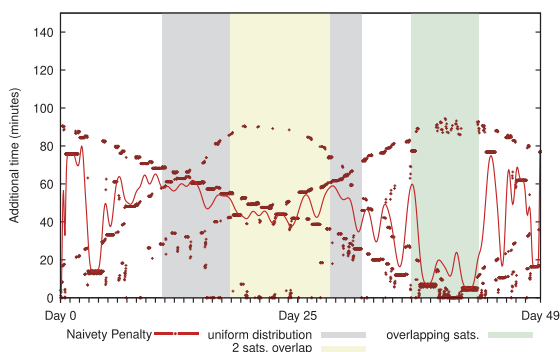

Figure 7. Overall time penalty of *Naive* routing.

In order to better visualise the negative impact of using a *Naive* routing approach, Figure 7 to Figure 10 illustrate the time penalty from selecting the first available BR. This penalty is determined by calculating the end-to-end time difference between the *Naive* and *Smart* approaches, per request.

The figure combines the requests issued for each of 3 destinations previously presented. It does however not include any requests where both routing approaches selected the same BR or outliers by unpredictable network behaviours.

The analysis of Figure 7 reveals that the penalty of the *Naive* approach is higher when the swarm is found in a *trailing* phase, due to the higher scattering of satellites. On the other hand, with *overlapping satellites* this penalty is less significant because the satellites' ground track is similar and fewer alternatives exist. Nonetheless, the *Naive* approach is penalised in almost all instances.
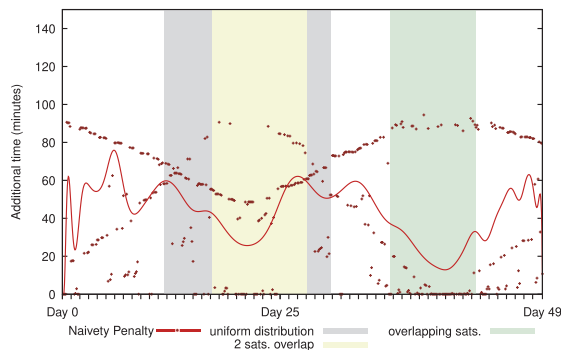

Figure 8. Time penalty of *Naive* routing at Rossøya.

Figure 8 shows the penalty when the selected destination node is located in Rossøya. Since this SN is fairly aligned with Vardø, whenever a satellite's ground track covers the GS it is also likely to reach Rossøya. In the performed evaluation, only 5 % of all the requests to this destination benefited from *Smart* routing. Nevertheless, their end-to-end delay was significantly reduced, with some improvements reaching nearly 100 min.
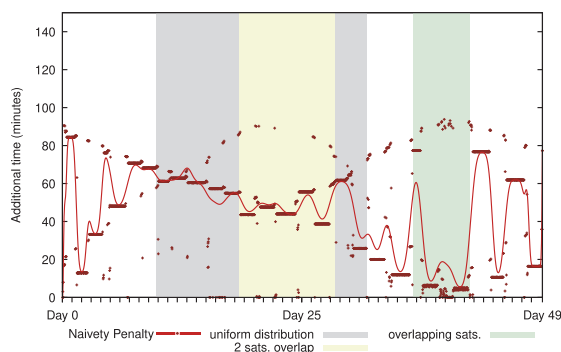

Figure 9. Time penalty of *Naive* routing at GR_north.

In different circumstances, GR_north is the farthest sensor node from the GS, leading to a higher misalignment. This results in more requests being penalised when selecting the first available BR, as seen in Figure 9. Approximately 27 % of the requests to GR_north (i.e. 9 % of the total number of requests), are negatively impacted by this.
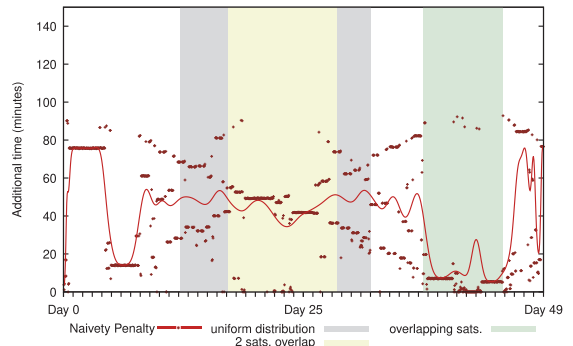

Figure 10. Time penalty of *Naive* routing at GR_south.

Finally, Figure 10 shows the impact of *Naive* routing for requests to GR_south. The number of affected requests is lower than in GR_north, with only 13 % of penalised requests. Despite this, both locations share similarities in how they are affected by different swarm phases.

V. CONCLUSION

In this paper, the concept of the Internet of Arctic Things was introduced, demonstrating how a freely drifting swarm of small satellites can be used for supporting communications in the Arctic. The different phases that such a satellite swarm can assume were analysed, as well as their impact on communications. These satellites do not require thrusters for station keeping, meaning that they are simpler and cheaper than solutions using a uniform constellation during the mission lifetime. This allows for launching more satellites within the same budget, adding redundancy to the system.

An experimental assessment was conducted, emulating real IoT-protocol implementations combined with 3 simulated satellite orbits and 4 ground nodes deployed in the Arctic. These protocols were chosen for their low computation and communication overhead. In particular, IPv6 and 6LoWPAN were used together with CoAP as the basis of the defined networking architecture.

The obtained results indicate that a low number of lost requests/replies can be achieved ($< 5 \%$), while keeping overhead as low as 27 % when using CoAP with non-confirmable messages. This confirms that low-cost smallsats can effectively be used to provide coverage for different locations in the Arctic using COTS communication technologies and standardised networking protocols. Moreover, this can be seen as a dedicated and affordable alternative to commercial satellite solutions.

A new satellite-aware cross-layer routing approach was also tested, revealing an improvement of the end-to-end time of request, up to 93 min less, when compared against a routing approach based on simple hop-count metrics. This result confirms that future networking solutions may be *smarter*, benefiting from upper-layer knowledge about satellites' ground tracks in relation to the ground nodes' positions.

REFERENCES

[1] R. Birkeland and A. Hornig, "On how a cubesat swarm can improve the coverage for an arctic ground based sensor network," in *Proc. ESA Small Satell. Syst. Services*, 2016, pp. 1–13.

[2] R. Birkeland, "Proposal for a satellite communication payload for sensor networks in the arctic area," in *Proc. 65th Int. Astron. Congr.*, 2014, pp. 6862–6865.

[3] Arctic Council. (2017). *Telecommunications Infrastructure in the Arctic*. [Online]. Available: https://oaarchive.arctic-council.org/bitstream/11374/1924/2017-04-28-ACS_Telecoms_REPORT_WEB-2.pdf

[4] ESA. (2011). *ESA Artes Articom*. Accessed: Apr. 2018. [Online]. Available: https://artes.esa.int/projects/articom

[5] Iridium Communications Inc. (2013). *Iridium Next: Advanced Technology. Iridium NEXT: Advanced Technology*. [Online]. Available: http://www.iridium.com/About/IridiumNEXT/Technology.aspx

[6] R. Birkeland, D. Palma, and A. Zolich, "Integrated smallsats and unmanned vehicles for networking in remote locations," in *Proc. 68th Int. Astron. Congr.*, 2017, pp. 6288–6295.

[7] R. Birkeland, "Freely drifting cubesat constellations for improving coverage for arctic sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[8] A. G. C. Guerra, F. Francisco, J. Villate, F. A. Agelet, O. Bertolami, and K. Rajan, "On small satellites for oceanography: A survey," *Acta Astronautica*, vol. 127, pp. 404–423, Oct./Nov. 2016.

[9] (2018). Sky and Space Global. [Online]. Available: https://www.skyandspace.global/

[10] (2018). Astrocast—The Nanosatellite IoT network. [Online]. Available: https://www.astrocast.com/

[11] (2018). *HeliosWire*. [Online]. Available: https://helioswire.com/

[12] L. Lambrinos, C. Djouvas, and C. Chrysostomou, "Applying delay tolerant networking routing algorithms in maritime communications," in *Proc. IEEE 14th Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2013, pp. 1–6.

[13] L. Torgerson *et al.*, *Delay-Tolerant Networking Architecture*, document RFC 4838, Oct. 2015. [Online]. Available: https://rfc-editor.org/rfc/rfc4838.txt

[14] C. Bormann, K. Hartke, and Z. Shelby, *The Constrained Application Protocol (CoAP)*, document RFC 7252, Jun. 2014. [Online]. Available: https://rfc-editor.org/rfc/rfc7252.txt

[15] M. Auzias, Y. Mahéo, and F. Raimbault, "CoAP over BP for a delay-tolerant Internet of Things," in *Proc. 3rd Int. Conf. Future Internet Things Cloud*, Aug. 2015, pp. 118–123.

[16] S. Deering and R. Hinden, *Internet Protocol, Version 6 (IPv6) Specification*, document RFC 2460, Dec. 1998. [Online]. Available: https://rfc-editor.org/rfc/rfc2460.txt

[17] M. de Sanctis, E. Cianca, G. Araniti, I. Bisio, and R. Prasad, "Satellite communications supporting Internet of remote things," *IEEE Internet Things J.*, vol. 3, no. 1, pp. 113–123, Feb. 2016.

[18] Y.-G. Hong, C. Gomez, A. R. Sangi, T. Aanstoot, and S. Chakrabarti. (Mar. 2018). IPv6 Over Constrained Node Networks (6lo) Applicability & Use Cases, Internet Engineering Task Force, Internet-Draft draft-ietf-6lo-use-cases-04. [Online]. Available: https://datatracker.ietf.org/doc/html/draft-ietf-6lo-use-cases-04

[19] G. Liu and S. Zhang, "A survey on formation control of small satellites," *Proc. IEEE*, vol. 106, no. 3, pp. 440–457, Mar. 2018.

[20] M. N. Sweeting, "Modern small satellites-changing the economics of space," *Proc. IEEE*, vol. 106, no. 3, pp. 343–361, Mar. 2018.

[21] N. H. Crisp, K. Smith, and P. Hollingsworth, "Launch and deployment of distributed small satellite systems," *Acta Astronautica*, vol. 114, pp. 65–78, Sep./Oct. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S009457651500171X

[22] A. Dono, L. Plice, J. Mueting, T. Conn, and M. Ho, "Propulsion trade studies for spacecraft swarm mission design," NASA, Washington, DC, USA, Tech. Rep. ARC-E-DAA-TN51390, 2018. [Online]. Available: https://ntrs.nasa.gov/search.jsp?R=20180001729

[23] A. Zolich *et al.*, "Survey on communication and networks for autonomous marine systems," *J. Intell. Robotic Syst.*, Apr. 2018.

[24] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE Standard 802.15.4-2011, Sep. 2011, pp. 1–314.

[25] G. Montenegro, J. Hui, D. Culler, and N. Kushalnagar, *Transmission of IPv6 Packets over IEEE 802.15.4 Networks*, document RFC 4944, Oct. 2015. [Online]. Available: https://rfc-editor.org/rfc/rfc4944.txt

[26] P. Thubert and J. Hui, *Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks*, document RFC 6282, Sep. 2011. [Online]. Available: https://rfc-editor.org/rfc/rfc6282.txt

[27] A. Lindgren, A. Doria, E. B. Davies, and S. Grasic, *Probabilistic Routing Protocol for Intermittently Connected Networks*, document RFC 6693, Aug. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6693.txt

[28] L. Wood, P. Holliday, D. Floreani, and W. M. Eddy, "Sharing the dream," in *Proc. Int. Conf. Ultra Modern Telecommun. Workshops*, Oct. 2009, pp. 1–2.

[29] D. T. Kelso. (1998). *Frequently Asked Questions: Two-Line Element Set Format*, [Online]. Available: https://celestrak.com/columns/v04n03/

[30] Aalborg University. (Sep. 2014). *AAUSAT3*. [Online]. Available: http://www.space.aau.dk/aausat3/

[31] Analytical Graphics, Inc. (2016). *STK*. Accessed: Apr. 2016. [Online]. Available: http://www.agi.com/products/stk/

[32] R. Birkeland and D. Palma, "Freely drifting small-satellite swarms for sensor networks in the arctic," in *Proc. 3rd Int. Congr. Inf. Commun. Technol.*, 2018, pp. 175–190.

[33] D. Palma, A. Zolich, Y. Jiang, and T. A. Johansen, "Unmanned aerial vehicles as data mules: An experimental assessment," *IEEE Access*, vol. 5, pp. 24716–24726, 2017.

[34] G. Tanganelli, C. Vallati, and E. Mingozzi, "CoAPthon: Easy development of CoAP-based IoT applications with Python," in *Proc. IEEE 2nd World Forum Internet Things (WF-IoT)*, Dec. 2015, pp. 63–68.

[35] B. Rhodes. (2015). *Pyephem Home Page*. Accessed: Oct. 2015. [Online]. Available: http://rhodesmill.org/pyephem/

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Appendix B

List of Other Papers and Contributions

The listed papers are results of work and contributions during the candidate's engagement at NTNU, but they are not included as a part of the thesis.

B.1 Papers and Contributions on Related Topics

The following works, deliverables to the Software-defined Intermittent Networking project, are linked to this research.

> D. Palma, A. Zolich, and R. Birkeland, " Software-defined Intermittent Networking - Architecture Specification," October 2016, H2020 grant number 699924. [Online]. Available: `https://sinet.item.ntnu.no/wp-content/uploads/2016/10/\D12_Architecture_SINet.pdf`

> D. Palma, A. Zolich, and R. Birkeland, "Software-defined Intermittent Networking - Reference Scenario and Requirements Definition," October 2016, H2020 grant number 699924. [Online]. Available: `https://sinet.item.ntnu.no/wp-content/uploads/2016/10/\D11_Scenario_SINet.pdf`

> A. Zolich, D. Palma, R. Birkeland and Y. Jiang, "A multi-hop intermittent wireless sensor network with unmanned aerial vehicles and satellite links for the Arctic," presented at *ReCAMP Flagship Workshop, 5–6 April 2016, Tromsø, Norway* .

The following papers are on related topics; a survey on CubeSat propulsion systems and a survey on the use of Software Defined Radio for satellite communications.

> P. E. Skanke and R. Birkeland, "CubeSat propulsion – expanding the possibilities of the affordable space platform," in *Proceedings of ESA Small Satellites Systems and Services 2018*, 2018.

> G. Quintana-Díaz and R. Birkeland, "Software-defined radios in satellite communications," in *Proceedings of ESA Small Satellites Systems and Services 2018*, 2018.

B.2 Papers from Workshops

The following selected works are result of contributions during various workshops during the PhD study, where the work have been published in journals and magazines.

G. E. Shephard et.al "Assessing the added value of the recent declaration on unregulated fishing for sustainable governance of the central arctic ocean," *Marine Policy*, vol. 66, pp. 50 – 57, 2016. [Online]. Available: `http://www.sciencedirect.com/science/article/pii/S0308597X1600018X`

O. Kara, R. Birkeland, L. L. Zhang, and U. Kaytaz, "Future cubesat swarms pose signifcant communications challenges," *ROOM - The Space Journal*, pp. 18–24, 2018.

L. Bacsardi, R. Birkeland, A. Hornig, M. Shar, B. Morrison, and Y. Tsodikovich, "Present and the future of space internet: The space generation perspective," *New Space*, vol. 5, no. 4, pp. 257–267, 2017.

B.3 Papers Related to the NUTS Student Satellite

These are papers related to the NUTS student satellite project, with contributions from the author.

Mathias Tømmer et.al, "Testing of radio communication subsystems for the NUTS CubeSat on a meteorological balloon flight from Andøya in 2014," in *Proceedings of the 22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research*, ser. ESA Special Publication. ESA, 2015.

Roger Birkeland et.al, "The NUTS CubeSat project: Spin-offs and technology development," in *Proceedings of the 22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research*, ser. ESA Special Publication. ESA, 2015.

J. Grande, R. Birkeland, A. Gjersvik, S. V. Mathisen, and C. Stausland, "Norwegian student satellite program – lessons learned," in *Proceedings of The 68th International Astronautical Congress*, 2017.

R. Birkeland, A. Gjersvik, and J. Grande, "The benefit of project based courses as a " first contact " between students and space industry," in *68th International Astronautical Congress*, 2017.

Appendix C

Comparable Solutions

In Table C.1 an evaluation of services discussed in Section 2.3.1. The table does not include all of the new IoT-constellations, but a selection of them. Currently 18 start-ups planning for 1600 satellites [49]. The sources for information are listed in Table C.1. The systems are classified as the following types:

A   Asset tracking
B   Narrowband
C   IoT
D   Broadband

Asset tracking is services that commonly only allow for transmission of a few short messages every day, for example, containing the position of an asset. A narrowband service means that two-way data communication is possible, with a bit-rate up to a few 100 kbps. IoT services resemble asset tracking, but other parameters than just position are expected. Also, two-way communication may be possible. Broadband services allows for two-way communication with data rates over some 100 kbps.

The column "Oper.?" lists if the system is operational, in test phase or when public information indicate start of operations. Column "Freq" lists which frequency band used (if known). Column "Type" classifies the system. Column "Capacity" indicates the bit rate available, where "high" means broadband and "low" means a few kb per day. Column " Con't cov" lists if continuous coverage can be expected. Column "Arctic" indicates if operations in the Arctic is expected. Column "Suitable" assesses if the system may be used for an application of the type discussed in this thesis.

	System	Oper.?	Freq	Type	Capacity	Con't cov.	Arctic	Suitable	Justification/comment
1	OrbComm	yes	VHF, (L)	A	low	no	some	no	Short, random messages, no Arctic coverage. Own set of satellites. Evolved from type A to C. L-band through Inmarsat
2	ARGOS	yes	UHF	A	low	no	yes	no	Short, random messages. Receivers on NOAA satellites
3	Iridium SDB	yes	L	A	low	yes	yes	no	Short messages only
4	AIS	yes	VHF, (L)	A	low	no	yes	no	Tracking vessels (and installations) only
5	ADS-B	testing	VHF	A	low	no	partial	no	Tracking airplanes only
6	Iridium	yes	L	B	2.4 kpbs	yes	yes	maybe	Too low throughput. Can be used for low-rate two-way comms. Bundle bands --> large terminals.
7	Globalstar	yes	L	B	9.6 kbps	yes	little	no	Limited tracking services in the Arctic
8	Inmarsat	yes	L	B	20 kpbs	yes	no	no	No Arctic service
9	Gonets	--	UHF	B	2.4 - 9.6 kbps	planned	yes	no	Too low rate
10	Thurya	yes	L	B	15 - 444 kbps		no		No Arctic coverage
11	Inclined GEO TRDS	yes	UHF, X	D		no	partial	no	Military or US gov't. For larger systems. Used in Antartctica. Used by NOR military too.
12	StarLink	2020	Ka, Ku, V	D	High	yes	partial	maybe	First deployment in 53 deg orbit! Max inkl 81 deg. No polar coverage the first period.
13	OneWeb	2020	Ku	D	High	yes	Probably	maybe	No ISL! More GWs Indications of development for mobile equipment. B2B service model?
14	Norwegian HEO	--	Ka, Ku?	D	High	yes	yes	No	Too big and power hungry terminal
15	Kepler's Kipp	testing	Ku	D	High	no	yes	No	Too big and power hungry terminal
16	Telesat	2022	Ku/Ka	D	High	yes	yes	No	Too big and power hungry terminal
17	VDES	testing	VHF	B	Low	no	yes	maybe	Shared system, limited capacity, low rate availability only? Consider use link-layer?
18	OQ Technology	--		C	Low	not known	not known	no	Too low rate
19	Astrocast	2020		A/C	Low	not known	not known	no	Too low rate
20	AISTECH	2020		A	Low	not known	not known	no	Too low rate
22	Helios Wire	2019?	S	A/C	low	no	not known	no	Too low rate
23	Sky and Space	testing	S	B/C	low	no	no	no	No polar coverage
24	Hiber Global	2020		C	low	no	probably	no	too low rate
25	Loon	testing	LTE	D	Medium	variable	likely not	no	Targeted for more populated zones?
26	HAPS	testing	LTE (?)	B	Medium/high	variable	maybe	maybe	Stratobus and Zephyr are under development and testing. Can be an alternative? But still "private" network
	System	Oper.?	Freq	Type	Capacity	Con't cov.	Arctic	Suitable	Justification/comment

Figure C.1: Comparable Communication Systems

C.1   Sources

Table C.1 lists available sources of information for each of the discussed systems.

C.2   Iridium NeXt

With the Thales MISSION link terminal, Iridium NeXT can provide up to 700 Kbps up and 352 kpbs down. Maximum power consumption is listed to be 132 W, typical power consumption is listed as 84 W [184].

Table C.1: Sources for information on various satellite systems

	System name	Link(s)
1	OrbComm	https://www.orbcomm.com/en/networks/satellite
2	ARGOS	http://www.argos-system.org/
3	Iridium SDB	https://www.iridium.com/services/iridium-sbd/
4	AIS	[38, 186]
5	ADS-B	[187]
6	Iridium	https://www.iridium.com/network/iridium-next/
7	Globalstar	https://www.globalstar.com/products
8	Inmarsat	http://inmarsat.com
9	Gonets	http://www.gonets.ru/eng/services/terminals/gonets-terminals/#abontermMO
10	Thurya	http://www.thuraya.com/
11	Inclined GEO and TDRSS	https://www.army-technology.com/projects/skynet/ https://www.tu.no/artikler/na-har-forsvaret-fatt-bredbandsdekning-i-arktis/347616 https://www.usap.gov/technology/contentHandler.cfm?id=1935
12	StarLink	https://www.nbcnews.com/science/space/how-spacex-plans-test-its-satellite-internet-service-2016-n370196 https://apps.fcc.gov/oetcf/els/reports/442_Print.cfm?mode=current&application_seq=6608&license_seq=66693
13	OneWeb	https://docs.fcc.gov/public/attachments/DOC-345467A1.pdf https://spacenews.com/oneweb-shifts-first-launch-to-years-end/ https://spacenews.com/oneweb-says-regulatory-concerns-main-reason-its-forgoing-inter-satellite-links/ http://www.itu.int/en/ITU-R/space/workshops/2017-Bariloche/Presentations/16%20-%20Mariah%20Shuman%20Oneweb.pdf http://www.oneweb.world/in-the-news/p3
14	Norwegian HEO	[52, 127]
15	Kepler's Kipp	http://www.keplercommunications.com/blog/item/first-launch
16	Telesat	https://www.telesat.com/services/leo/why-leo
17	VDES	[122]
18	OQ Technology	http://www.oqtec.space/other_services/
19	Astrocast	https://www.astrocast.com/ https://spacenews.com/d-orbit-to-launch-10-astrocast-satellites-on-vega-rocket/
20	AISTECH	http://www.aistechspace.com/ https://www.satellitetoday.com/launch/2018/07/16/aistech-gomspace-will-build-6-more-nanosatellites/
22	Helios Wire	https://helioswire.com/technology/ https://spacenews.com/helios-wire-sees-a-hidden-fortune-in-finding-lost-assets/
23	Sky and Space Global	https://www.zdnet.com/article/sky-and-space-completes-nano-satellite-testing/ https://www.skyandspace.global/operations-overview/
24	Hiber Global	https://support.hiber.global/hc/en-us
25	Loon	[80]
26	HAPS	https://www.nbcnews.com/tech/innovation/facebook-wi-fi-drone-size-747-could-fly-2015-n210546 [78] [79]

Appendix D

Justifications for Cost Estimates

The following values have been used as basis for the cost comparison analysis presented in Section 7.4. Values are informal, best effort, estimates based on public available information from suppliers, or based on discussions with colleagues.

Proposed satellite system

- Development costs: $ 256 000 USD
- HW cost per satellite: $ 64 000 USD
- Launch per satellite: $200 000 USD
- Operational costs: $ 6 000 USD (per year)

Iridium

Cost for Iridium Pilot (OpenPort) is calculated from information available: `http://www.groundcontrol.com/Iridium_Openport.htm#Plans`

UAV-Campaigns

- Operational cost per campaign: $ 38 400 USD
- Data harvesting time per campaign: 5 hours
- Data rate: 50 Mbps
- Data volume per campaign 112 500 MB

Airplane Campaigns

- Trip cost: $ 26 900
- Flight time: 7 hours
- Data harvesting time: 3 hours
- Data rate 15: Mbps
- Data volume per campaign: 20 250 MB

Appendix E

Data Volume Calculations

The following values are the basis for yearly data volume presented in Section 7.3.2. Data for one frequency channel is presented. The data volume for 19.2 kbps is presented in Figure E.1 and the data volume for 100 kbps is presented in Figure E.2.

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Baseline - 1 satellite	Usable rate pr. sat [kbps]	19,2	16,8	14,2	12,4	18,2	16,0
	Pass [kB]	1 440	1 260	1 066	932	1 368	1 197
	Day [MB]	20	18	15	13	19	17
	Year [MB]	7 358	6 439	5 445	4 765	6 990	6 117
	Year (90% avail) [MB]	*6 623*	5 795	4 901	4 288	6 291	5 505
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	100 %	88 %	74 %	65 %	95 %	83 %

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Constellation - 2 satellites	Usable rate pr. sat [kbps]	19,2	16,8	14,2	12,4	18,2	16,0
	Scale factor	2					
	Pass [kB]	2 880	2 520	2 131	1 865	2 736	2 394
	Day [MB]	40	35	30	26	38	34
	Year [MB]	14 717	12 877	10 890	9 529	13 981	12 233
	Year (90% avail) [MB]	13 245	11 589	9 801	8 576	12 583	11 010
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	200 %	175 %	148 %	130 %	190 %	166 %

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Swarm - 3 satellites	Usable rate pr. sat [kbps]	19,2	16,8	14,2	12,4	18,2	16,0
	Scale factor	2,65					
	Pass [kB]	3 819	3 342	2 826	2 473	3 628	3 174
	Day [MB]	53	47	40	35	51	44
	Year [MB]	19 514	17 075	14 441	12 636	18 539	16 221
	Year (90% avail) [MB]	17 563	15 368	12 997	11 372	16 685	14 599
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	265 %	232 %	196 %	172 %	252 %	220 %

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Swarm - 9 satellites	Usable rate pr. sat [kbps]	19,2	16,8	14,2	12,4	18,2	16,0
	Scale factor	6,91					
	Pass [kB]	9 953	8 709	7 365	6 445	9 456	8 274
	Day [MB]	139	122	103	90	132	116
	Year [MB]	50 861	44 504	37 637	32 933	48 318	42 278
	Year (90% avail) [MB]	45 775	40 053	33 874	29 639	43 486	38 051
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	691 %	605 %	511 %	448 %	657 %	575 %

Figure E.1: Calculation of goodput and yearly data volume for 19.2 kbps link

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Baseline - 1 satellite	Usable rate pr. sat [kbps]	100	88	74	65	95	83
	Pass [kB]	7 500	6 563	5 550	4 856	7 125	6 234
	Day [MB]	105	92	78	68	100	87
	Year [MB]	38 325	33 534	28 361	24 815	36 409	31 858
	Year (90% avail) [MB]	*34 493*	30 181	25 524	22 334	32 768	28 672
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	100 %	88 %	74 %	65 %	95 %	83 %

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Constellation - 2 satellites	Usable rate pr. sat [kbps]	100	88	74	65	95	83
	Scale factor	2					
	Pass [kB]	15 000	13 125	11 100	9 713	14 250	12 469
	Day [MB]	210	184	155	136	200	175
	Year [MB]	76 650	67 069	56 721	49 631	72 818	63 715
	Year (90% avail) [MB]	68 985	60 362	51 049	44 668	65 536	57 344
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	200 %	175 %	148 %	130 %	190 %	166 %

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Swarm - 3 satellite	Usable rate pr. sat [kbps]	100	88	74	65	95	83
	Scale factor	2,65					
	Pass [kB]	19 890	17 404	14 719	12 879	18 896	16 534
	Day [MB]	278	244	206	180	265	231
	Year [MB]	101 638	88 933	75 212	65 811	96 556	84 487
	Year (90% avail) [MB]	91 474	80 040	67 691	59 229	86 900	76 038
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	265 %	232 %	196 %	172 %	252 %	220 %

		Raw		6loWPAN		Custom	
		Not coded	Coded	Not coded	Coded	Not coded	Coded
Swarm - 9 satellite	Usable rate pr. sat [kbps]	100	88	74	65	95	83
	Scale factor	6,91					
	Pass [kB]	51 840	45 360	38 362	33 566	49 248	43 092
	Day [MB]	726	635	537	470	689	603
	Year [MB]	264 902	231 790	196 028	171 524	251 657	220 200
	Year (90% avail) [MB]	238 412	208 611	176 425	154 372	226 492	198 180
	Rel goodput	90 %	79 %	67 %	58 %	86 %	75 %
	Rel goodput vs. baseline	691 %	605 %	511 %	448 %	657 %	575 %

Figure E.2: Calculation of goodput and yearly data volume for 100 kbps link

Appendix F

Calculations for Coverage and Satellite Overlap

Systems Toolkit (STK) was used to simulate coverage from the satellite swarms and compare this to the coverage of a constellation of the same number of satellites.

The satellites in the swarm have orbit orbital properties as defined in Table 4.1. For nine satellites, all satellites are used. For three satellites, satellites 1, 5, and 9 are used. All satellites in the swarm are deployed at the same location with simulation start date 2 Jan 2018 11:00:00.000 UTCG. STK slices the area of interest into three regions; the northern most region is evaluated.

F.1 Three Satellites

Between `17 Jan 2018 02:10:00.000 UTCG` and `19 Jan 2018 02:10:00.000 UTCG`, the three satellites are approximately uniformly distributed. The swarm is simulated between `2 Jan 2018 11:00:00.000 UTCG` to `14 Feb 2018 11:00:00.000 UTCG`, a period of 43 days, from full overlap to full overlap.

Results

- Coverage from constellation: 43% of total simulated time
- Equivalent coverage time from constellation for the full simulation duration of 43 days: 443.78 hours
- Average simulated coverage time from swarm: 392.3 hours
- Swarm coverage compared to constellation coverage: $392.3/443.78 = 0.884$
- Effective number of satellites in swarm: 2.652

F.2 Nine Satellites

Between `22 Jan 2018 11:00:00.000 UTCG` to `24 Jan 2018 11:00:00.000 UTCG`, the nine satellites are uniformly distributed, so coverage from this period is used as comparison for coverage from the swarm. The swarm is simulated between `2 Jan 2018 11:00:00.000 UTCG` and `3 Jul 2018 11:00:00.000 UTCG`

Results

- Coverage from constellation: 100% of total simulated time
- Equivalent coverage time from constellation for the full simulation duration of 182 days: 4368 hours
- Average simulated coverage time from swarm: 3353.48 hours
- Swarm coverage compared to constellation coverage: $3353.48/4368 = 0.768$
- Effective number of satellites in swarm: 6.912

Acronyms

6LoWPAN IPv6 over Low power Wireless Personal Area Networks. 31–33, 36, 90, 92, 93, 95, 103, 109, 154, 161, 166, 167

ACK ACKnowlegde. 49, 85, 88, 99, 100, 106–108, 125

ACM Adaptive Coding and Modulation. 84, 116, 118, 123, 124, 134, 135, 162, 168

ADCS Attitude Determination and Control System. 57, 67, 75, 76, 80, 118, 129, 139, 140, 144, 146, 149

ADS-B Automatic Dependent Surveillance – Broadcast. 24

AIS Automatic Identification System. 24, 52

AMOS Centre for Autonomous Marine Operations and Systems. vi, 18, 167

ARQ Automatic Repeat reQuest. 49, 85, 88, 89, 111, 125

ASV Autonomous Surface Vehicles. 44

AUV Autonomous Underwater Vehicles. 44, 45

AWGN Additive White Gaussian Noise. 89, 113

BER Bit Error Rate. 21, 22, 121, 124–127, 134, 135, 162

CAMOS Coastal and Marine Operations and Surveillance. vi, 6, 18

CCSDS Consultative Committee for Space Data Systems. 32

CDMA Code Division Multiple Access. 85

CDS CubeSat Design Specification. 137

CMS Coding and Modulation Scheme. 124

CoAP Constrained Application Protocol. 30, 32, 33, 36, 91–93, 95, 103, 109, 166, 167

COTS Commercial Off-The-Shelf. 27, 32, 38, 138, 155, 164, 167

CPS Cyber-Physical System. 18

CRC Cyclic Redundancy Check. 88

DTN Delay-Tolerant Network. 91, 93, 96, 106

ECSS European Cooperation for Space Standardization. 132, 137

EESS Earth-Exploration Satellite Service. 21, 55, 112, 113, 118, 129, 135, 142, 143, 162

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NOAA National Oceanic and Atmospheric Administration. 25

NORM NACK-Oriented Reliable Multicast. 33

NRC Norwegian Research Council. vi, 168

NSC Norwegian Space Center. vi

NTNU Norwegian University of Science and Technology. vi

NWN Network node. 46–49, 79, 83, 89, 105, 106, 110, 164

OBC On-Board Computer. 139, 140, 144, 145

OSI Open Systems Interconnection. 83

PER Packet Error Rate. 125

PHY Physical Network Layer. 84, 85

Protobuf Google Protocol Buffers. 33

QoS Quality of Service. 81, 110, 142, 143

RA Random Access. 86

RAAN right ascension of the ascending node. 58, 61, 62

RFI Request for Information. 156

RFP Request for Proposal. 156

SAR Search-and-Rescue. 2

SC&C Science Command and Control. 21, 43, 47–49

SCADA Supervisory Control And Data Acquisition. 31

SDB Short Data Burst. 19, 24, 148

SDG Sustainable Development Goals. 4

SDN Software-Defined Networking. 48

SDR Software Defined Radio. 32, 36, 89, 124, 144, 155, 163, 167, 168, 257

SEE Single Event Effect. 27

SLR Satellite Laser Ranging. 68

SN Sensor node. 46, 48, 49, 69, 134, 143

SoC System on Chip. 145

SPG4 Simplified perturbations model. 62, 90

SSO Sun-Synchronous Orbit. 61, 63, 64, 79

SSTL Surrey Satellite Technology Ltd. 28

STK Systems Toolkit. 37, 59, 62, 69, 116–118, 122, 130, 150, 269

TCP Transmission Control Protocol. 32, 33, 36, 82, 90

TDMA Time Division Multiple Access. 30, 31, 85, 87, 93, 162

TDRSS Tracking and Data Relay Satellite System. 26, 28, 32, 262

List of Definitions

ADS-B A tracking system for aircrafts. Used as replacement for secondary radar. 24

AIS An anti-collision and tracking system for marine vessels. 24

ALOHA A method for granting random access to a physical channel. A user will send the data it has, when it has data to send. It will listen for data from other users, and if it receives data when it transmits, it will decide it was a collision and therefore re-send its data later. 86

altitude The distance between the Earth surface and the satellite orbit. Also called orbit height. 59

ARGOS A satellite services providing tracking of devices or marine life. 2, 24

argument of the perigee Orbital parameter (ω) that describes how the orbit plane is oriented relative to the reference plane. 58

assigned mode A node producing (larger) amounts of data on a regular basis can operate in assigned mode. 86

AX.25 AX.25 is a link layer format, much used by radio amateurs, and also for several CubeSat missions. 32, 36

CDMA Use of spread spectrum in order to share the available RF bandwidth between users. Users can access the channel at the same time, using the full bandwidth. Will also uniquely identify messages meant for one recipient. 85

CPS A Cyber-Physical System is a system controlled by computer algorithms. Such as AUVs or other auto-pilots. 18

CubeSat A much-used form-factor for small satellites. Based on unit cubes of 10 cm^3, which equals 1U. Typical sizes are 1, 2, 3, 6 and 12U. The mass of 1U can be 1.33 kg. 4, 11, 26, 30–32, 63–66, 73, 86, 112, 137–139, 142–146, 158, 163–165, 167, 168

DGSN A proposed network of small and cheap ground stations for tracking satellites. 67, 68

eccentricity Orbital parameter (e) that describes the form (elongation) of the orbit ellipse. 58

elevation The elevation angle is the angle between the horizon and the line between the observer on Earth and the satellite. 59, 60

FDMA The RF resource is divided into a set of independent channels using a partition of the total available bandwidth allocated for the system. Users can operate simultaneously. 85

frame A structured chunk of data on the link-layer is called a frame. 82

GENSO Global Educational Network for Satellite Operations. An educational program coordinated by ESA for creation of a global ground station network for HAM/educational use. 25

GEO Geostationary orbit, where the orbital plane is aligned with the equator. The height of the orbit is approximately 36000 km. 2

Globalstar US company offering low-rate satellite data communications employing a LEO constellation. 2, 28

goodput The goodput of a system is the rate of transmitted application level data. This is lower than the systems throughput, as goodput excludes any protocol overhead or re-transmissions. 88, 105, 266, 267

HAM Popular "slang" for amateur ratio operations or equipment. 32, 112

HumSAT An educational satellite communication service, supported by ESA, IAF and UNOOSA. 25

inclination Orbital parameter (i) that describes the angle between the orbital plane and the Earths equator plane. 58, 59, 61

INMARSAT A maritime satellite communications system. 2

IPv6 The Internet Protocol (IP) version 6. 33, 48, 95, 103, 161

Iridium A planet-wide voice-and-data satellite communication network using LEO satellites. 3, 19, 24, 26, 28, 148, 156, 157

Iridium NeXT The next generation Iridium system capable of higher data rates. 24–26, 34, 261

Ka Ka-band (K-above) is a radio communication band that spans the 26.5 - 40 GHz frequency range (IEEE definition). 26, 36

Ku Ku-band (K-under) is a radio communication band that spans the 12 - 18 GHz frequency range (IEEE definition). 26, 36, 55

L-Band A radio communication band that spans the 1 - 2 GHz frequency range (IEEE definition). 24

LEO Low Earth Orbit. This is orbits with arbitrary inclinations and orbit heights between approx. 300 km to 2000 km. 2

LSTS Toolchain A toolchain from the Underwater Systems and Technology Laboratory at UPorto. 33

MAC Functions for how to divide the channel resource and grant access to individual users. Placed on Layer 2 of the OSI-model. 85

message A structured chunk of data on the application-layer is called a message. 82

new space New space (NewSpace) is a much used term representing the shift in the space industry from huge governmental funded programs and satellites to more commercial endeavors aiming to build better, cheaper and faster space systems. 6–8, 26, 161, 164, 167, 168

NORAD The North American Aerospace Defense Command are tracking satellites and other items in orbit (debris) in order to manage for example collision risk. 68

OneWeb A company aiming to provide mobile satellite communication planet wide, by launching a mega constellation of more than 800 satellites. They will base their network on using LTE. 3, 161

Orbcomm US company offering M2M communications for tracking, monitoring and control of mobile devices. Orbcomm uses a LEO constellation. 2, 24, 28

OSI model A much used model that describes the functions of the network stack of a communication system. 83, 84

packet A structured chunk of data on the network-layer is called a packet. 82

pyephem Python module for astronomical calculations. 59

RAAN Orbital parameter (Ω) that describes where the satellite crosses the equator plane (upward) with reference to the vernal point of the reference coordinate system. 58

random mode A node producing (smaller) amounts of data on non-regular (random) basis can operate in random mode. 86

RMS Root-mean-square, a way of describe an average signal level. 115

S-Band A radio communication band that spans the 2 - 4 GHz frequency range (IEEE definition). 112, 117, 118, 120, 129, 131–133, 142, 143, 145, 146

semi-major axis Orbital parameter (a) that is defined by the half the sum of the perigee and apogee distances from the center of the Earth. 58

sensitivity The sensitivity (level) of a receiver can be described as the signal needed at the receivers input in order to get the required signal-to-noise ration on the output for a given bit-error-rate and modulation [188]. 113

signaling Auxiliary traffic needed to allocate or change resources (frequency, modulation, TDMA-slots and more). Also, "non-user data"-traffic necessary for higher-level operation. 49

Single Event Effect the ionizing effect a charged particle may inflict on an electronic component. SEEs can be non-destructive (bit-flips), but in some cases it may be destructive latch-ups that can burn and destroy transistors [189]. 27

SSO A sun-synchronous satellite has a constant angle wrt. to the sun. 61

Starlink A mega constellation planned by SpaceX. The aim is to launch thousands of satellites.. 3

TDMA The RF resource is divided into time-slots, where individual users are allocated a pre-defined set of one or more slots in which the user is granted access to the full bandwidth of the RF-channel. 85

Total Ionizing Dose The total absorbed radiation dose experienced by a component. A component may be damaged if the TID exceeds its radiation hardening level [189]. 27

true anomaly Orbital parameter (ν) that describes the position of the satellite in the orbit. This is the only time-varying orbital parameter. 58, 65

TT&C Telemetry, Tracking and Command. 43, 52, 140, 144

UHF Ultra High Frequency. A radio communication band that spans 300 - 3000 MHz (ITU definition). Usually used to denote frequencies from 300 - 1000 MHz (IEEE definition). 29, 32, 51, 52, 55, 112, 114–118, 120, 123, 129, 131–133, 142, 143, 145, 146, 163

VHF Very High Frequency. A radio communication band that spans 30 - 300 MHz (ITU and IEEE definition). 32, 38, 51, 52, 55, 109, 112, 114, 115, 117, 123, 134

X X-band is a radio communication band that spans the 8 - 12 GHz frequency range (IEEE definition). 26

ZeroMQ ZeroMQ or ØMQ is a distributed message protocol that can be used on top of various network protocols. 33

Note: Not all definitions (especially regarding the network architecture) are identical in this thesis compared with the included papers.