Jakob Lund Johannessen

Evaluating the Effect of Satellite Communication on the Data Dissemination Protocol CAMFlooP in Areas with Limited Cellular Connectivity

Master’s thesis in Communication Technology and Digital Security
Supervisor: Peter Herrmann
Co-supervisor: Ergys Puka
July 2023

Master’s thesis

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Norwegian University of Science and Technology
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Title: Evaluating the Effect of Satellite Communication on the Data Dissemination Protocol CAMFlooP in Areas with Limited Cellular Connectivity
Student: Johannessen, Jakob Lund

Problem description:

Satellite systems like Starlink are supposed to help people staying connected in large deadspots, i.e., areas without cellular network connection, that can be found in large countries like Australia or Canada. Another method for large deadspots is the Context-Aware Message Flooding Protocol (CAMFlooP), that was developed at IIK. It uses device-to-device (D2D) communication like Sidelink from 3GPP to allow the data exchange between vehicles passing in the deadspot. This allows to forward messages to the vehicle supposed to leave the deadspot first. A simulator for CAMFlooP was developed based on the well-known Simulation of Urban MObility (SUMO).

The task of the master's thesis is to extend the SUMO simulation in a way that the impact of CAMFlooP can also be simulated for scenarios in which certain shares of vehicles in a deadspot are equipped with satellite connectivity like Starlink. Based on that, measurements shall be undertaken to find out about the benefit of CAMFlooP in a mixed environment, in which some vehicles use satellite access.

Approved on: 2023-05-18
Main supervisor: Herrmann, Peter, NTNU
Co-supervisor: Puka, Ergys, NTNU

Abstract

Today's cellular networks have large dead spots where there is no connectivity, according to connectivity maps such as [23a]. When vehicles find themselves in a dead spot, they could communicate with each other, relaying emergency messages over satellite links. Some emergency messages might be more visible than others, like an engine failure. In these cases, other drivers might stop by and offer assistance to the unfortunate vehicle. However, using Vehicle-to-vehicle (V2V) communication technology, messages can be transmitted between vehicles without human interaction, making all, including the non-visible emergency messages, available for message transmission by another vehicle. When some vehicles have satellite capabilities, emergency messages might be delivered much faster, compared to situations where the best carrier will deliver it once out of the dead spot.

Using protocols with flooding techniques, a lot of bandwidth is used for duplicate message transmission. Context-Aware Message Flooding Protocol (CAMFlooP) on the other hand is a protocol designed to reduce duplicate deliveries. In this thesis, CAMFlooP is evaluated when satellite capabilities are added to some of the vehicles in the simulation. Message delivery time improvement, as well as transmission duplication is considered, where it is seen that the CAMFlooP protocol performs very well.

Sammendrag

Dagens mobile nett har flere soner uten dekning, hvilket er synlig på sider som [23a]. Biler som befinner seg i disse sonene kan derimot kommunisere med hverandre med lokale nettverk de oppretter. På denne måten kan nødmeldinger bli overført til andre biler, slik at de kan bli sendt over Internett raskere. Noen nødmeldinger er mer synlig enn andre, slik som et motorstopp. Andre bilister kan se et motorstopp, og selv velge å stoppe for å hjelpe til. Derimot er det ikke like lett å oppdage andre nødsituasjoner, hvor det raskeste alternativet kan være å fortsette å kjøre. Ved å bruke kommunikasjon mellom biler, kan man også sende meldinger som ikke er synlige for mennesker i andre biler uten kontekst.

Dersom man legger til satellitt-tilkobling i noen av bilene, kan man sørge for at noen biler alltid har dekning til å overføre slike nødmeldinger, selv om de befinner seg i en sone uten dekning. Ved bruk av teknologi som masse-sender meldinger til alle mulige bærere av meldingen, vil man oppnå en stor grad av dupliserte meldinger. CAMFlooP, en protokoll utviklet på NTNU, kan sørge for raskere levering av meldingene, men samtidig redusere antall dupliserte leveranser. Denne masteroppgaven evaluerer hvorvidt satellitt-tilkobling i bilene påvirker leveringstiden på meldingene, og hvorvidt CAMFlooP er nødvendig for å redusere mengden duplikate meldinger som blir overført. Totalt sett leverer protokollen veldig bra, både når det gjelder leveringstid, og å redusere mengden dupliserte meldinger som blir overført.

Preface

This thesis is written at spring 2023, for the Department of Information Security and Communication Technology at the university Norwegian University of Science and Technology (NTNU).

I really want to thank Peter Herrmann, the responsible professor, and Ergys Puka, supervisor, for the excellent help and guidance when conducting this study. This thesis would not have been realized without their help. Their earlier work with the CAMFlooP protocol is at great interest for me, and having the opportunity to dive into how such a complex protocol can be combined with satellite connectivity has been very interesting. Working on all the different edge cases, and ensuring results are valid have been such an enjoyable task with their excellent guidance! The topic of the thesis was developed by myself, in cooperation with Herrmann and Puka. I am very happy to be able to write a thesis in such an interesting field of study.

Herrmann and Puka have help me a lot with my academic writing, which have been very important when writing this thesis!

Jakob Lund Johannessen
2023-07-17

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List of Acronyms

3GPP 3rd Generation Partnership Project.

5G NR 5G New Radio.

5G N.T.N 5G Non-Terrestrial Networks.

BTS base transceiver station.

CAMFlooP Context-Aware Message Flooding Protocol.

CDMA Code-division multiple access.

C-V2X Cellular Vehicle-to-everything.

GEO Geostationary orbit.

GPRS General Packet Radio Service.

GSM Global System for Mobile Communications.

LEO low Earth orbit.

LTE Long-Term Evolution.

MMS Mobile Satellite system.

OFDM Orthogonal Frequency Division Multiplexing.

SUMO Simulation of Urban MObility.

UE User Equipment.

V2V Vehicle-to-vehicle.

Chapter 1

Introduction

1.1 Motivation

As half of the worlds population lack access to broadband Internet [Har18], more work is needed to increase connectivity. According to Gartner, cell phones continue to have a huge incline in sales [Gar22]. With more smart phones being present, either more connectivity is needed, or more efficient way of communication. For a long time, development have been about sending more data, and finding faster ways to deliver it. Evaluating how one of these protocols with future technology may therefore be relevant.

1.2 Cellular networks

For decades, cellular networks have consisted of a base transceiver station (BTS) and a cellular phone User Equipment (UE). Both, the BTS and UE are abbreviations defined in [3GP21]. A BTS is a cell tower responsible cell coverage for UE's in a given area. These cell towers have been trough much development during the years. For a UE to establish connectivity, it must be within a certain range of the BTS. Large-scale networks span vast areas, forming a cellular network in which UEs hop from one station to another, see [3GP22]. According to [EAS+22], these networks perform sufficiently well in cities and urban areas. However, the cost of constructing base stations in regions with low population density is relatively high per square meter [MMK+11].

Cellular networks initially served merely as a medium for voice communication, similar to a landline. The first generation of cellular networks, known as 1G, was adopted during the 1980s and 1990s. Prior to 1G, portable phones had to connect to central operators and did not offer the high level of mobility that 1G provided. Global System for Mobile Communications (GSM) introduced a standard for analog voice communication having the same capabilities as the previos landline communication protocols. However, the paradigm began to shift with the advent of 2G, which did not only allow speech communication, but introduced the packet-switched digital cellular networks. General Packet Radio Service (GPRS) was a widespread packet-switched network standard based on the well-known GSM network [KSL12].

As the Internet gained much traction, and more users came to have their own devices, new technology was needed to meet the demand [KSL12]. The 3rd Generation Partnership Project (3GPP) is a collaboration between groups developing communication technology, created in order to standardize the development of radio technologies. In their publication [3GP99], 3G was introduced, with several package based communication technologies. Later Long-Term Evolution (LTE) was released from 3GPP, better known as 4G. [KSL12]. 5G is now the latest radio technology deployed, with numerous new features compared to the dated GSM standards. In 5G, technology such as 5G New Radio (5G NR) and 5G Non-Terrestrial Networks (5G N.T.N) is introduced. The new radio includes features using the new PC5 interface for device to device communication, while 5G N.T.N is the technique where satellite communication can be in stead of a traditional cell.

The traditional network topology has faced numerous challenges that have been addressed over the last 20+ years since the adoption of GPRS in 2000. For cellular networks, the key factors for improving network performance include:

- Coverage area
- Bandwidth
- Packet delay

Every base station has a limit to the amount of bandwidth, it can provide within its coverage area, similar to how a fiber optic cable has a total bandwidth limit. However, unlike a fiber optic cable, a base station also has a limit to how many parallel signal carriers it can handle. Both fiber optic cables, and the air interface use multiplexing in order to increase the total amount of throughput available. For years, different multiplexing techniques have been used, such as Orthogonal Frequency Division Multiplexing (OFDM) and Code-division multiple access (CDMA). Using multiplexing, one can achieve greater performance in networks by creating parallel data channels on the same medium. Several studies have looked into the performance of different multiplexing algorithms, such as [Faz93]. When the maximum number of users are connected, or the total bandwidth is already in use, it is not possible to deploy another BTS next to the one at capacity, because there is no more space on the air interface. However, with fiber optic cables, a completely other medium for communication is available if another cable is installed. Even though it is not possible to install another BTS using the same air interface, smaller celles can be used in order to increase the bandwidth in a geographical area.

1.3 Increasing bandwidth by smaller cells

Parallelizing base stations is not possible due to physical limitations associated with electromagnetic signals. Therefore, one way to increase the total bandwidth within the same physical space is by using smaller cells. By employing smaller cells, more base stations can serve the same land area, though they would need to be distributed at different locations. However, this approach would inevitably lead to higher infrastructure development costs.

The development of portable devices that can function as base stations could further advance this field of telecommunication. This concept is incorporated in the latest releases from 3GPP, which include specifications for 5G NR and 5G N.T.N. In [NHM+18], the authors have, using Wi-Fi Direct, divided one large network of nodes into smaller groups, which are communicating via a group owner to the backbone router. Using this technique, radios can use less transmission power, leading to less interference, and better network performance. Having capabilities to deploy smaller cells of connectivity with less transmission power, may therefore lead to better performing networks, also with the new technologi introduced with 5G.

1.4 Dead spots

Cellular networks span great distances on earths surface. However, some areas might be in the middle of some mountains, or just very remote, that the cellular connectivity is not prioritised in these areas. These places where there is no connectivity, is called a dead spot in this thesis. In dead spots, local Wi-Fi Direct networks can be created, and satellite networks are reachable. Cellular networks, on the other hand, are completely unavailable in a dead spot. A map of cellular connectivity for most of the carriers can be seen at some websites, such as nperf [23a].

1.5 Flooding techniques of routing messages

When flooding, all messages are transmitted to all other vehicles when possible. The technique guaranties the fastest possible delivery of messages as it is a brute force way of delivery messages. Just like a depth first search, all possible carriers are given the message, and will relay it to all other possible carriers. Technologies using flooding techniques may therefore use much more bandwidth than what is actually needed to transmit a message.

1.6 Sustainable networking

Over the last couple of years, applications have become more bandwidth-intensive, capitalizing on robust Wi-Fi at home and extensive cellular networks in cities.

However, this approach is not sustainable as the number of cellphones sold continues to increase [Gar22]. Instead of focusing solely on developing a network capable of supporting the increasingly high bandwidth usage of today's applications, an alternative approach is to reduce the bandwidth consumed by the applications themselves. This is one of the goals with the CAMFlooP protocol. The protocol was developed during the research of Ergys Puka and Peter Herrmann at NTNU. When vehicles find themselves in a dead spot, it is important that some messages, for example emergency messages, are delivered as fast as possible. Using flooding techniques, many messages are duplicated [PH19]. CAMFlooP, on the other hand, use navigation data from vehicles in order to calculate whether one vehicle will gain connectivity before another, thereby being a faster message carrier. Having this information, only the vehicles that gain an improvement in message delivery times will receive other vehicles' messages. These capabilities reduce the total number of messages sent in respect to flooding by a great factor, as seen in the study of Puka and Herrmann [PH21]. In this study, how CAMFlooP will perform in future networks with the new capabilities introduced in 5G is evaluated by further extending the simulator.

1.7 Satellite networks

Mobile Satellite system (MMS)s will integrate terrestrial networks with cellular networks in order to increase global connectivity [DFG00]. These satellites can extend connectivity where traditional cellular networks might be to expensive, or cellular traffic might be handed over when at capacity [DFG00]. As mentioned in [Har18], every other person on the planet lack a broadband Internet connection. Many companies are developing networks that will enhance the overall connectivity. For years, companies such as Viasat [Via23b] have delivered satellite broadband. The satellite Viasat-2, launched in 2017, and had its service launch date in February 2018 [Via23c]. These, Geostationary orbit (GEO) satellites have provided the Earths surface with satellite network for several years, but now other companies start taking on Viasat for building networks that outperform current satellite networks. GEO satellites certainly have a huge problem concerning network latency due to the long distance from the earths surface. Further, low Earth orbit (LEO) satellites, being closer to earth, have signification lower latency [HK99]. Actually, 25ms compared to 600ms+ according to Starlink themselves [Sta23].

Space X's Starlink [23b] and OneWeb [One23] are some of these companies, developing new networks using LEO satellites. Utilizing satellites as an alternative to traditional cellular network base stations can facilitate the deployment of communication networks in countries with underdeveloped infrastructure. These LEO satellites also currently support emergency messages from the iPhone 14 [App23].

As in [Har18], a lot of infrastructure is needed to build robust cellular networks. If this infrastructure is moved into space, fewer satellites can reach a larger area on land, thereby requiring less infrastructure. On the other hand, building these space networks is quite complex and energy consuming.

1.8 Research questions

When developing the CAMFlooP protocol, Puka and Herrmann did not consider the feature of satellite networks in future cell phones. Having an idea of this feature, we brainstormed, and figured out this capability can be of great interest. CAMFlooP's great performance in reducing the number of duplicate deliveries, as seen when using flooding techniques, ref [PH21], might be very well suited for these networks, while still improving message delivery time. Therefore, multiple research questions were developed:

- RQ1: How will satellite connectivity improve message delivery time?
- RQ2: In what factor will the CAMFlooP protocol reduce flooding with satellite enabled vehicles?

1.8.1 RQ1

The chances you survive in a medical emergency depends on the time it takes for an ambulance to get to your location [PSM+01]. Getting an emergency message out to the rescue team is therefore very important when in danger. Some emergencies might be more visible than others. If for instance a vehicle has an engine failure, other vehicles could stop by and relay the message when they gain connectivity. However, if there is an emergency where the best option is to continue driving, this emergency is invisible for other vehicles. In a scenario with V2V communication, these emergency messages could be seen by other vehicles, as they communicate with more than visual signals, such as a vehicle on the side of the road. Seeing how these messages delivery times will improve by adding satellite connectivity might therefore be very interesting. RQ1 is designed to find out how these extensions to the network will have an influence in future communication, or if V2V networks already perform sufficiently.

1.8.2 RQ2

The first possible delivery route would of course be found with flooding techniques, as the messages would find the fastest possible delivery route, similar to a depth first search. However, reducing the total transmits, and therefore also network cost, CAMFlooP might be an important part of these networks. RQ2 is therefore designed to conduct a study where we find out if CAMFlooP is relevant in these kind of networks, or if the factor of duplication is further reduced with more vehicles being satellite capable, practically reducing the seen size of dead spots.

In light of the argument suggesting that CAMFlooP might be redundant in situations where 'dead spots' have transient connectivity zones, this research aims to examine the continued relevance of CAMFlooP. The research questions are designed to evaluate whether CAMFlooP can still contribute to more sustainable networks, or whether this field of research might become less promising or even unproductive as satellite connectivity becomes more widely accessible to the public.

1.9 Synopsis

During this thesis a chapter about background for the study is presented in chapter 2. Much of this study is based on the previous work Puka and Herrmann have done with the CAMFlooP protocol and the simulator they have developed. Also some of the motivation is based on the new technology presented with 5G. Later a chapter about the implementation when extending the CAMFlooP simulator is presented in chapter 3. Several hours are used in the python based simulator to ensure results are correct. These results are then presented in the chapter 4, Results and Discussion. At the end of the thesis, future work is presented in chapter 5, before a conclusion is presented in chapter 6.

Chapter 2
Background

Several wireless technologies lay the foundation for studies like this, where multiple technologies are combined. Offloading data using Wi-Fi Direct is a field of study that has been extensively explored by many researchers, with Puka and Herrmann being particularly experienced in this field through their work on the CAMFlooP protocol [PHT20; PH21]. However, the integration of device-to-device communication technologies with satellite technology and the CAMFlooP protocol, done in this master project, is a novel extension of CAMFlooP. While heavily relying on the work of Puka and Herrmann, this study brings an interesting enhancement to CAMFlooP.

2.1 Wi-Fi Direct

Wi-Fi Direct [Wi-23] enables device-to-device communication. Devices can form their own local Wi-Fi network, where they can communicate without having the need for a router. With this capability, devices can create ad hoc multi hop networks, thereby presenting numerous new opportunities.

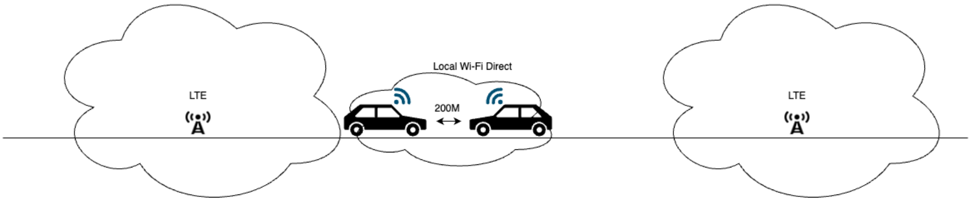


Figure 2.1: An illustration of non-satellite vehicles communicating via Wi-Fi Direct in a dead spot.

2.2 Simulation of Urban MObility

Testing with real vehicles on the roads can be very expensive. On the other hand, using Simulation of Urban MObility (SUMO) allows us to put vehicles in a simulated environment. This makes it much easier to do large studies without needing physical cars and costly equipment.

SUMO is responsible for the physics engine and running cars in pre defined routes. It will spawn and move all vehicles during a simulation. We have used the 86400 seconds of a day as the duration of a simulation. The simulator is developed by employees of the Institute of Transportation Systems [Deu23b] at the German Aerospace Center [Deu23a], according to [LBB+18]. It is an open source traffic simulator tool [LBB+18], under the EPL 2.0 license [Ecl23]. Using SUMO, different traffic behaviours can be simulated without the need for writing a custom physics engine from scratch. The APIs in SUMO is great interfaces for controlling the behaviour of vehicles or other traffic entities, while also having support to integrate with other simulators, such as Omnet. With the CAMFlooP protocol, a complex connectivity simulator such as Omnet would not be as effective as modeling it ourselves. Omnet is a great tool, but comes with large complexitiy, and it is seen as too heavy for our simulator. Several tools supporting SUMO exist, making the development of simulators easy, and gives great room for making complex applications. One of them is introduced in the following.

2.2.1 Traci

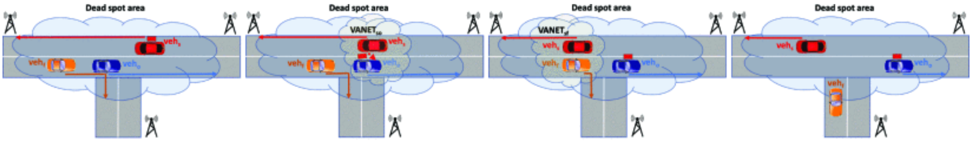
Traci [Ger23] is one of the tools provided with SUMO. It is an application programmable interface (API) to communicate with the SUMO server in real time. Using the interface, clients can communicate with the server to retrieve information, or dynamically make changes to the simulating environment, for example vehicles or routes. Using TCP/IP, Traci makes simulations easy to implement as the SUMO simulator is connected with high coherence, and loose coupling.

2.3 Data dissemination protocol

In research conducted by Puka and Herrmann, [PH19], a data dissemination protocol was introduced. The protocol was tested on Android Phones using Wi-Fi Direct for ad hoc communication, and cellular networks for delivering messages to external recipients. Later, this research was taken further when developing CAMFlooP protocol [PHT20], and the CAMFlooP simulator [PH21]. Using results from [PH19], a simulator with a more advanced protocol could be developed.

2.4 CAMFlooP

CAMFlooP [PHT20; PH21] is a context-aware messaging flooding protocol. It was designed by Puka and Herrmann during their research at NTNU. The protocol ais to reduce message delivery time for vehicles finding themselves in a dead spot, while also reducing the number of copies delivered. In this way, messages are only transmitted between vehicles if there is a practical benefit for speeding up the delivery. When speeding up message delivery, many vehicles can be a better choice than the current carrier. Flooding is therefore guaranteed to find the fastest message delivery, as all possible carriers will have the message. However, flooding the messages will lead to many duplicate deliveries [PH21].



(a) Time: 15:00. (b) Time: 15:05. (c) Time: 15:10. (d) Time: 15:15.

Figure 2.2: Example of message missing an opportunity. Source: [PHT20]

As seen in one example from [PHT20], in figure 2.2, a message is transmitted from the red vehicle to the blue vehicle, and then removed from the red vehicle. Unfortunately, the red vehicle meets an orange vehicle just after handing the message over to the blue vehicle. Since the orange vehicle is headed out of the dead spot with another route, the orange vehicle would have been the fastest route.

Therefore, Puka and Herrmann have introduced a transmission buffer and an opportunity buffer. These buffers are important in order for the protocol to have comparable performance in message delivery as flooding.

2.4.1 Transmission buffer

The transmission buffer is a buffer of messages where the vehicle, with it's context, does not know about any faster carriers. All messages in the transmission buffer will be delivered once the vehicle gains connectivity. If a vehicle A has a message in it's transmission buffer, and meet vehicle B, the two vehicles will evaluate which vehicle will leave the dead spot first. In the cases where vehicle B is fastest, vehicle A will transmit the message to vehicle B, which stores the message in it's transmission buffer. Messages in the transmission buffer can, therefore, be moved over to the opportunity buffer, when the vehicle meets another carrier with a possibility to deliver the message faster. Vehicle A therefore moves the message from it's transmission buffer, over to the opportunity buffer as more opportunities may arise.

2.4.2 Opportunity buffer

When a vehicle meets another vehicle that will be a faster carrier, the message is still stored in the opportunity buffer in stead of being removed from the vehicle. This way, another copy of the message is then transmitted to the other vehicle, when a new opportunity arises. The opportunity buffer is the feature of CAMFlooP, that ensures messages have the same possibilities for message improvement as flooding techniques. In the example in 2.2, the red vehicle would keep the message in its opportunity buffer, and transmit this message when meeting the orange vehicle. The orange vehicle would then keep the message in its transmission buffer, and deliver it at 15:15, upon leaving the dead spot. For this example, the message is duplicated once, which would be the same amount of copies as using flooding techniques. However, for larger studies, this feature of CAMFlooP shows that the duplication factor is massively decreased compared to flooding [PH21].

All messages are given an expiry time. Once the message is created, the originator estimates when it will leave the dead spot. This is then set as the expiry time for the message. After a message is expired, it is removed from the opportunity buffer, as the message most likely is delivered.

2.4.3 Development of CAMFlooP

In order to develop the CAMFlooP protocol, Puka and Herrmann have developed a simulator in Python based on the SUMO simulator for vehicle handling, see [PH21]. This Python-based simulator is responsible to run the CAMFlooP protocol and collect statistics from simulation runs in order to evaluate how the protocol behaves for V2V communication. Therefore, the project is based on three main components.

- CAMFlooP protocol
- SUMO simulator
- CAMFlooP simulator

CAMFlooP protocol

CAMFlooP protocol is developed in Python. Using the SUMO simulator, CAMFlooP is used to evaluate if messages should be transmitted to other vehicles or not in every simulator step, which is modeled as one second. The protocol is responsible for evaluating what messages to be transmitted or not over the V2V communication technology. SUMO updates each vehicle position, which is later used to evaluate what vehicles is inside the desired V2V communication range, and can from a Wi-Fi Direct group. Using SUMO, the CAMFlooP protocol evaluate each message for all vehicles every simulation step. The message buffers are therefore frequently updated, ensuring messages are only transmitted when an improvement is possible.

SUMO simulator integration

SUMO is responsible for the physics engine and running cars in predefined routes. It will spawn and move all vehicles during the 86400 seconds of a day used in the simulator. The vehicle simulator is instructed using the CAMFlooP simulator, and is then responsible to reroute vehicles if instructed to do so by CAMFlooP simulator.

The CAMFlooP simulator is a unique tool developed by Puka and Herrmann [PH21]. It is specifically designed to test various Wi-Fi Direct approaches when constructing V2V networks. The simulated environment is the route from Broken Hill to Mildura in New South Wales, Australia, a remote stretch of over 300km that is characterized by minimal cellular coverage. This makes it an ideal test bed for studying V2V connectivity in challenging conditions.

Road traffic patterns are accurately simulated using the SUMO software, while the wireless communication aspect is implemented in Python, leveraging real Wi-Fi Direct performance data to increase realism. The routes available in the simulator mirror the real-world route, offering a choice of driving from Broken Hill to Mildura or the reverse.

A unique feature of the simulator is the introduction of a variable p, which represents the probability of a vehicle abruptly changing its destination to side roads that also exist on the real highway between Mildura and Broken Hill. This side road is an endless, connectivity-free route, symbolizing situations where vehicles reside in a cellular dead spot or venture into areas with no connectivity such as when going camping. The number of vehicles in the area is taken from real traffic data, presented in [PH21]. The behavior of the vehicles is however, designed to be modular, in order to evaluate how the protocol is influenced in different scenarios.

CAMFlooP simulator

The CAMFlooP simulator is responsible for making the right instructions to the SUMO simulator in order to make sure the vehicles are spawned and ran at the correct way based on real world data. In the simulations, a simulator step of one second is used. Vehicles and messages might therefore be created every second. The CAMFlooP protocol is also evaluated every simulation step, making sure messages are transmitted between vehicles, or to its final destination when necessary.

Vehicles

During the simulations, several vehicles are spawned and traverse the roads modeled. These vehicles are equipped with devices capable of Wi-Fi Direct communication, as well as cellular LTE connectivity. The vehicles can accelerate, decelerate, and suddenly change their routes, all subject to the specified probability parameters. Traffic is generated based on real traffic probability data, thereby enhancing the accuracy of the simulations.

Creating messages

In the CAMFlooP simulator, data is evaluated looking at duplication of messages. A message is a simple "message" originating from a vehicle, and for simulating delivery times, the payload size of the message is not very important. Looking at large messages, delivery times might be slower, as the time used for transmitting the messages is increased, however, emergency messages are usually quite short. Therefore, message delivery times can be simulated without considering larger message payload sizes. Message prioritisation is also out of scope for this thesis, as that work is already carried out in another protocol of Puka and Herrmann. Different payload sizes will therefore be more important in that study. In order to evaluate the protocol performance compared to flooding techniques, seeing what messages are duplicated can be done using a simple approach where messages have a fixed length, and only contain their unique id. In Puka's and Herrmann's study, messages can be created by any vehicle, also when a vehicle has cellular connectivity.

2.5 New 5G technology

With 5G, new technologies are introduced, with many new capabilities. Tomorrows 5G network will be equipped with the 5G NR, and the future developed 5G N.T.N that don't depend on the typical base station topology [JC22]. Therefore, more work is necessary to evaluate how a protocol like CAMFlooP will fit in with the new technology. Future 5G networks are expected to revolutionize autonomous driving and contribute to improved road safety. [MVH21] discusses the evolution of Cellular Vehicle-to-everything (C-V2X), utilizing the PC5 interface. The PC5 interface enables direct communication from one vehicle to another without routing through a base station. Research of this nature has been important when considering the CAMFlooP protocol for further technologies.

2.6 Offloading data

In [PJAK13], it is seen that offloading data from a star topology to hybrid topologies, where nearby communication has an important role, can increase the overall bandwidth in the network. In [NHM+18], an SDN controller manages a better network of Wi-Fi Direct nodes, making the network more efficient. Using technology this way, more transmission channels can be utilized, as the same channels can be used in the same BTS station cell with less transmission power, or completely other frequencies are used with other technologies. Having these capabilities, the total bandwidth can be increased in a physical area.

2.7 Smartphones with satellite connectivity as of 2023

Currently, the iPhone 14 is one of the smartphones to have satellite connectivity [App23]. The Huawei Mate 50 series was the first smartphone to be launched with satellite connectivity, according to The Verge [Joh22].

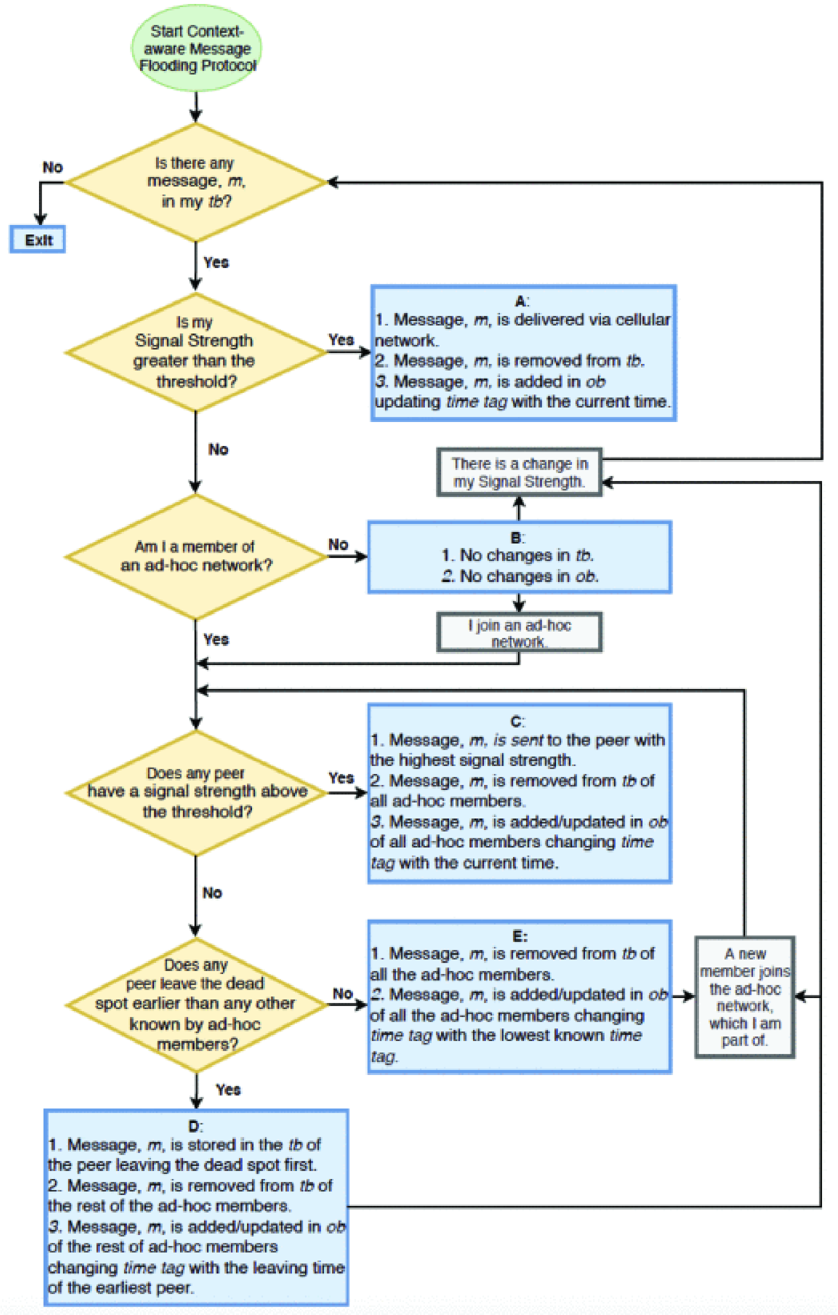


Figure 2.3: An overview of the Context-aware message flooding protocol of Puka and Herrmann. Source: [PHT20]

Chapter 3
Implementation

Numerous companies, including Starlink [23b] and Viasat [Via23a] ensure connectivity via satellite networks, even in absence of services from traditional base stations. Soon there will be a situation with more vehicles having satellite capabilities on the road. These vehicles will have the possibility to deliver messages right away, without having to wait for signal upon leaving a dead spot. Therefore, they can have huge impact on message delivery in dead spots. Even tough these vehicles do not find them selves in a dead spot, connectivity vise, they can still participate in the CAMFlooP protocol, and the impact these vehicles have is at great interesting when doing further development on the CAMFlooP protocol.

This study builds on previous work conducted on the development of the CAMFlooP protocol. The simulator used in this work has been extended to support newer technologies, facilitating the testing of the ongoing relevance and efficiency of the protocol in the context of these advancements. The use of simulations and subsequent evaluation of varying results has proven to be an effective approach to achieving the research goals outlined. As [NHM+18] suggest, network performance is enhanced when smaller groups of wireless devices are managed using an SDN controller. This method can potentially increase the total bandwidth within a given area by utilizing distributed networks instead of traditional star topology. This research primarily focuses on the impact of satellite connectivity when using distributed networks. When comparing different wireless technologies, particular attention is given to the performance of CAMFlooP in comparison with flooding techniques.

3.1 Extending the CAMFlooP simulator

As mentioned above, over the last few years, Puka and Herrmann have developed a comprehensive simulator, which utilizes numerous input fields to conduct different studies [PH21]. Within this simulator, the performance of CAMFlooP is evaluated using several metrics. The most interesting metrics are the improvements in terms of message delivery and the reduction in duplicate copies being delivered. To conduct a study that incorporates satellite capabilities, an extension of this simulator is needed.

In order to extend the simulator, a thorough understanding of how the simulation software operates is required. The CAMFlooP simulator is notably complex, composed of over 8000 lines of Python code. Consequently, the initial weeks of the study were devoted to examining and testing the simulator code to enable later extensions of its functionality.

When extending the simulator, it was necessary to add functionality to simulate satellite capabilities. This was achieved by introducing a new parameter *satellite_percentage* that represents the probability of a vehicle having satellite capabilities. Each vehicle would then determine whether it has satellite capabilities by generating a random number and comparing it with the probability p. Despite these changes, the overall behavior of the vehicles was not significantly altered in the study. However, vehicles with satellite capabilities could be perceived as moving connectivity spots. In this study, these vehicles do not generate messages, as the data they provide is less relevant in the context of the CAMFlooP protocol, where vehicles that find themselves in a dead spot, are examined.

An iterative approach was used to ensure the validity of the results from simulations. Changes were implemented, followed by new simulations to test the effects. Log files were then reviewed to verify that the vehicles within the simulation were behaving as expected. Several weeks were needed to achieve the correct system design. This iterative approach to system design and validation allowed more robust and reliable findings that will be presented in Chap. 4.

3.1.1 Creating messages

When implementing the satellite features, message creation was adjusted to only occur when vehicles are inside a dead spot. Given that satellite-enabled vehicles maintain connectivity throughout the simulation, they might be viewed as being outside of a dead spot, even in the absence of cellular connectivity. Therefore, these satellite-enabled vehicles could generate numerous messages that would be delivered immediately, potentially influencing the results. In effect, messages are only created by non-satellite vehicles when they are in a dead spot. This modification means that the total number of messages created decreases as more vehicles gain satellite capabilities, leading to less stable data when almost all vehicles have satellite capabilities.

3.2 Simulation parameters

In simulations, different parameters are used. All simulations use the same base parameters, with maximal vehicle speed, maximum connectivity range, and maximal probability for taking a side road. However, the percentage of satellite-enabled vehicles differ for all runs. The step size in satellite percentage is 1 percent point, giving a range of simulations for (1..100).

3.2.1 Vehicle communication maximum range

By setting a maximum range, the simulator can mimic the performance of various radio technologies. Some of these newer technologies may enhance the range of V2V communication. In our simulations, we set a fixed maximum range of 200 meters. This choice is justified by the findings from [PH21], which suggest that extending the communication range beyond 200 meters does not significantly improve performance. Thus, we can say that the need for communication range is well enough.

3.2.2 Vehicle maximal speed

In the simulator, a speed limit prevents cars from exceeding a certain velocity while traversing the roads. While cars can still accelerate and decelerate, emulating real-world behavior, a speed limit is set in SUMO. Just like in normal roads, speeding is also simulated in SUMO, giving the vehicles a maximum speed of about the max speed parameter.

In [PH21], it was observed that the protocol performs better at higher speeds. As cars traverse the roads at higher speeds, they can deliver messages faster upon exiting a dead spot. This implies that higher speeds might reduce the relevance of satellite communication. Therefore, a speed limit of 110 km/h is used in all simulations for this study, that is also used on the real highway between Broken Hill and Mildura.

3.2.3 Traffic density

The traffic density parameter is used to control the number of cars in the simulation. As the traffic used is based on real traffic data, this parameter can be used to scale the design traffic up or down. For all the simulation runs in this study, a traffic density of 100 percent is used. For future work, studies with other traffic densities might be interesting.

3.2.4 Route file

For having a shorter feedback loop, the simulator was designed to be able to run simulations with shorter routes, see [PH21]. The distances on these routes are 10 percent, 25 percent, and 50 percent of the original one. A side effect of the shortening is that results can be computed more quickly. This is very nice when one is developing the simulator. For all the simulation runs, however, the 100 percent configuration is used in order to simulate the entire dead spot area.

3.2.5 Possibility vehicle is satellite enabled

satellite_percentage is a parameter used to evaluate if vehicles should have satellite capabilities or not. When a vehicle is created in the simulation, the probability parameter is used to determine whether the vehicle is equipped with satellite capabilities or not. The simulations are carried out with a granularity of 1 percentage point, resulting in scenarios ranging from 0 to 100 percent likelihood of a vehicle being satellite-enabled.

3.2.6 Possibility vehicle go out of simulation

Much like in real traffic, not all cars in the simulation are headed to the same destination. Some might be modeled as if they live by the road, while others might be on a journey to a more remote location. Therefore, like in the original CAMFlooP, the possibility of a vehicle exiting the simulation is incorporated into the study. Vehicles that take one of the side routes, will not regain connectivity and may essentially be considered as removed from the simulation. In all simulations, a fixed likelihood of 1% is used for a vehicle taking such an exit.

3.2.7 Simulation random seed

Using a fixed random seed, simulations can be repeated. Changing the value of the random seed can lead to a totally different outcome of a simulation run. When comparing results, four simulation runs with the same satellite percentage but differing random seeds are used. Using the means and medians of the four simulations, the results should be less chaotic than with considering only a single run for a certain percentage of with satellite access provided vehicles.

Further in this document, a “simulation configuration” is used to represent a set of 100 simulation runs, all using the same random seed. Hence, different simulation configurations refer to distinct sets of 100 simulation runs, where all runs within a particular set share a common random seed. The random seeds used in simulations where 0, 3, 7 and 11.

By using these random seeds, the vehicle positions within each simulation configuration can be repeated. Consequently, the only variance across simulation runs is from whether the vehicles are satellite-enabled or not. For instance, in the simulation configuration with a random seed of 0, vehicles will encounter each other at the same position, with a satellite percentage ranging from 0 to 100. Through this methodology, we achieve a more accurate measure of the impact of satellite contribution on the vehicles' behaviour.

3.3 Gathering data

Within the simulator, various statistics including those related to Wi-Fi Direct groups, message delivery times, and duplication, among others, are collected. Once this data is processed, it can be used to generate a variety of graphs, focusing on mean and median values for each simulation configuration. To facilitate this study, modifications were made to the statistical tools, leading to the creation of additional metrics specifically for the satellite component of the simulator.

3.4 Satellite connectivity

Satellite connectivity is modeled as a binary capability for each vehicle. A vehicle either has the capacity to transmit messages via satellite, or it is a standard vehicle that relies solely on cellular connectivity. For a comprehensive study, one should consider real satellite performance when modeling. Assuming that vehicles can retransmit messages once satellite connectivity is reestablished, we simplistically modeled that the satellite connection have 100% uptime, even though, in reality, the actual uptime may be influenced by various factors such as weather conditions, solar flares, and technical issues.

In this study, the CAMFlooP protocol is also evaluated as a potential solution for reducing the overall bandwidth used by satellite data transfers. Therefore, the availability of the satellites is not as crucial. This assumption aligns with the one made by Puka and Herrmann when developing the CAMFlooP protocol, where cellular connectivity is modeled the same way. 100% availability is not realistic in a communication network, however, the impact of connectivity issues, is expected to have little effect on the results. More about this in chapter 5.

Vehicles that have satellite connectivity are capable of transmitting messages even when they are in a dead spot. Consequently, they can function like moving base stations. This feature, in practice, could lead to a general decrease in dead spots.

3.5 Running simulation

Utilizing a computer cluster allows for the parallelization of simulations. Given that each simulation run is entirely independent, the task of parallelizing the simulations is straightforward. In this study, a total of 10 virtual machines from NTNU's clutser, SkyHigh at Gjøvik [NTN23], were used to reduce the overall time spent on simulations.

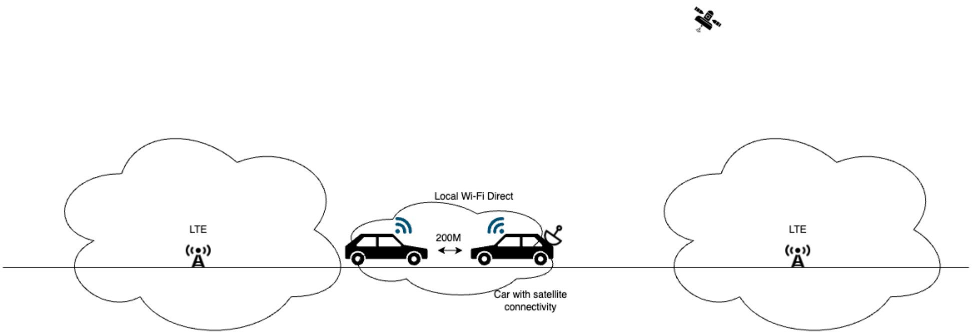


Figure 3.1: One satellite capable vehicle, and one non-satellite vehicle communicating via Wi-Fi Direct.

Each node has 2vCPU cores, and 2Gb of ram. The average simulation run time is 2 hours and 6 minutes on the nodes with a full 100 percentage road configuration. When more vehicles have satellite capabilities, the average run time is reduced, as the total amount of created messages are reduced. For runs where satellite percentage is above 90 percent, the average runtime is 1 hour and 31 minutes.

A database was established to manage of all the servers. These servers continuously poll the database to retrieve a simulator configuration before initiating a simulation. Upon completion of the simulations, all results are downloaded to a single machine. They are then summarized and processed for graphical representation.

3.6 Data science

Pandas serves as an excellent tool for handling large datasets in Python. By utilizing Pandas, all results can be efficiently retrieved when creating scripts to extract insightful data. Numerous graphs are generated from the data to identify the most compelling metrics and to better understand the simulator's performance.

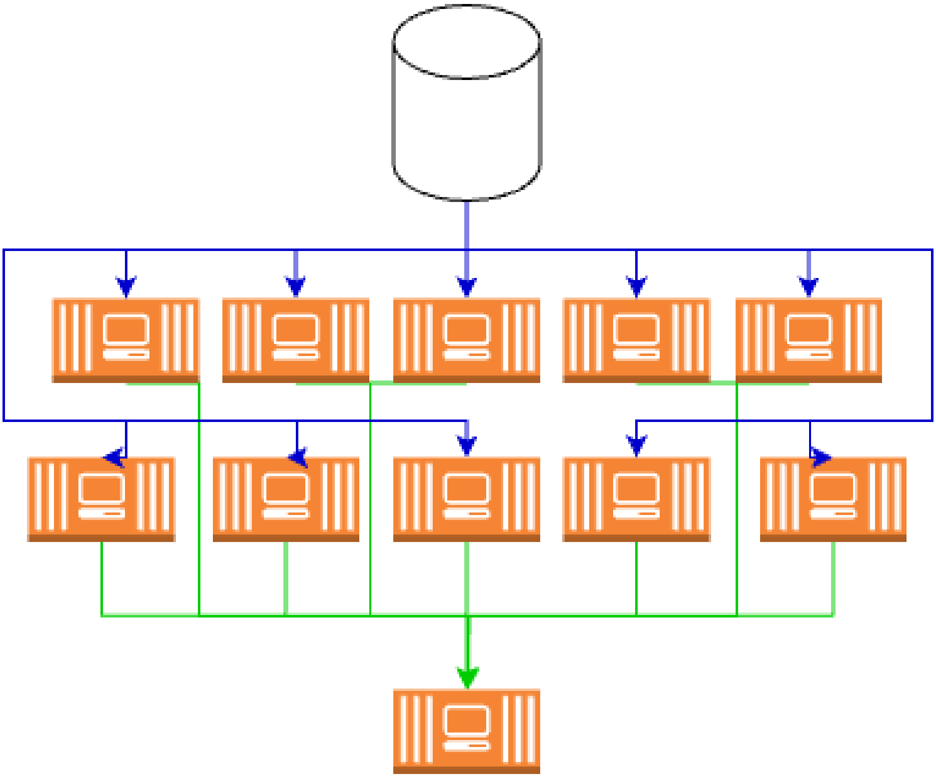


Figure 3.2: Computer cluster consisting of one management database, feeding 10 computers (blue lines), and one summary computer (green lines)

Chapter 4
Results and discussion

This chapter presents the results that were found during the simulations. Altogether about 400 simulations were completed, using four different random seeds. Each seed was used in a set of 100 simulations, resulting in four similar but distinct simulation configurations. Within each configuration, the satellite percentage was varied from 0 to 100, with a step size of 1 percent point.

Results from the simulations is presented in this chapter. Mainly plots are used in order to present the data from simulation runs. In all the plots, the x-axis is the satellite percentage which vary in simulations.

First the improvement in message delivery time is presented and discussed. Later CAMFlooP is compared to flooding techniques and the need for the protocol is discussed. Duplication is the main focus when comparing the protocol to flooding techniques. At the end of the chapter, a brief discussion about the willingness to contribute to such networks is included.

4.1 Improvement in delivery time

An important metric for measuring performance of the protocol, is the message delivery time. Particularly for messages created in a dead spot. This metric was previously used by Puka and Herrmann during the protocol's creation, where an approximately 40 percent improvement in delivery time was observed, see [PH21].

The thesis utilises several figures to illustrate the improvements observed in the study. Each of the plots in figures 4.1 and 4.2 corresponds to one of the four different simulation configurations, each based on 100 simulations as detailed in 3.2.7. Figure 4.3 and 4.4 are aggregated plots where mean and median values are used from the 100 simulations with four different random seeds. All of the plots 4.1, 4.2, 4.3, 4.4, 4.5 have two lines. One blue and one orange. These represent the improvement in delivery time for all vehicles (orange) and all vehicles that have participated in at

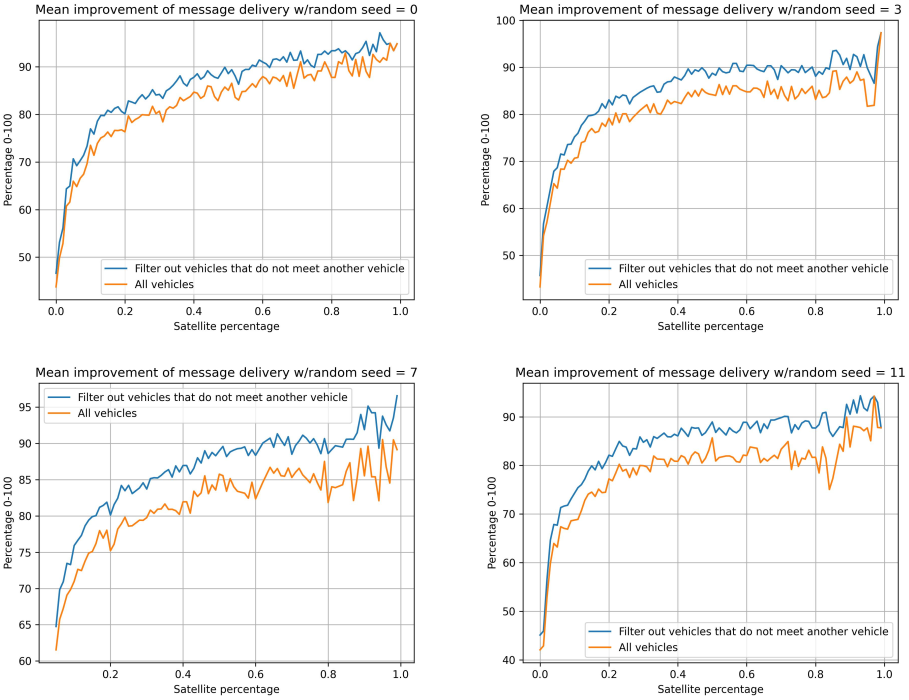


Figure 4.1: Mean message delivery improvement. Each plot is representing one simulation config

least one V2V communication group (blue). Vehicles that did not meet anyone is therefore filtered out in the blue line, as they did not get a chance at improving the message delivery time. Figure 4.4 is the same plot as presented in the upper left plot in 4.3. The same way, figure 4.5 is the same plot as the lower left plot in 4.3. These plots are included as its own figure, and not only referred to in 4.3, as they are highly relevant for the study. Later, these plots are referenced when discussing the median and mean improvement of message delivery time.

In figure 4.3, the collective data from all simulation configurations is displayed, showcasing both the mean and median message delivery times. The upper left plot in this figure represents the mean of each plot from 4.1. The upper right plot is the median of the mean delivery times from the same figure. Meanwhile, the lower left plot indicates the mean of the medians from figure 4.2. Lastly, the lower right plot displays the median of these median values. This way, figure 4.3 illustrates a comprehensive overview of the observed message delivery improvements.

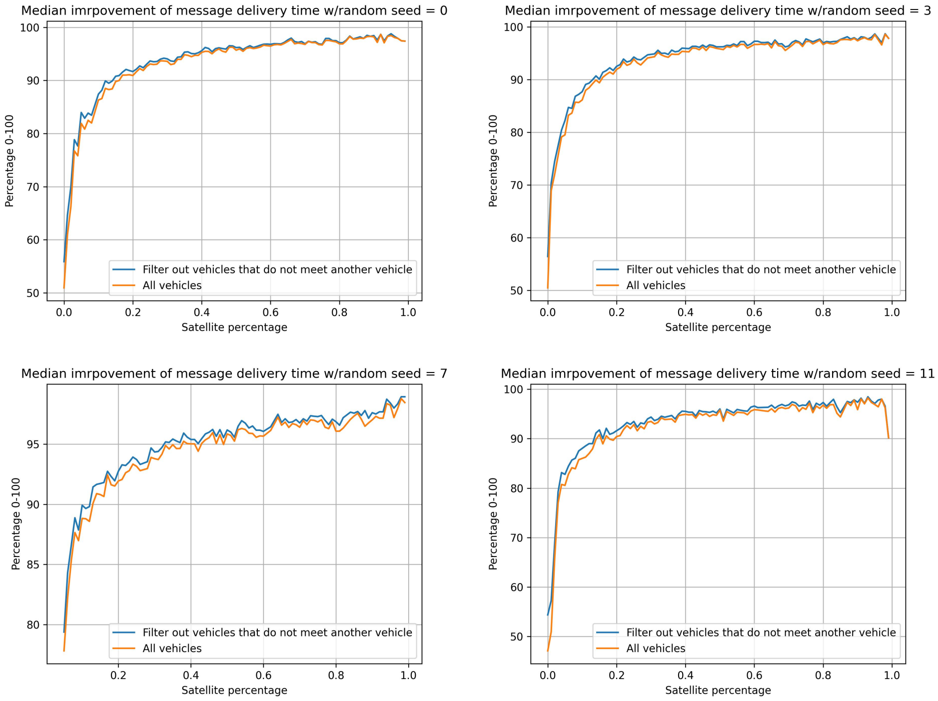


Figure 4.2: Median message delivery improvement. Each plot is representing one simulation config

If there was a 0 percent improvement, it would mean that the vehicles are only able to send the message just after they leave a dead spot, without utilizing V2V communication. With Puka's and Herrmann's CAMFlooP, we see an improvement of about 40 percent. Therefore, the plots usually starts at around 40 percent, even with no vehicles are satellite enabled, just running CAMFlooP with V2V communication and relaying message upon leaving the dead spot. In this study, a rapid increase of improvement is seen when only a small portion of the vehicles have satellite capabilities. Remarkably, with just 10 percent of the vehicles equipped with satellite connectivity, there is in average 70 percent improvement in message delivery time. With an increasing percentage of satellite technology-equipped vehicles, messages are delivered much faster, compared with using only cellular network technologies. So, when 20 percent of all vehicles have satellite access, the improvement will be around 80 percent, that means, the value presented in [PH21] will be doubled. However, with further growing the percentage of satellite vehicle will only lead to a slow linear increase of the improvement and eventually stagnate. Considering the median values,

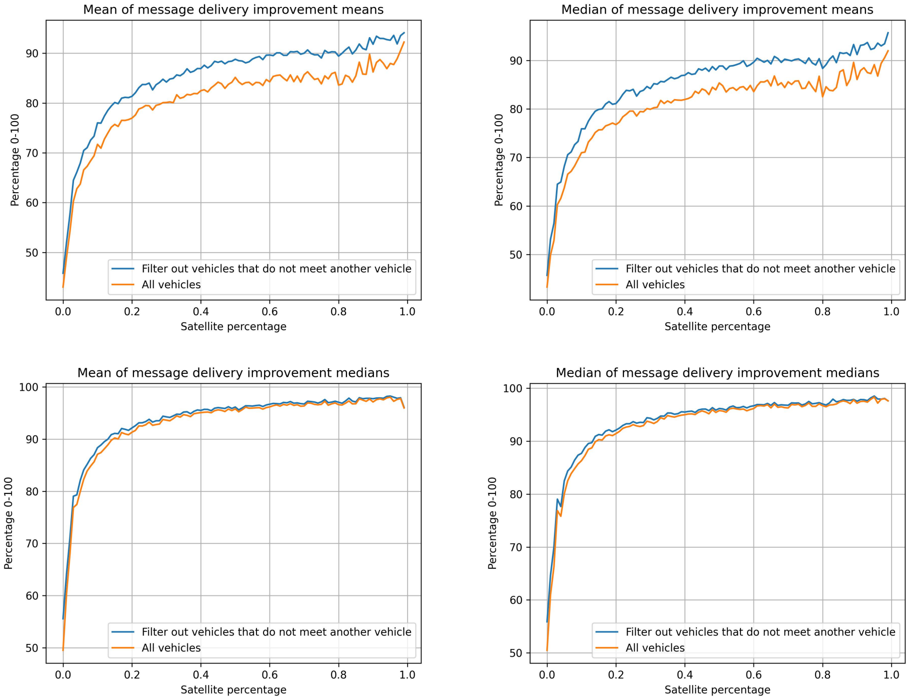


Figure 4.3: All improvements in delivery time compared to no V2V communication, with both the median of simulations runs per config (1/4) and also the mean and median of message deliveries. Aggregated data of setups with mean and medians are presented in this plot.

an even great improvement is seen. As seen in figure 4.3, the mean and median of the median improvement delivery time have already passed 80 percent when only 10 percent of the vehicles have satellite connectivity. Further, the value increase rapidly passing 90 percent with 20 percent of the vehicles capable of satellite communication. As with the mean of the mean delivery time values, the mean of the median values have a slower increase when more than 20 percent of the vehicles are satellite capable. The likelihood of meeting a satellite capable vehicle is also increasing, therefore, each satellite vehicle does not have the same impact as earlier.

Considering figure 4.1 and 4.2, the trend is very similar, but some differences are visible. Different simulation runs will have a varying improvement. This is because in some random seeds, the satellite vehicles might be in a sub optimal spot, and maybe one vehicle going out of the simulator, in the "dead road" might be creating many messages. However, looking at the four different graphs from the four

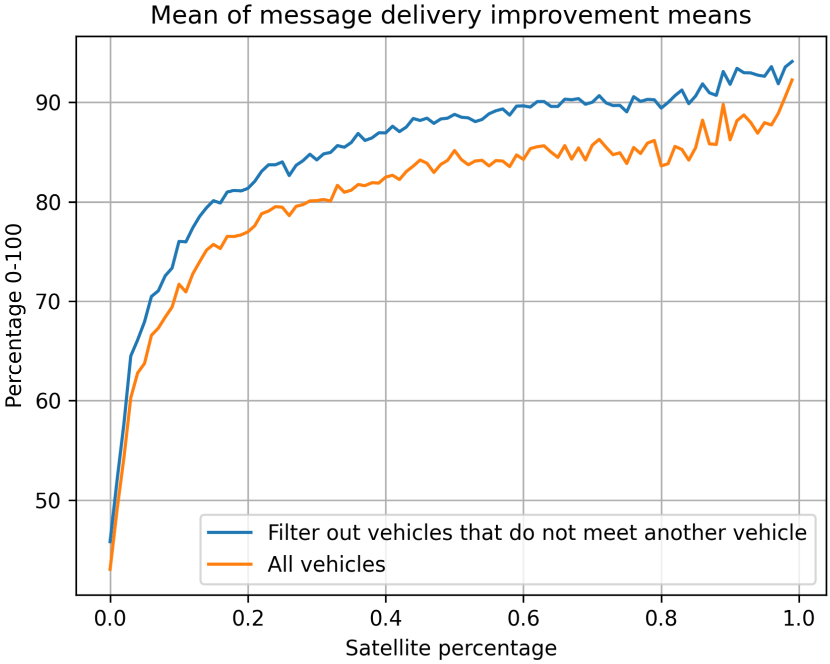


Figure 4.4: Mean improvement in delivery time compared to no V2V communication

different random seeds, it is clear that the trend is very similar, and the average of the improvement is performing very well.

When examining figure 4.4 and 4.5, it becomes evident that the median improvement performs better than the mean. This variation is likely due to outliers, which massively affect the mean. Consequently, the improvement seen from an average vehicle's perspective might be much better than the mean improvement suggests, as the robustness of the median measurement illustrates the significant improvement experienced by over half of the vehicles.

4.1.1 Stable linearly improvement

When more than 50 percent of vehicles are already satellite-enabled, a further increase of the number of satellite technology-equipped vehicles becomes less significant. Given that every other vehicle has the capability to deliver messages via satellite, there is a high likelihood that instead of storing the message for later delivery, the adjacent vehicle will deliver it immediately. The size of the dead spot is greatly reduced

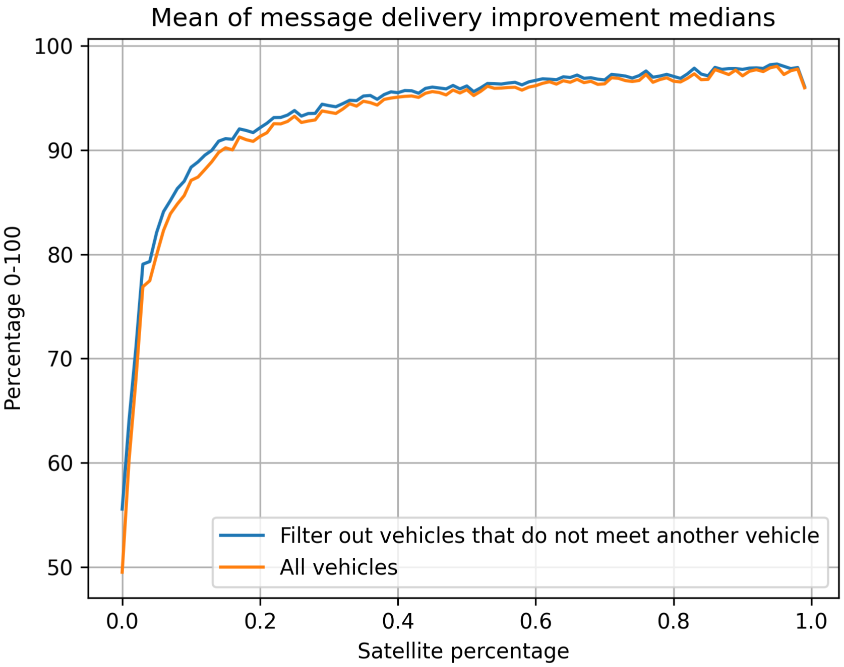


Figure 4.5: Median improvement in delivery time compared to no V2V communication

when every other vehicle has satellite capabilities. Thereby, the improvement seen with this high amount of vehicles being satellite capable, is looking to be linearly. When examining the different simulation configurations, it is important to note that this improvement may also be influenced by outliers, which could have a significant impact. It is also worth noting that the duplication reduction feature functions quite effectively, conserving bandwidth for other messages when many vehicles possess satellite capabilities.

In simulation runs where the satellite vehicles are unfortunately positioned, there is not much improvement. This is because the satellite vehicles need to interact with other vehicles in order to facilitate improvement. It could be interesting to compare road side units, which are fixed with a satellite backbone, to this study. This would guarantee that vehicles will encounter mitigation measures during their simulation run through the dead spot. If the satellite vehicle does not encounter any other vehicle, it is not possible to achieve any improvement.

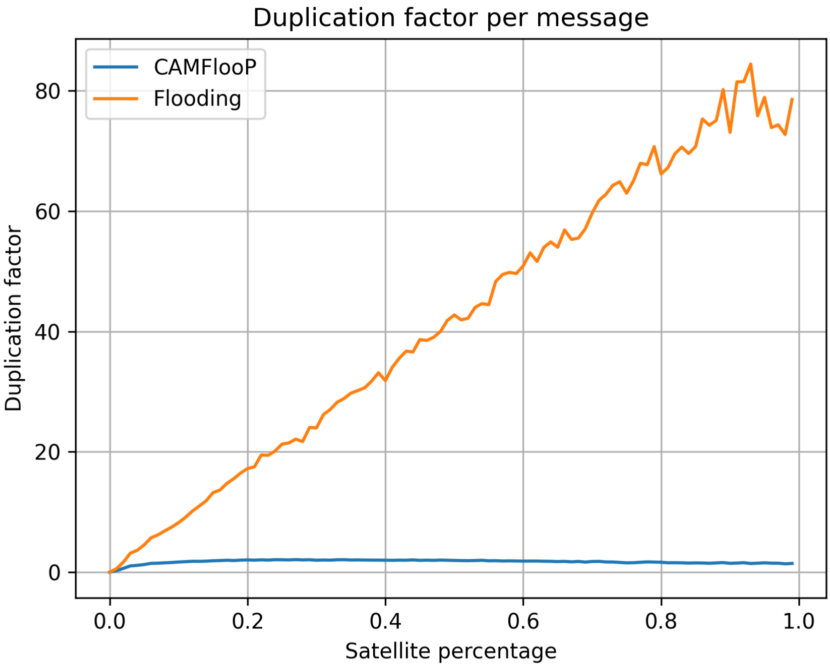


Figure 4.6: Duplication factor per delivered message, using CAMFlooP compared to flooding technology. The duplication factor is calculated using transmitted messages per the respective technology, divided by the number of created messages

4.1.2 Decision about creating messages on satellite vehicles

The improvement seen in this study is way above what we would have expected. As shown in the various figures, the improvement increases rapidly, and then linearly increases with a slow pace towards the point where all vehicles are satellite capable. An even higher increase in improvement could have been seen, when we would also consider messages produced by satellite access-equipped vehicles. Then an even more remarkable improvement would have been present.

In figure 4.7, the green line represents the number of created messages. The total number of created messages decreases linearly as the number of satellite vehicles increases. If satellite vehicles were to create messages, each message created on a satellite vehicle would instantly see a 100 percent delivery time improvement. Therefore, the improvement would have been shifted higher, at least from the point where half of the vehicles in the simulations are satellite enabled. However, when conducting a study on the performance gain using CAMFlooP in V2V communication, the interesting field of study is, of course, the impact that satellite communication has on vehicles that do not yet have this capability.

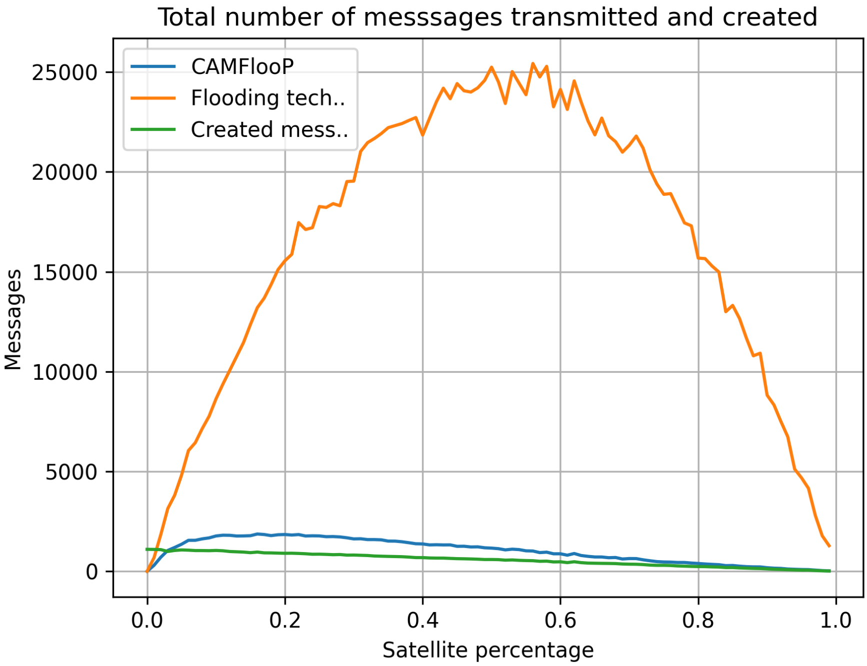


Figure 4.7: Created messages, and delivered messages using both protocol and flooding techniques

4.1.3 Movable base stations

When vehicles with satellite connectivity move through the dead zone, they will enhance the connectivity in that local area, practically mitigating the connectivity issue. Having larger communication range, less vehicles are needed in order to have great improvement, as more of the dead zone is removed temporary with satellite capable vehicles moving through the dead spot. Satellite enabled vehicles can thereby be seen as movable base stations travelling through a dead zone, enhancing other vehicles with connectivity. It is also very important to note the difference between a movable base station that is LTE or 5G compatible with emergency routes trough satellite via Wi-Fi Direct. In this study, the vehicles is seen as movable emergency relays rather than movable cellular base stations. The case with cellular compatible movable base stations is also interesting. More about this is presented in 5.3

4.2 The need for CAMFlooP

As seen in [PH21], the amount of duplicates using a flooding technique is decreased as the size of dead spots is decreased. The articles demonstrates that CAMFlooP, on the other hand, have a more stable number of duplicate deliveries regardless of the size of the dead spot. This is also demonstrated in figure 4.6, where CAMFlooP have a stable curve whilst flooding techniques rapidly increase. From the results of [PH21], the 10% scenario sees 17.25 copies per message using flooding techniques, while CAMFlooP only have 1.36. Even if the dead spots are such greatly reduced, the duplicate deliveries will use great amounts more bandwidth than what is actually needed. Taking the parallel to this study, when more vehicles are satellite enabled, flooding techniques will lead to increased number of duplicates over the satellite links. Network usage can be massively reduced using protocols like CAMFlooP, while still having a greatly improved message delivery time. CAMFlooP is therefore still highly relevant for networks where new capabilities is added, such as the satellite features of 5G.

4.2.1 Effective networks

While increased satellite connectivity does enhance message delivery times, it is important to note that this is not the primary factor driving this study. A significant acceleration in message delivery can be achieved with only a small proportion of vehicles equipped with satellite connectivity. This level of improvement is similar for both flooding techniques and the specific protocol, as the initial message delivery route established by the first mobile dead spot (i.e., the vehicle) would be the same for both methods. The features of the CAMFlooP protocol, as compared to flooding, can be used for effective utilization of satellite communication. In figure 4.7, it is seen that way less messages are delivered using the protocol than flooding. This implies a protocol to reduce duplication is even more important in satellite networks, than in today's cellular-only networks as satellite connectivity infrastructure has a higher development and operation cost than traditional cellular networks.

As the first vehicle with satellite communication would transmit the message using flooding, the protocol is not important when it comes to delivery improvement. However, the total bandwidth utilization for each message is drastically reduced with CAMFlooP. As seen in figure 4.6, the duplication factor per message is increasing linearly per satellite percentage. In 4.6, data used for plots, is the mean of duplication factor for the four different simulation configurations. The lines in the figure are the duplication factors for the respective V2V routing technologies used. The orange line is the duplication factor plotted against the satellite percentage when flooding techniques is used, while the blue line illustrates the duplication factor when using CAMFlooP. In this study, the duplication factor is the number of transmitted messages, divided by the total amount of created messages. For example, in a simulation where only one message is created, if CAMFlooP transmitted a message 2 times, the duplication factor would be 2 for CAMFlooP. Using flooding techniques, the same message could have been transmitted 90 times, giving a duplication factor of 90 for flooding techniques. As illustrated in figure 4.7, the duplication factor using CAMFlooP for each message is drastically lowered compared to flooding techniques. In figure 4.7, the total amount of transmitted and created messages is plotted. On the horizontal axis, the satellite percentage is plotted, whilst the y-axis is both transmitted messages in the blue and orange line and the total amount of created messages is the green line. Compared to figure 4.6, the lines seen in 4.6 are number of transmitted messages via CAMFlooP or flooding techniques divided by created messages (green line) from 4.7. This reduction is achieved because the protocol is designed to distribute messages only when it can accelerate the delivery time after distribution. Figure 4.8 presents the normalized curves representative of duplication. From this graph, it is clear that message duplication decreases linearly with an increase in satellite connectivity.

4.2.2 Duplication

The total number of delivered messages is a crucial metric for determining the necessary throughput for message delivery. However, in practice, the total number of created messages can vary greatly. In a study of this nature, the efficiency of messaging and the reduction of message duplication become very important. Figure 4.6 clearly demonstrates that the duplication factor increases linearly as satellite connectivity increases. There's also a noticeable increase in local variance in duplication as satellite connectivity is increasing, which can be seen as a side effect of the decreasing total number of created messages. Since vehicles enabled with satellite do not create messages, an increase in variance is expected.

4.2.3 Duplication cost

Overall, the duplication factor was seen to be about 80-90 per message in the original studies conducted by Puka and Herrmann, seen in [PH21]. In LTE networks, the cost for transmitting messages are way lower than what is seen with satellite networks, as discussed in an article published by McKinsey [DKMW20]. For scaling satellite networks, more satellites are needed. Upgrading land based cellular networks have lower complexity, and lower cost than scaling satellite networks. Thereby, reducing bandwidth utilization is even more important when worldwide cellular traffic get the capability to transmit using satellite based connectivity.

On a different note, when the majority of vehicles are equipped with satellite capabilities, the number of created messages decreases significantly seen in figured 4.7.

As the number of created messages are reduced in this study, due to only non-satellite vehicles creating messages, one could argue that the need for the bandwidth is also decreasing as fewer messages require the satellite capabilities of other vehicles. However, satellite vehicles probably have the need to transmit messages as well, using some of the bandwidth available. Therefore, it is important to remember this decrease in message creation is special for this study, and the need for the bandwidth is probably not decreasing in real environments.

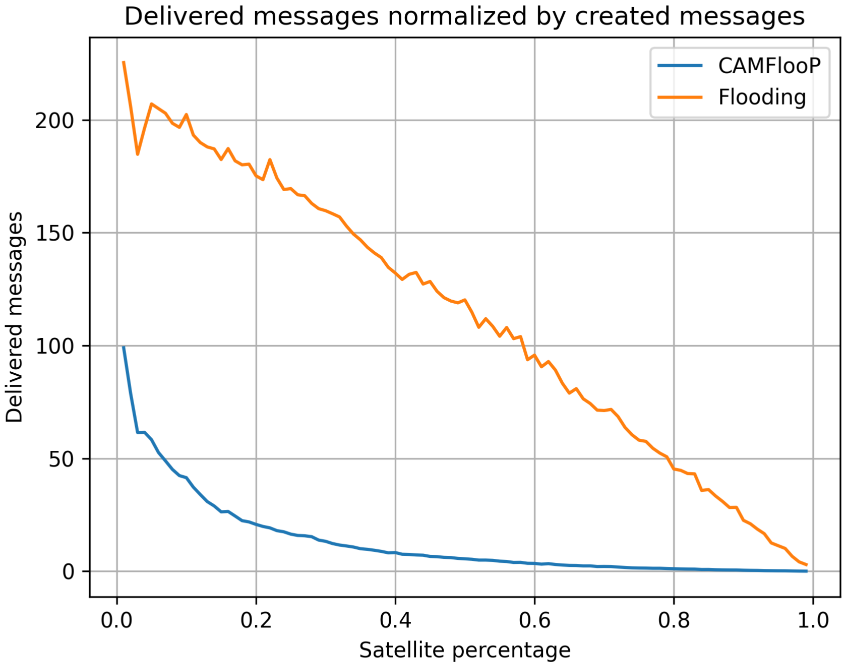


Figure 4.8: Delivered messages for both protocol and flooding compared to the number of created messages, normalized by created messages

In figure 4.8, the total amount of delivered messages is normalized by the amount of created messages. It is clear that the bandwidth utilization is decreasing linearly when the satellite capabilities increase for both the CAMFlooP protocol, as well as flooding techniques. What is really interesting, is that even though the decrease in corrected, delivered messages is quite stable. The number of delivered messages for flooding techniques is high, compared to the performance of CAMFlooP. Also when you consider the case where as much as 90 percent of the vehicles have satellite connectivity. Therefore, also when 90 percent of vehicles have satellite capabilities, the CAMFlooP duplication reduction is at great significance. These normalized message delivery graphs is highly interesting, as they are one to one mapped with the excess bandwidth usage for satellite communication. All of these duplicated messages have a very high cost. Protocols that reduce duplicate copies may therefore have a huge impact on the future of satellite networks, also when almost all vehicles have satellite connectivity.

4.3 Real implementations

A study investigating the case where only a portion of the vehicles have satellite or V2V connectivity could be interesting. Given that the development with smartphones moves in the direction of most people renewing their phones frequently, one could think there might not be a need for CAMFlooP, as most people soon will have satellite capable phones. However, results seen in figures clearly states effects given by CAMFlooP, also when as much as 90 percent of all vehicles having satellite capabilities. As Wi-Fi Direct is a technology widely integrated into current smartphones, a data dissemination protocol could be broadly implemented through a simple software update. Then, CAMFlooP can contribute to more efficient networks.

However, only a small number of phone manufacturers have the capability to widely deploy such a protocol. Standardization would be a limiting factor in order to have sufficient amount of carriers using nearby communication. Samsung smartphones might not use the same standard as Apple, and LG might also make their completely own service. Apple is the most expected candidate of implementing a protocol on their smartphones, without considering standardization with other phone manufactures. Considering Apple's successful deployment of the Find My network [App21], the idea of seeing a protocol being deployed is not far-fetched. Having the capability to widely deploy such technology across numerous smartphones should increase the interest in CAMFlooP. On the other hand, if users were required to purchase new equipment, they might opt to buy the latest iPhone model with satellite capabilities instead [App23]. User studies could be conducted to evaluate patterns in phone purchasing behaviors, and phone updating behaviors, in order to see whether people are buying the newest tech instead of updating their current phones. On the other hand, if users could have about the same message delivery time as with satellite connectivity by just a simple phone update, they might be more interesting in these updates. Seeing such high message delivery time improvement for most messages in this study, there might be an option that CAMFlooP will perform sufficiently well. Individuals do not necessary have to buy satellite connectivity in order to achieve rapid message delivery. This does not only contribute to more efficient networks, but also more sustainable phones, as all individuals do not have to buy a new phone right away. Used phones with capabilities to have their emergency messages relayed over such a network, might also be interesting. Having such improved emergency message delivery times, using CAMFlooP, satellite connectivity might not be for everyone, as the improvement might be sufficient enough. This can really affect many smartphone users.

Considering the likelihood of all vehicles, or all smartphones suddenly supporting V2V connectivity, it is very unlikely that the case where everyone suddenly will start flooding their messages to be relayed over satellite. Thereby, looking at a case where all vehicles either are flooding or have satellite connectivity might not be that relevant for real life implementations of the protocol. Different results could be found if not all vehicles were to create messages, or contribute in Wi-Fi Direct groups. In fact, this suddenly generates an important field of study that should be further investigated. CAMFlooP might also be adapted for such a scenario, being even more relevant in these networks. More about this in section 5.1 and 5.2.

4.3.1 5G development

The network part of V2V communication can be seen as a networking layer, and CAMFlooP as an application layer protocol. It could then be argued that the results using Wi-Fi Direct and 5G NR will be the same. Using this argumentation, it is highly important to remember what technology is discussed. In this study, CAMFlooP does only deliver emergency messages, while a movable base station with full 5G support, as drafted in the latest 3GPP releases, could have a fully compatible backbone network over satellite. As of now, these networks could also just use the 5G NR technology to do V2V communication without utilizing the satellite capabilities introduced in 5G N.T.N. A study with 5G N.T.N as a backbone and 5G NR for V2V could be interesting, while changing Wi-Fi Direct for 5G NR alone, should have the same conclusions as this study, as longer communication ranges than 200 meters have been proven to have low effects on the networks according to [PH21]. More about this is discussed in section 5.2.

4.4 Maximum number of messages per vehicle

Figure 4.9 plots the max number of messages a satellite vehicle has delivered in the simulation. Unsurprisingly, the maximum number of delivered messages is quite high when the percentage of satellite-enabled vehicles is low. Moreover, the maximum number of messages delivered decreases as more vehicles become satellite-enabled. This is as expected.

Maximum number of delivered messages can be an interesting metric when it comes to pricing of these networks. The willingness of people to contribute with 50 messages for other vehicles could be quite low if the cost of each message is somewhat high. More work could be done considering a pricing model in these networks, as mentioned in 5.4.

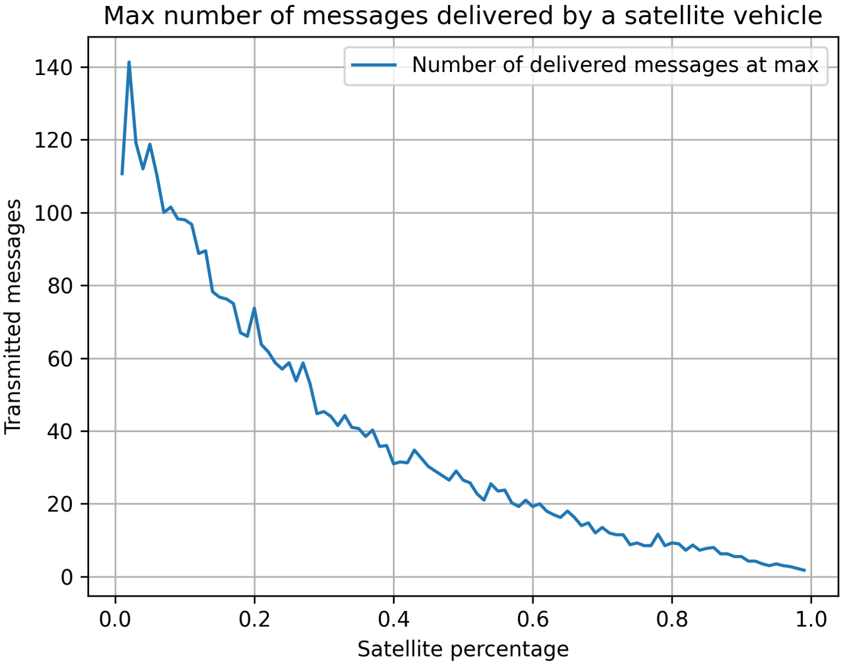


Figure 4.9: Maximum number of messages that have been delivered by a satellite vehicle

Chapter 5 Future work

As seen in [PH21], and this study, CAMFlooP performes very well in reducing duplicate deliveries, while speeding up potential message deliveries. When it comes to developing a world wide used protocol, there is always a trade-off between usability, and performance. Thereby, more research should be addressed in order to evaluate if the trade of with the context needed for today's protocol is a good fit.

5.1 New simpler protocol

In future research, a study evaluating a satellite hybrid CAMFlooP might prove necessary. Given that vehicles in this study use CAMFlooP for all vehicles, it is possible that some transfers might be unnecessary. For the case where most vehicles have satellite capability, it will be very likely that every vehicle you meet is satellite capable. Therefore, there could be potential of speeding up message delivery by using just one step of wireless communication. Vehicles could transmit their messages only to satellite capable vehicles, and stop transmitting the message once the satellite vehicle confirms they deliver the message. Probably, the average message delivery time will be somewhat slower, but could be sufficient.

Such a protocol could be much less complex than CAMFlooP, yet still achieve a similar level of performance in some of the cases. The current simulator lacks the data needed to conduct such a study. However, extending the simulator to collect this data should be a straightforward task.

The primary difference between CAMFlooP and the proposed implementation is that the protocol was not originally designed for satellite usage. CAMFlooP's complexity lies in its ability to calculate the fastest possible delivery route using navigation data, and knowledge about dead spots. However, a protocol designed to stop transmission after encountering a satellite vehicle could be less complex, because it would then know the message has been delivered and keep the message for itself otherwise. For instance, if a vehicle has satellite capabilities, it could transmit the message and remove it from the message queue. The results from such a study would be important and interesting because a simpler protocol, without the need for navigation data, would be easier to implement on modern smartphones. Conducting more studies in this field of research can help adapt CAMFlooP if proven necessary to be an even better fit considering complexity and performance.

Satellite networks might also be more unreliable than cellular network. Maybe CAMFlooP will perform better than such a simple protocol, when considering the reliability of satellite networks? There are many more questions considering this technology, that should be addressed.

5.1.1 Implementation

If one were to implement the simulator needed for such a study, the timestamp a message was seen at a vehicle should be added to the statistics, and used to evaluate if the message should be transmitted and removed from buffers, or simply ignored by other vehicles. Such a study would not be to comprehensive, and could be achieved during another master's thesis.

5.2 User patterns

As discussed earlier, only traffic patterns based on real-life data have been considered. A more comprehensive study evaluating different adoption metrics of V2V communication would have great value. Distinct results could be expected if only 20 percent of vehicles were contributing to the networks, and 50 percent of those had satellite connectivity — which might indeed be the case. This possibility arises from the fact that technology enthusiastic users, who would be eager to contribute in these networks, could also be the same individuals who consistently purchase the latest iPhone models and thus have access to satellite connectivity.

There certainly is room for a study concluding about user patterns as the technology has been proven to be a good choise when evaluating it isolated.

5.3 Movable base stations

In earlier CAMFlooP studies, and this study as well, V2V communication have been evaluated using Wi-Fi Direct. In 3GPP's intiative with 5G NR, V2V communication is part of the spec. As discussed in section 4.3, a study looking at whether CAMFlooP would be necessary if movable base stations had a satellite backbone, and vehicles could access the Internet. Since 5G N.T.N introduces the 5G satellite backbone, results could be different having this capability. Results using 5G NR for V2V, however, is covered by this study, as features in the new radio does not improve any metrics that have proven to increase performance. The communication range of Wi-Fi Direct is considered sufficient, as seen in [PH21].

5.4 Pricing

What is really interesting in these networks is how they should be operated commercially. As seen in figure 4.9, some satellite vehicles deliver a lot of messages. Bandwidth over commercial satellite networks is at today's prices quite expensive, seeing the cost at the Starlink website [23b]. Another aspect of pricing is the fact that smartphone producers can take the Starlink pricing in their service, as Apple seemingly does. In the support page for Apple iOS emergency feature, [App23], it is clear that the satellte service is included for two years, but the price after two years is not known publicly at today's date.

The willingness of people to participate in such networks is a factor that should be considered in future research. It may be necessary to offer some form of compensation or incentive to encourage users to opt in and join these networks. A user study could be conducted to develop a compensation model, encouraging users to opt in.

Chapter 6 Conclusion

The study conducted and presented in this thesis reveals a remarkable improvement in the performance of the CAMFlooP protocol when integrated with satellite capabilities, as detailed in chapter 4.

6.1 Research questions

In order to find answers to the research questions, the simulator were extended, adding satellite capabilities to a set of vehicles. Several simulations were used in order to conclude on research questions. Statistics were used to consider how these vehicles contribute in networks.

6.1.1 RQ1

Some complexity were needed for extending the simulator to have satellite capable vehicles. The simulator already had features to see the improvement of message deliverers, so when the features of satellite capabilities were implemented, the statistic features of the simulator could be used to evaluate the message delivery time improvement. Using an iterative approach when developing, the improvement could be confirmed to be correct after adding the satellite capabilities. As seen in chapter 4, the improvement with satellite vehicles has a rapid increase, and the protocol performs very well in these scenarios.

6.1.2 RQ2

New statistic features were needed in the simulator for evaluating RQ2. While extending the simulator with satellite capable vehicles, statistic features for evaluating how the CAMFlooP protocol performs for these vehicles were also added. Looking at the results, it is clear that CAMFlooP performed very well on reducing duplicate transmission over satellite links.

6.2 Summary of Improvements

The integration of satellite technology into the CAMFlooP protocol resulted in significant message delivery time improvement. Messages were delivered 80 percent faster when only 20 percent of the vehicles had satellite capabilities, and the duplication factor remained relatively stable compared to flooding techniques.

6.3 Implications of the Study

The results obtained have substantial implications for the broader field of study. The evolution of several new radio technologies, in line with the development of 5G technology, is expected to significantly impact the networks of tomorrow. The CAMFlooP protocol could be one of the tools that help reduce the bandwidth utilized for satellite communication during the transitional phase towards equipping all vehicles with satellite capabilities, thereby having great impact on this field of study. Also, as CAMFlooP performs so well, also in smaller dead spots, it might be relevant in cases where all vehicles have satellite capabilities. Considering the reliability of satellite networks, more work should be done in this field of study.

6.4 Future Directions

The promising results may be a foundation for more work with future research. Different radio technologies may be tested, as well as different routing techniques, such as stationary road side units. Given the fact that CAMFlooP might be very relevant also for vehicles with satellite connectivity, more work might be necessary in order to fully utilize the potential in future networks.

In conclusion, the results underline the potential that the CAMFlooP protocol holds in improving the performance of V2V communication when vehicles find themselves in a dead spot. It points to a promising direction for further exploration and development in this field of study. The protocol from Puka and Herrmann is really performing well in reducing duplicate deliveries, also when some vehicles have satellite capabilities.

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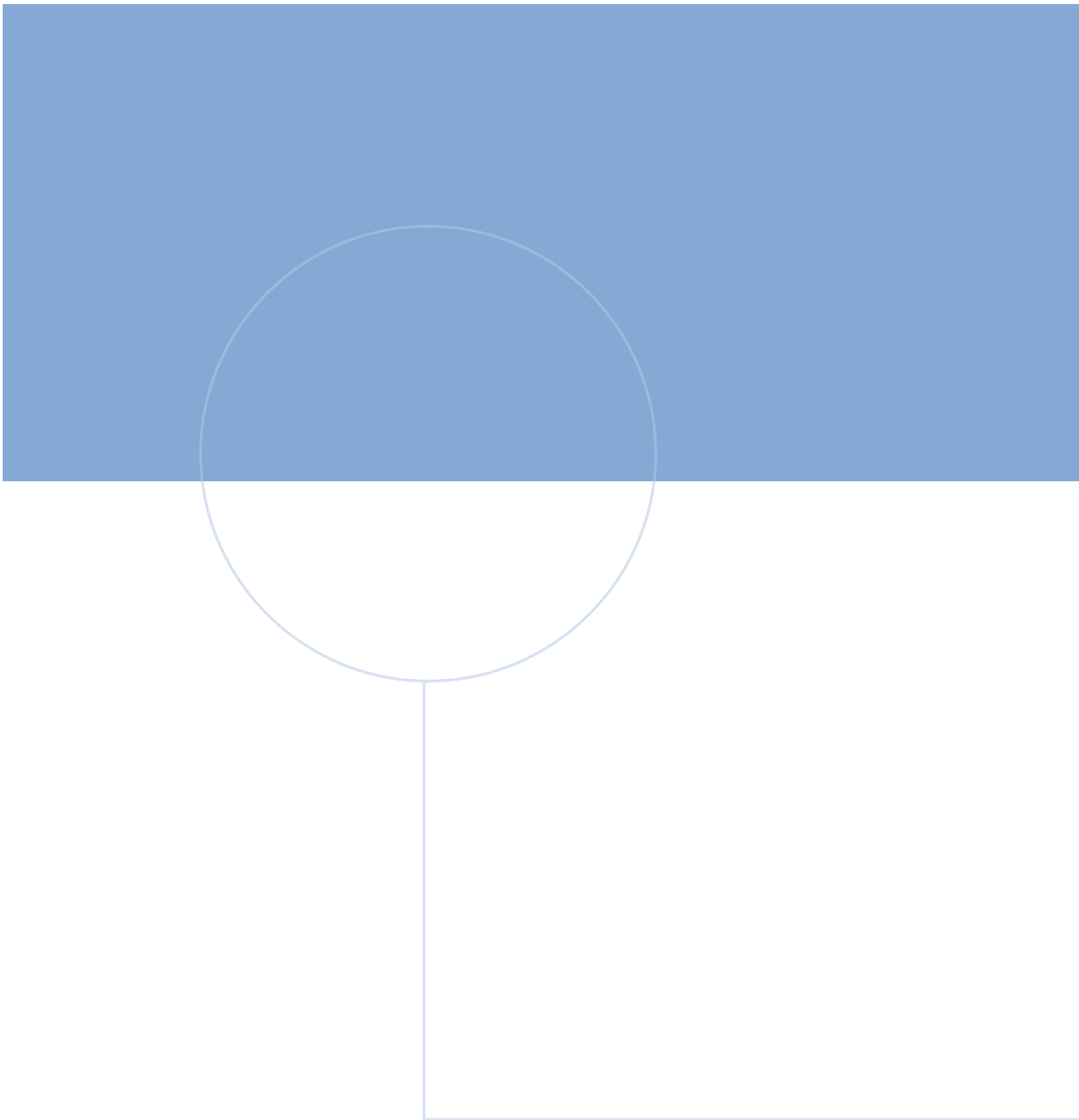

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