Wi-Fi based Telecommunication Infrastructure Delivered as a Service by UAV for Emergency Response

Artur Zolich*, David Palma†, Roger Birkeland‡, Krzysztof Cisek* and Tor Arne Johansen*
* Center for Autonomous Marine Operations and Systems, Department of Engineering Cybernetics,
† Department of Information Security and Communication Technology, ‡ Department of Electronic Systems,
Norwegian University of Science and Technology, Trondheim, Norway,
{artur.zolich,tor.arne.johansen}@ntnu.no

***Abstract*—In this paper we discuss Wi-Fi and complementary technologies that can be used to mitigate telecommunication gaps in search and rescue (SAR) activities and during natural disaster (ND) response scenarios. We present and evaluate a standalone communication system solution in a field experiment. It utilizes a fixed-wing Unmanned Aerial Vehicle (UAV) to enable Wi-Fi based, audio-video communication between users equipped with a smartphone and the operation control center. We describe a custom, actuated, UAV payload that compensates the fixed-wing UAV's bank angle for improved antenna pointing. Through a qualitative analysis, the field trials confirm the suitability of a UAV solution for SAR, using Wi-Fi and standard protocols available on most smartphones.**

I. Introduction

Events of natural disaster (ND) and Search and Rescue (SAR) missions can face challenges due to lacking or disabled telecommunication infrastructure in the area of operation. The available literature covers several ND scenarios, in which failures related to telecommunication infrastructure caused significant challenges [1]–[5].

There is a number of identified means of telecommunication used by the public during ND response, such as television, radio, landlines, cellular network, or social media [1]. First responders on the other hand communicate between themselves using private/closed networks with specialized equipment such as VHF radios or satellite phones [1].

In this paper we focus on means of two-way communication which can be useful for both first responder teams as well as for contact with victims.

SAR operations often take place in remote or less developed locations, where access to telecommunication infrastructure is often limited [2]. Even if the telecommunication infrastructure is available and it survives an ND event, it can be overloaded by the number of users trying to call for help, contacting others or get more information about what happened [3], [4]. During past events telecommunication operators were not able to distribute resources, so even though the network was operational, the high demand caused payment distribution to fail and disabling calls [1].

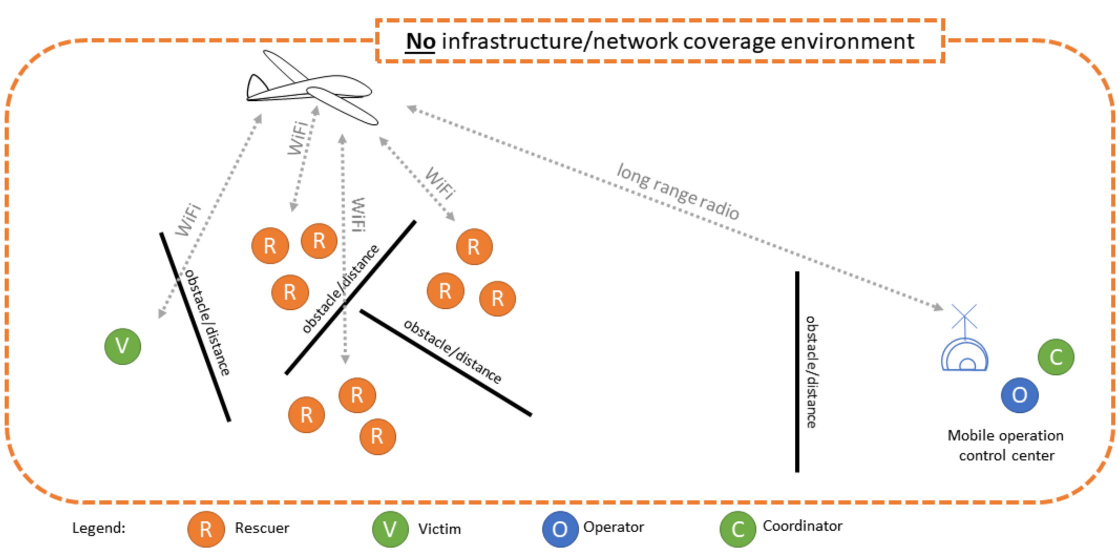


Fig. 1: Concept of operation

Moreover, during a ND event telecommunications and other infrastructure are often damaged or even destroyed by natural forces, e.g. wind, flood, land slides or avalanches [3], [4]. Loss of power, caused by damage to power lines or power stations, causes communication network nodes to either switch off instantly or use backup power that lasts only a few hours [3], [4]. A related risk is that when infrastructures fail, user terminals such as mobile phones, discharge faster due to constant search for network signal [5]. In the event of power grid loss, charging user terminals is challenging. This causes the availability of user devices to drop significantly over a short period of time. Studies show that one week after a disaster occurs, only 10% of devices remain active [1]. Quick recovery of the network infrastructure or rapid deployment of an alternative solution is therefore vital.

There are a number of projects investigating potential use of new technologies in SAR and ND scenarios, e.g. [6]–[11]. A broad overview of disaster response applications of UAVs, including standalone communication systems, is covered in [12] and [13]. The concept of Flying Cellular Base Station (FCBS) mounted on an UAV or a helicopter is also explored in literature [14] and the technology has been adopted in SAR equipment [15]. A challenge in FCBS is the use of licensed frequencies, so deployment requires cooperation with the frequency operator of a given country. Use of Industrial, Scientific, Medical (ISM) band communication technologies allow to establish standalone networks without interfering with existing cellular networks. Field experiments with UAV and Wi-Fi networks are presented in [16] and [17]. A mobile device's localization based on Wi-Fi signal from UAV has been demonstrated as a part of [18], while a UAV swarm use case in SAR missions is presented in [19].

A. Main idea and contribution

The main contribution of this paper is the demonstration of a proof-of-concept in which we provide a communication infrastructure as a service, delivered by a UAV (Figure 1). The designed system architecture consists of Wi-Fi connectivity being provided by a custom UAV payload. This enables audio and video communication in SAR and ND scenarios, which we evaluated in a field experiment.

The paper describes an architecture of the solution and evaluates a field trial in which a video-call was established, without access to the mobile network or Internet, using free Session Initiation Protocol (SIP) [20] communication software. The solution is scalable and it can provide necessary infrastructure to enable communication as an independent network or in cooperation with telecommunication operator approved Wi-Fi Calling network.

II. Available technologies and new solutions

A classic telecommunication infrastructure is a complex system-of-systems which depends on multiple actors and regulations to operate. Recovery from a failure due to a disaster may require action of several institutions and it may take significant time to re-establish the service. A rapid-response technology should allow to streamline the pipeline of decisions and actions, which are required to re-establish the communication chain.

Progress in Internet technologies, UAVs, and the mobile phone market create opportunities for new types of telecommunication infrastructures which are standardized, modular and can be quickly deployed when needed. Moreover, ISM license-free frequency radio technologies and services, such as Wi-Fi, have been accepted, standardised and introduced worldwide.

While several developments in communication continuously take place, such as beyond 5G networks [21], in this section we focus instead on widely deployed and available solutions, taking into account future opportunities, but mostly focusing on reaching everyday users in an emergency situation.

A. Evolution of user terminals

Although there are various types of user terminals, we consider two main categories in this paper: *Smartphones*, and *Smart Feature Phones*.

The smartphones market expands in a wide range of devices. Low-end devices are getting more accessible thanks to affordable components and mass production, but also thanks light-weight operating systems, e.g. Android GO [22].

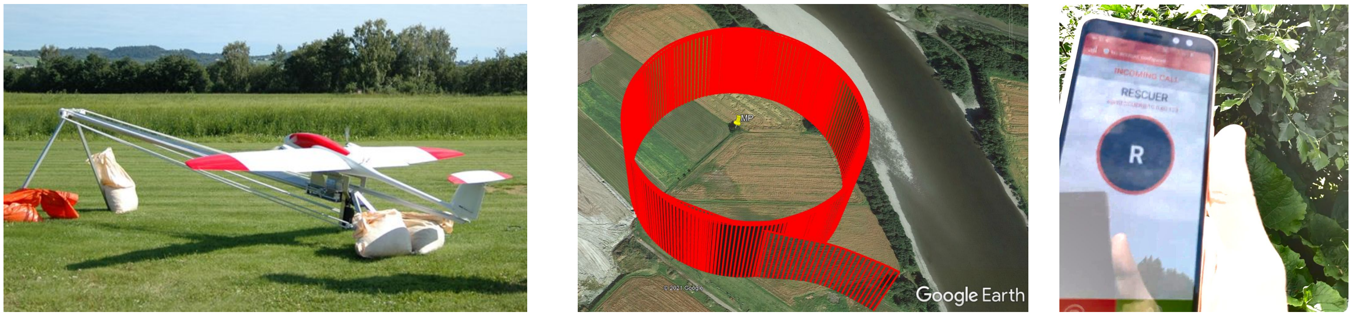
Smart Feature Phones rapid market demand growth is observed since 2018 [23]. These devices are hybrids which join affordability of a basic mobile phone with feature technologies typically associated with smartphones, such as GNSS (global navigation satellite system), Bluetooth, and Wi-Fi. Smart Feature Phones allow to run apps which have advanced support of modern web features, providing access to globally recognized social media, navigation tools or even Artificial Intelligence voice assistant. In 2019 the Smart Feature Phones running KaiOS became second-most popular mobile platform in India [22].

It is estimated that 48% of the global population has a smartphone, while 62% has access to a mobile phone [24]. In fully developed economies these values are higher. In 2019 96% of adults in USA had mobile phone, of which 81% was a smartphone [25]. Based on [26], only in 2 countries in the world, less than 20% of population owns a mobile phone.

B. Network infrastructure

Wi-Fi is a worldwide established standard for providing network wireless connectivity, both for private local area networks (LANs) and as an entry-point for many users to access the Internet (e.g. home routers or public access points). A benefit from the Wi-Fi technology is the use of radio frequencies (typically 2.4 and 5.8 GHz) in ISM license-free band. This allows not only a quick and on-demand deployment of a wireless infrastructure without obtaining a frequency license (or even an ad-hoc infrastructure-less setup), but also data-rates of several of Gbps [27], [28].

As an example, in India the PM-WANI initiative aims at deploying a public Wi-Fi Access Network providing coverage to the whole country, including regions which do not have access to 4G mobile coverage [29]. The PM-WANI aims to connect 600 million users via 10 million public access points by 2022 [30].



(a) The UAV used in field-trial (b) Flight path around the mobile device (c) User receiving a call

Fig. 2: Selected highlights of the field-trial

The importance of Wi-Fi is also seen in the investment on successively updated standards and features. For example, the latest generations of Wi-Fi Access Points (AP) supporting Wi-Fi 6 (IEEE 802.11ax) can serve an increasing number of clients (e.g. Wi-Fi 6 is expected to serve up to 1024 clients per AP), supporting denser networks while also improving on throughput and latency compared to previous versions.

C. Network protocols and tools

The importance of web-based applications is proven not only by their flexibility (i.e. any device with a web-browser will suffice), but also by the various proving and emerging standards/developments such as HTML5, ECMAScript, WebAPI, Websockets, WebRTC. These developments have increasingly brought to light other well-established concepts and protocols such as VoIP and SIP, which are now used in several web-based apps. Telecom operators have progressively moved their voice services to all-IP systems (e.g. 4G and 5G). Moreover, in 2020 the COVID-19/SARS-cov-2 pandemic has more than ever increased the use of IP-based voice and video calls, not only through traditional PC applications but also through multiple web-based applications, requiring only a web-engine to conduct such calls.

D. Cellular networks operators

Another area where Wi-Fi technologies get increasing support are cellular network operators. Telecom operators have started introducing *VoWiFi* – Wi-Fi calling – support in some areas of the world. The Compound annual growth rate (CAGR) of VoWiFi in 2020-2030 period is expected to be 24.5% [31].

Despite the popularity of the 5^{th} Generation of Mobile Wireless Networks (5G), both Wi-Fi and 5G are expected to co-exist, as Wi-Fi will complement and support 5G in different use cases (e.g. indoor) [28]. By using Wi-Fi, both Telcos and users will be able to reduce costs and improve performance. The typical lower-range of Wi-Fi networks will allow the users' equipment to reduce energy consumption all while reducing interference, which will allow for improved data rates.

III. Experimental setup and field-trial

Seeing the opportunities related to progress in Wi-Fi networks and complementary technologies we have developed a custom UAV payload and evaluated its behaviour in a field experiment.

In our standalone communication system solution, we utilized fixed-wing UAVs to enable audio-video communication between users equipped with a smartphone and the UAV operator. During the field evaluation an audio-video call was established between a user with a smartphone in the field and a coordinator at the operator control center. No mobile network service was used.

The mission scenario assumed to fly the UAV and loiter around the expected user position. At the operator control center one computer was used to command the UAV, while a second computer was used to perform the call testing the telecommunication quality. The user in the field was equipped with a regular smartphone. The user's smartphone and ground station equipment both had SIP clients installed (Linephone, Belledonne Communications SARL, France). This scenario is also valid for solutions discussed in Section IV.

The field trial took place at Udduvol RC airfield in Norway. The UAV was set to loiter at 100 meters altitude, and with 100 meter radius around the expected location of the user with the mobile phone (Figures 2 and 3). Even though different trajectories were not used, this could be further explored to improve the communication link [32].

The fixed-wing UAV was a Cruiser-Mini (ET-Air, Slovakia) platform controlled with autopilot (Hex Cube Black, Hex/ProfiCNC, Taiwan) running the ArduPlane firmware. For telecommunication a custom payload module, fixed inside the UAV payload bay, was used. The payload consists of directional antennas (HyperGain RE09P, L-COM, USA), a 2.4 GHz Wi-Fi radio module (Rocket M2, Ubiquity, USA), and a SOM9331 based router running an open-source OpenWRT operating system (Fig. 4). The link between UAV and its ground station was a separate, secured connection using 5.8 GHz radio nodes (Rocket M5, Ubiquiti, USA), running in AirMax mode. However, in order to extend the communication range, other solutions could also have been considered, such as directional tracking antennas [33].

The UAV payload radio module was configured as an Access Point (AP) providing an open (non-secured) Wi-Fi network access to users within its service area. Each antenna has beam width of 75° horizontal and 65° vertical. The

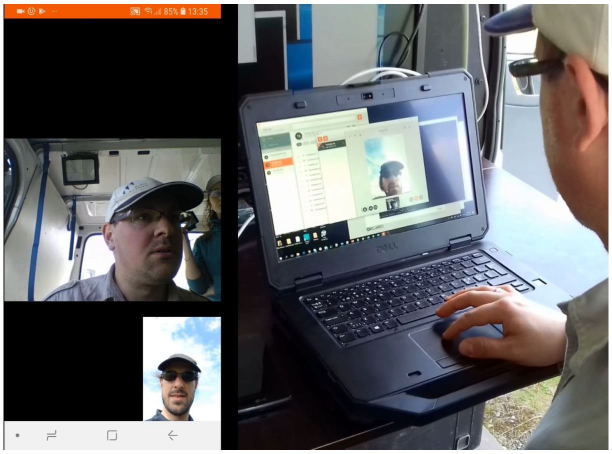


Fig. 3: Screenshot of a mobile phone and a photo of operations control center during the audio-video call

antennas were installed perpendicularly to the hull, facing the UAV's side (Fig. 4b). In order to keep the antenna beam orientation towards the center of the UAV circular path during loiter, its orientation needs to be compensated for the UAV bank angle. Therefore, the payload angle was controlled with a servo, counteracting the UAV rotation in turns. The servo was controlled directly by the autopilot, taking advantage of the available camera/gimbal roll output.

The router in the UAV's telecommunication payload provided Dynamic Host Configuration Protocol (DHCP) server leasing a range of IP address to the connected stations (mobile phone). By monitoring the IP-leases we were able to detect the user mobile phone presence in the network. Knowing the user IP, we were able to make a call directly to the mobile-phone with pre-installed SIP client (Fig. 3).

Prior the audio-video call demonstration, a set of Access Point configurations were tested. The AP was set to maximum locally-allowed transmission power. Although the tested AP supported several channel widths – 5, 10, 20, and 40 MHz – the mobile phone that was used could connect only to 20 MHz and 40 MHz-wide channels.

During the flight, connections were established several times testing call quality on various fixed Wi-Fi Modulation and Coding Schemes (MCS) settings ranging from 0 to 7. The audio-video connection was successfully established in all these configurations. Each of the connection modes provided enough throughput for peer-to-peer communication with clear audio quality and sufficient video experience between two devices. Since the UAV was constantly in motion, some fluctuations could be observed in link quality. These were most likely caused by natural obstacles, (e.g. a large bush close to the user), periodically obscuring radio line-of-sight between the UAV antennas and user's smartphone. None of the interlocutors reported link quality fluctuations to impact audio quality. However, it had periodic impact on the video quality. During the call some frames were dropped or featured noise, however the quality was restored with further flight of the UAV.

In order to better quantify the experiments' outcomes, another set of tests flights have been performed. This time the measurements focused on network performance under selected geometries between the UAV and ground node. The UAV loitered over 5 waypoints (WPs). The WPs have been set 50 meters apart of each other as presented on Figure 6. That also resulted in a set of antenna alignment geometries favoring WP1 over other WPs (Figure 5). The ground node was an independent computer connected to a WiFi radio (Rocket M5, Ubiquiti, USA) with omnidirectional antennas. The network performance has been measured using iperf v2.0.10. When the UAV was loitering over each WP, a total of 31 repetitions of the performance tests were executed per WP, each taking 180 seconds.

In addition, a new set of experiments was performed, measuring radio performance with the radio configured to automatically adjust the used MCS, as well as fixed radio configuration to operate on MCS 7 only. MCS 7 was selected based on experience from previous work with a similar setup [32].

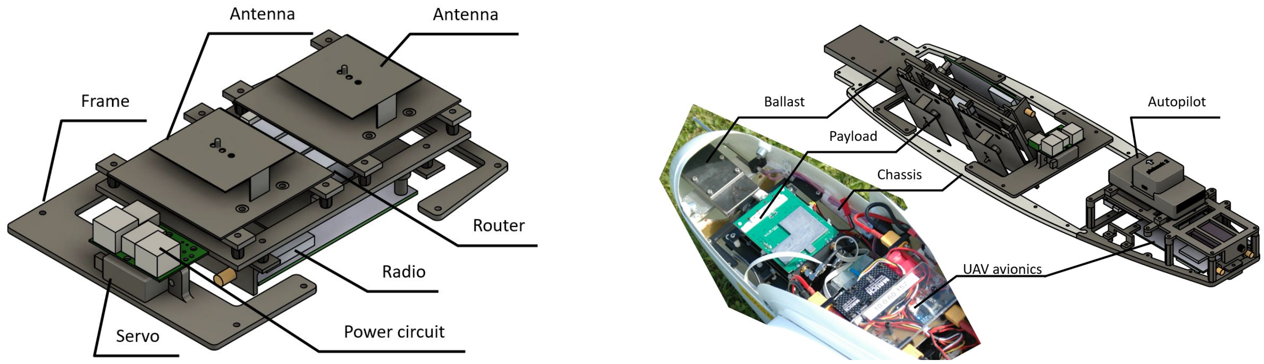
Figures 6 and 7 show network performance during the flight. They reveal that the average bitrate was highest when the UAV flew in circles with the ground node in the center. That result can be justified by favourable antenna alignment geometry – as presented on Figure 5. Less favourable geometries yield lower bitrate. Moreover, Figure 7 shows that there was a number of moments when network bitrate dropped bellow 64 kbps (recommended for mono-music in RFC7587). The results further show that although the average bitrate is sufficient for video transmission for all waypoints, the signal variability could potentially result in communication drops — not only of video transmission but also the audio. Therefore, precise victim localisation and precise flight-planning may be important for good communication quality. The results also show that in the studied scenario, for less favourable configurations (WP4 & WP5), the radio internal algorithms for automatic MCS selection achieve better performance in both bitrate and number of performance drops, compared to the fixed MCS7.

IV. Further opportunities

Providing an Wi-Fi network accessible with mobile devices by the UAV enables implementation of various solutions. We can consider two main scenarios. First, the case when UAV can provide Wi-Fi network with access to the Internet via a backbone link. Second, when UAV can not provide Internet access within the Wi-Fi network. If the UAV can bridge users with the Internet, mobile device users can access various communication channels of their own choice, such as VoWiFi, VoIP app, or social media.

For the second scenario following, the solutions can be implemented: (1) audio-video with pre-installed SIP app; (2) text-chat over non-secure HTTP connection with "Captive Portal"; (3) providing SIP app via a "Captive Portal"; (4) P2P audio-video conversation via "Captive Portal" and HTTPS connection.

In practice, the first solution requires action in advance. It is most suitable for organized teams which would like to keep communication within the group, e.g. first responders.



(a) Diagram of the payload

(b) Payload inside the UAV

Fig. 4: The communication payload

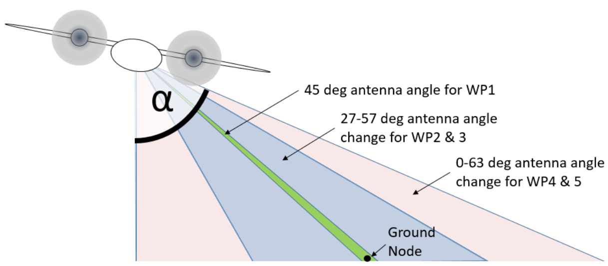


Fig. 5: Summary of communication performance

For ad-hoc users, access to communication channel via open Wi-Fi network can be provided with help of a "Captive Portal", e.g. using redirect by a local DNS. Mobile devices which connect to the UAV open Wi-Fi network will automatically check for internet connectivity. The station detects the limited connectivity, and prompt user to access the open Wi-Fi network. That opens the captive portal website on the mobile device browser. A selection of strategies can be implemented at this point.

1) The captive portal can provide direct text communication channel over non-secured HTTP connection.
2) The captive portal may enable video and audio features supported for the modern browsers and allow to establish video-conversation, e.g. using WebSockets mechanism.
3) User can download from the UAV a locally stored app which can be installed on the mobile device.

A barrier for audio-video Captive Portal features may be modern web browsers security policy. In some cases mobile device modules, such as camera or microphone, cannot be accessed through a non-secured HTTP connection. The HTTPS server can be set up to run on the local network, however the security certificate validation may be challenging if the Internet access is not provided.

A. *Other Available technologies*

The purpose of the previously outlined implementation is twofold: either to relay information from *isolated* users to users with more resources; e.g. rescuers in a SAR-scenario or access to government officials outside the damaged area or even general network access to the Internet, or to enable communication within an isolated group, without relaying data out of the area. Both purposes are depicted in Figure 1. Creating a local communication cell is the simplest and was demonstrated in a field trail evaluated in Section III.

There are several existing and also new communication infrastructures providing the back-bone links needed for relaying data to the Internet (or telecom networks). As shown in Figure 1, the flying node can relay between the isolated group and either a permanent or ad-hoc ground node connected to regular back-bone, given that the extent of the ND is small enough.

As an alternative, an ad-hoc ground node can be set up within the isolated area and relay communication either through a radio line out of the area, or even through satellite through the emerging mega-constellation infrastructure such as OneWeb or StarLink. In this case, one or several ground terminals for a mega-constellation can be deployed either inside or bordering the isolated area and network capacity can be shared with a larger number of users through the UAV.

B. *Emergency satellite communications*

Mobile satellite systems such as Iridium are used during NDs to provide (voice) communication from inside a damaged area. A challenge with such systems is the limited availability of terminals and handsets as well as the relatively low throughput. Therefore, relaying data services through an UAV connected to a broad-band service (satellite or radio-line) has advantages.

For SAR events (in developed areas – again due to user terminal availability), basic information to rescuers can be forwarded through services such as the SAR/Galileo service (part of the Cospas-Sarsat initiative) on the 406 MHz band. From 2020, the SAR/Galileo service Return Link Service can also provide a confirmation to the person(s) in distress that their emergency message has been received by relevant authorities. However, no other communication service can be offered through these systems.

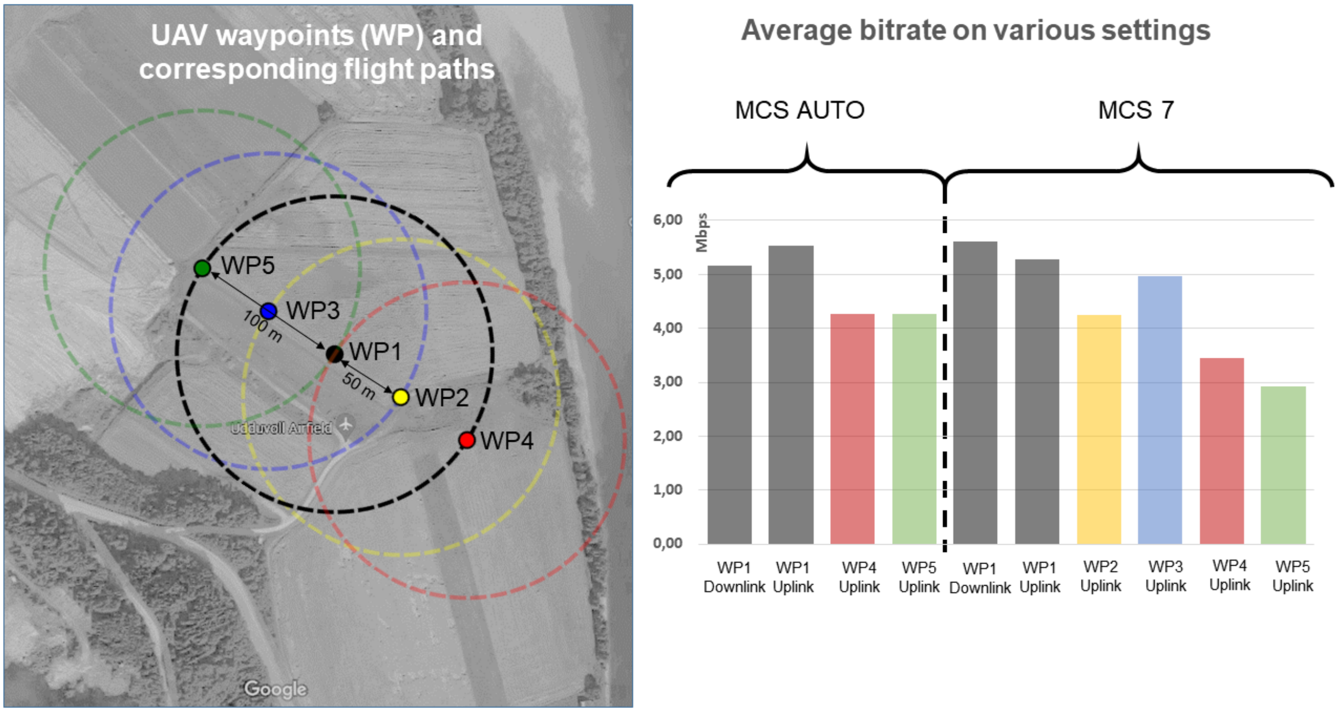


Fig. 6: Test of communication

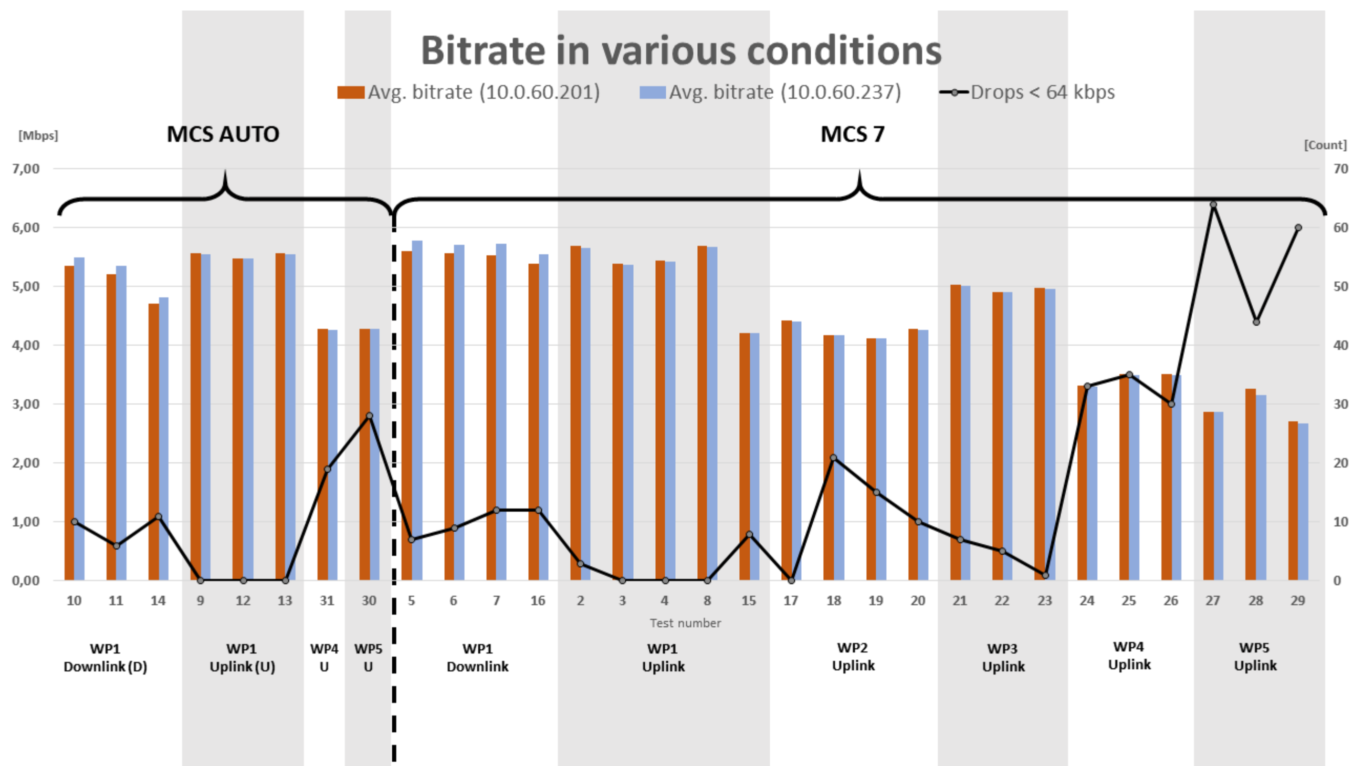


Fig. 7: Details of communication performance. Average bitrate [Mbps], and number of occurrences of bitrate drop below 64 kbps [Counts] (recommended for mono-music in RFC7587) .

C. Future long-range solutions

If the extent of the ND is vast (in space and time), solutions provided by (or similar to) High Altitude Platforms (HAPs) such as the Airbus Zephyr UAV [34] or Googles' Project Loon [35] have gained some interest in the community. However, in January 2021 Alphabet (Google) shut down the Project Loon, which has been performing tests over Kenya [36]. A certain drawback with HAPs is that the range is beyond reach of regular Wi-Fi nodes [37]. HAP platforms are commercial systems in various stages of test and development, meant to cover larger areas and provide services on a more permanent basis.

V. Conclusions

Wi-Fi is a worldwide available technology in Smartphones and Smart Feature Phones. Continuous improvement of the standard, equipment and services, makes Wi-Fi a valuable asset in Search and Rescue and Natural Disaster Response scenarios.

In this paper we discussed Wi-Fi and complementary technologies that can be used to rapidly deploy a telecommunication infrastructure when in need. We presented, and evaluated in a field experiment, a standalone communication system solution, delivered by a UAV which can reach areas where other telecommunication infrastructures are not available. We showed that a Wi-Fi network delivered by a fixed-wing UAV, flying at an altitude of 100 meters, is accessible with a regular smartphones and can be used to establish an audio-video call between smartphone user and the UAV operator.

Acknowledgements

Authors would like to thank Pål Kvaløy for help in field trials and NTNU Technology Transfer Office for the evaluation of the concept. This research was funded by the Research Council of Norway through the Centres of Excellence funding scheme, grant number 223254 – NTNU AMOS and an innovation scholarship provided by the Norwegian University of Science and Technology.

References

[1] T. Girard, "Barriers to communicating disaster response information to the public during disaster situations," Ph.D. dissertation, Karlsruhe Institute of Technology - KIT (2017), 2017.

[2] N. I. of Disaster Management, *Disaster communication*, https://nidm.gov.in/easindia2014/err/pdf/themes_issue/technology/disaster_comm.pdf [Online; accessed 15-February-2021].

[3] Z. E. Khaled and H. Mcheick, "Case studies of communications systems during harsh environments: A review of approaches, weaknesses, and limitations to improve quality of service," *International Journal of Distributed Sensor Networks*, vol. 15, no. 2, p. 1 550 147 719 829 960, 2019. DOI: 10.1177/1550147719829960. eprint: https://doi.org/10.1177/1550147719829960. [Online]. Available: https://doi.org/10.1177/1550147719829960.

[4] V. G. Menon, J. P. Pathrose, and J. Priya, "Ensuring reliable communication in disaster recovery operations with reliable routing technique," *Mobile Information Systems*, vol. 2016, p. 9 141 329, Feb. 2016, ISSN: 1574-017X. DOI: 10.1155/2016/9141329. [Online]. Available: https://doi.org/10.1155/2016/9141329.

[5] J. McKay, *Sandy created a black hole of communication*, G. Technology, Ed., https://www.govtech.com/em/disaster/Sandy-Black-Hole-of-Communication.htmlGovtech.com [Online; posted 28-January-2013], Jan. 2013.

[6] *ResponDrone situational awareness system for first responders*, https://respondroneproject.com/, Accessed: 2021-02-25.

[7] *ARCSAR arctic and north atlantic security and emergency preparedness network*, https://arcsar.eu/, Accessed: 2021-02-25.

[8] *INGENIOUS the first responder of the future*, https://ingenious-first-responders.eu/, Accessed: 2021-02-25.

[9] *CURSOR coordinated use of miniaturized robotic equipment and advanced sensors for search and rescue operations*, https://www.cursor-project.eu/, Accessed: 2021-02-25.

[10] *FASTER first responder advanced technologies for safe and efficient emergency response*, https://www.faster-project.eu/, Accessed: 2021-02-25.

[11] *DRIVER+ driving innovation in crisis management for european resilience*, https://www.driver-project.eu/, Accessed: 2021-02-25.

[12] M. Erdelj and E. Natalizio, "Uav-assisted disaster management: Applications and open issues," in *2016 International Conference on Computing, Networking and Communications (ICNC)*, 2016, pp. 1–5. DOI: 10.1109/ICCNC.2016.7440563.

[13] H. Hildmann and E. Kovacs, "Review: Using unmanned aerial vehicles (uavs) as mobile sensing platforms (msps) for disaster response, civil security and public safety," *Drones*, vol. 3, no. 3, 2019, ISSN: 2504-446X. DOI: 10.3390/drones3030059. [Online]. Available: https://www.mdpi.com/2504-446X/3/3/59.

[14] H. Shinbo, Y. Kunisawa, T. Sakai, Y. Kitatsuji, A. Endo, and K. Tanaka, "Flying base station for temporary mobile communications in an area affected by a disaster," in *2018 5th International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*, 2018, pp. 1–7. DOI: 10.1109/ICT-DM.2018.8636379.

[15] Leonardo, *Transforming airborne search and rescue missions*, https://uk.leonardocompany.com/en/news-and-stories-detail/-/detail/transforming-airborne-search-and-rescue-missions [Online; posted 03-December-2018].

[16] D. Hague, H. T. Kung, and B. Suter, "Field experimentation of cots-based uav networking," in *MILCOM 2006 - 2006 IEEE Military Communications conference*, 2006, pp. 1–7. DOI: 10.1109/MILCOM.2006.302070.

[17] T. A. Johansen, A. Zolich, T. Hansen, and A. J. Sørensen, "Unmanned aerial vehicle as communication relay for autonomous underwater vehicle —

field tests," in *2014 IEEE Globecom Workshops (GC Wkshps)*, 2014, pp. 1469–1474. DOI: 10.1109/GLOCOMW.2014.7063641.
[18] *SMAVNET II swarming micro air vehicle network*, https://smavnet.epfl.ch/, Accessed: 2021-02-25.
[19] R. D. Arnold, H. Yamaguchi, and T. Tanaka, "Search and rescue with autonomous flying robots through behavior-based cooperative intelligence," *Journal of International Humanitarian Action*, vol. 3, no. 1, p. 18, Dec. 2018, ISSN: 2364-3404. DOI: 10.1186/s41018-018-0045-4. [Online]. Available: https://doi.org/10.1186/s41018-018-0045-4.
[20] J. Rosenberg, H. Schulzrinne, G. Camarillo, A. Johnston, J. Peterson, R. Sparks, M. Handley, and E. Schooler, *Rfc3261: Sip: Session initiation protocol*, USA, 2002.
[21] W. Saad, M. Bennis, and M. Chen, "A vision of 6g wireless systems: Applications, trends, technologies, and open research problems," *IEEE Network*, vol. 34, no. 3, pp. 134–142, 2020. DOI: 10.1109/MNET.001.1900287.
[22] H. Simons, *Kaios is doing well in india, but it's pulling some big numbers in us too*, A. Authority, Ed., https://www.androidauthority.com/kaios-usa-india-958519/AndroidAuthority.com [Online; accessed 15-February=2021], Mar. 2019.
[23] J. James, "The smart feature phone revolution in developing countries: Bringing the internet to the bottom of the pyramid," *The Information Society*, vol. 36, no. 4, pp. 226–235, 2020. DOI: 10.1080/01972243.2020.1761497. eprint: https://doi.org/10.1080/01972243.2020.1761497. [Online]. Available: https://doi.org/10.1080/01972243.2020.1761497.
[24] bankmycell, *How many smartphones are in the world?* https://www.bankmycell.com/blog/how-many-phones-are-in-the-world, Accessed: 2021-02-25.
[25] P. R. Center, *Mobile fact sheet*, https://www.pewresearch.org/internet/fact-sheet/mobile/, Accessed: 2021-02-25.
[26] T. W. Bank, *Mobile cellular subscriptions*, https://data.worldbank.org/indicator/IT.CEL.SETS.P2, Accessed: 2021-02-25.
[27] CISCO, "802.11ac: The Fifth Generation of Wi-Fi Technical White Paper," CISCO, Tech. Rep., 2018. [Online]. Available: https://www.cisco.com/c/dam/en/us/products/collateral/wireless/aironet-3600-series/white-paper-c11-713103.pdf.
[28] ZTE, "Wi-Fi 6 Technology and Evolution White Paper," ZTE, Tech. Rep., 2020. [Online]. Available: https://res-www.zte.com.cn/mediares/zte/Files/PDF/white_book/Wi-Fi_6_Technology_and_Evolution_White_Paper-20200923.pdf?la=en.
[29] S. Sharma, *Modi's wifi revolution: Cabinet okays setting wifi across country*, F. Express, Ed., https://www.financialexpress.com/ economy/ ease-of-doing-business-in-digital -india-cabinet-approves-setting -up -public-wifi-hotspots-across-country/2146655/ [Online; accessed 15-February=2021], Dec. 2020.
[30] N. Christopher, *Public wifi to contribute $20 billion to india's gdp by 2019: Study*, T. E. Times, Ed., https://economictimes.indiatimes.com/tech/internet/public-wifi-to-contribute-20-billion-to-indias-gdp-by-2019-study/articleshow/64856557.cms?from=mdr [Online; accessed 15-February=2021], Jul. 2018.
[31] P. S. Intelligence, Ed., *Global vowifi market overview*, https://www.psmarketresearch.com/market-analysis/voice-over-wifi-vowifi-market [Online; accessed 15-February=2021], Jul. 2020.
[32] 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. DOI: 10.1109/ACCESS.2017.2769658.
[33] 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. DOI: 10.1109/RED-UAS.2015.7441026.
[34] Airbus, *Zephyr - pioneering the stratosphere*, 2021. [Online]. Available: https://www.airbus.com/defence/uav/zephyr.html.
[35] Loon, *Connect people everywhere*, 2021. [Online]. Available: https://loon.co/.
[36] A. Teller, *Loon's final flight*, online, Jan. 2021. [Online]. Available: https://blog.x.company/loons-final-flight-e9d699123a96.
[37] 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. DOI: 10.1109/ESTEL.2012.6400206.