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PERFORMANCE MODELING AND PROTOTYPING OF DIRECTIONAL RADIO LINK FOR MOVING MACHINES

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ABSTRACT

Zeinab Khosravi: Performance Modeling and Prototyping of Directional Radio Link for Moving Machines
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Usage of smart devices and the amount of mobile data traffic have grown exponentially in the past decade. Also, novel applications have specific bandwidth and latency requirements. All of these combined are calling for a new networking technology. Upcoming 5G wireless networks aim to answer the current and potential future needs of wireless technology. In the context of the implementation and development challenges, we can highlight two important use cases of 5G: Enhanced Mobile Broadband, which promises high data rate with low latency during rush hour, and Machine-Type-Communication, where wireless devices can communicate with each other in a fully automated manner with no need for human interaction. Concerning the first use case, this work has focused on evaluating the core performance metrics, including throughput and Signal-to-Interference plus Noise Ratio (SINR), of suggested radio technology for 5G (mmWave) in a dense urban deployment. In this work, additional Unmanned Aerial Vehicle (UAV)-assisted Access Points (APs) are considered to provide extra coverage. For this reason, a number of appropriate scenarios were simulated and evaluated using NS-3 platform. Regarding the second use case, this work has focused on enabling high-speed long-range communication specifically used in autonomous robotic off-shore operations and modeling the performance of such systems in terms of throughput and Received Signal Strength (RSS). For this purpose, a system of directional radio links utilizing IEEE 802.11 Wi-Fi and 3GPP LTE was designed, installed and tested on an autonomous boat to enable a high-speed bi-directional connection. This thesis describes the details of these research directions along with obtained results.

Keywords: 5G, antenna, antenna tracking, beamsteering, drone cell, mmWave, NS-3, wireless networks

PREFACE

This thesis contains the results of my work during nearly one and a half years being a member of W.I.N.T.E.R. research group in Computing and Electrical Engineering Faculty of Tampere University of Technology.

First, I would like to express my gratitude to Dr. Mikhail Gerasimenko who was my mentor from the beginning, guiding me through every step. Then many thanks to Asst. Prof. Sergey Andreev for always supporting me and showing me the bigger picture. Much gratitude to Prof. Yevgeni Koucheryavy who always supports every member of our research group and does what makes us more comfortable and productive. I would like to sincerely thank Dr. Alexander Pyattaev who is the reason I had this amazing experience with W.I.N.T.E.R. research group. Many thanks to Jani Urama and Dr. Aleksandr Ometov for being supportive and helpful colleagues. Special thanks to the Department of Mechanical Engineering and Alamarin-Jet Oy for giving me the opportunity to participate in aColor project as well as providing the necessary equipment for the research. I would like to sincerely thank Nick Memminger and all my friends who dealt with me during the hardest times of my studies. Much gratitude to my family who always believed in me and supported my choices.

Finally, I would like to dedicate this work to my mother's memory.

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Tampere, 14.03.2019

Zeinab Khosravi

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LIST OF ABBREVIATIONS AND SYMBOLS

3G	Third Generation of Cellular Network
3GPP	3rd Generation Partnership Project
4G	Fourth Generation of Cellular Network
5G	Fifth Generation of Cellular Network
aCOLOR	Autonomous and Collaborative Offshore Robotics
AP	Access Point
AR	Augmented Reality
AUV	Autonomous-Underwater-Vehicle
BFDM	Bi-orthogonal Frequency Division Multiplexing
BS	Base Station
CPU	Central Processing Unit
DC	Direct Current
EHF	Extremely High Frequency
eNB	evolved Node B
EPC	Evolved Packet Core
E-UTRAN	The Evolved UMTS Terrestrial Radio Access Network
FBMC	Filter Bank Multi-Carrier
GC	Ground Control
GFDM	Generalized Frequency Division Multiplexing
GPIO	General Purpose Input/Output
GPS	Global Positioning System
HSS	Home Subscriber server
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
LAN	Local Area Network
LOS	Line Of Sight
LTE	Long-Term Evolution
NS-3	Network Simulator 3
NYU	New York University
M2M	Machine-to-Machine
MAC	Medium Access Control
MAN	Metropolitan Area Network
MEI	Mechanical Engineering and Industrial Systems Laboratory
mmWave	millimeter Wave
MIMO	Multiple Input Multiple Output

MME	Mobility Management Entity
MTU	Maximum Transmission Unit
MTC	Machine-Type Communication
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open System Interconnection
PAN	Personal Area Network
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
P-GW	Packet data network Gateway
PHY	Physical layer
PID	Proportional-Integral-Derivative
PoE	Power over Ethernet
PWM	Pulse-Width Modulation
RAN	Radio Access Network
RANaaS	RAN-as-a-Service
RF	Radio Frequency
RPM	Revolutions Per Minute
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SBC	Single-Board Computer
S-GW	Serving GateWay
SHF	Super High Frequency
SINR	Signal-to-Interference plus Noise Ratio
SNR	Signal-to-Noise Ratio
TCP	Transmission Control Protocol
TDMA	Time Devision Multiple Access
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UE	User Equipment
UFMC	Universal-Filtered Multi-Carrier
UMi	Urban Micro cellular
USV	Unmanned Surface Vessel
VR	Virtual Reality
WAN	Wide Area Network
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

r	distance
γ	path loss exponent
P	power
T	time period

1. INTRODUCTION

1.1 Motivation

In the past decade, the use of mobile communication and smart devices has grown substantially. The growth in usage of smart devices such as tablets, smartphones and IoT machines along with the feasibility of accessing Internet easily everywhere at anytime in most countries, leads to enhancement of mobile data traffic. In the following years, the rise of new technologies such as bandwidth hungry applications like ultra HD streaming and VR/AR (Virtual reality/Augmented reality) plus low latency needed applications like online gaming, health care, and mission-critical applications, will cause the annual growth of 40% in data traffic demand [1–3].

The substantial increase in data traffic and number of users leads to the necessity of developing the next generation of mobile networks such that it can answer the upcoming needs of all users. More detailed information about the fifth generation (5G) of wireless networks can be found in Section 2.4, here we will only mention one of its core use cases – Machine-Type-Communications (MTC) and intelligent transportation that have attracted the automotive industry.

MTC, which is also called Machine-to-Machine (M2M) communications, refers to communications that happen directly between autonomous nodes or between them and central servers provided for MTC devices [4]. These communications can happen via both fixed and wireless networks. The main use cases of MTC are focused on smart industry like automation in industry, smart agriculture such as environmental sensing, automation in driving and road infrastructure, which can happen by utilizing surveillance cameras and vehicular automation, and health-related applications consisting of wearable devices communicating with a central server to aggregate the health-related data [5].

High-speed long-range communications are important aspects of MTC because of their accuracy and low power consumption [6]. At the same time, use of highly-directional antennas on the access link can provide better coverage for, e.g. networks utilizing Unmanned-Aerial-Vehicle (UAV or drone)-mounted access points (APs) in urban deployments, or in any scenario where the high-speed wireless backhaul is required [7–9], such as autonomous robotics [10,11], which in the scope of this thesis focus on the offshore Unmanned Surface Vehicle (USV) operations.

In general, autonomous robotics aim at decreasing the human interaction's effect on offshore operations, which is important for supporting the services needed in the oncoming unmanned maritime ecosystem. In this regard, both industry and academia are putting significant effort in the appropriate research in order to get the competitive advantage on the future market. For example, to the end of 2016 Finland launched the project supported by 60 companies together with Finnish Funding Agency for Technology and Innovation (Tekes) and the Ministry of Transport and Communications aiming to promote unmanned maritime systems[1]. The goal of this project is to create the world's first unmanned maritime systems and services by the year 2025[2].

The novel applications mentioned above introduce new requirements on throughput, latency, and reliability [12–14] of future wireless communications. Since the current network infrastructure and access technologies do not fully satisfy the mentioned requirements, it is crucial to evaluate the suggested solutions alone and together with existing technologies to shape the future system and model its performance [15].

1.2 Objectives

The objective of this work is to research and present a performance evaluation and modeling of different directional radio links for moving vehicles. The radio technologies used in this thesis are IEEE 802.11 Wi-Fi[3] and 3GPP LTE (Long-Term Evolution)[4] together with 5G working in the millimeter Wave (mmWave) band. As it was mentioned in Section 1.1, directional radio interfaces can be used in the connection between user and access network (access link) or connection between access network entities and the backbone (backhaul link). The first part of this work, studies and evaluates the performance of directional mmWave access link in urban deployment using fixed and UAV-mounted moving APs in three different simulation scenarios.

In the second part of this thesis, we discuss the performance evaluation and modeling of Wi-Fi and LTE radio links established between an automated USV and Ground

[1] `https://www.lvm.fi/-/suomi-edellakavijaksi-merisektorin-automaatiokokeiluissa`
[2] `https://www.trafi.fi/en/maritime/maritime_automation_experiments`
[3] `http://www.ieee802.org/11/`
[4] `http://www.3gpp.org/technologies/keywords-acronyms/98-lte`

Control (GC) station. Both USV and GC sides are equipped with the same radio technology interfaces aiming to start a new era in offshore operations where human interactions are minimized. This work will also show how the use of multi-radio technology solutions can be beneficial in order to meet the substantially growing demands of future wireless networks.

The main performance metrics, which are discussed in this work are throughput, reliability of connection in different conditions and received signal strength (RSS) level. Also, as the world is moving towards automation especially focused on MTC and transportation, prototyping a communication solution for unmanned maritime is one of the first steps towards creating an efficient autonomous maritime ecosystem. Our designed system is flexible, which makes it an appropriate prototype and a suitable vessel for testing the connectivity of different radio technologies.

1.3 Scope and structure of the work

As it was mentioned before, this work consists of two parts. The first part focuses on exploring the usage of the mmWave band as a solution to address the traffic demands of future wireless networks and evaluate its performance in an urban environment when pedestrian users are present. This part also includes the evaluation of shortcomings of mmWave-based communication technologies and offers potential ways for further improvements. The second part addresses the current state of well-known and widely used wireless radio network technologies and exploring their performance in a specific scenario of offshore operation. Two different scenarios of directional radio links for moving machines have been implemented under the scope of this thesis. The rest of the thesis is organized as follows:

- Chapter 1 contains a general explanation of the considered topic emphasizing the motivation, objectives, scope, and structure of the work.
- Chapter 2 describes the core metrics used for performance evaluation. It also provides the basic background on existing modern wireless networks (4G) and shows the necessity of 5G implementation, along with its use cases, requirements and current development proposals.
- Chapter 3 describes the first considered use case, concentrating on directional mmWave access link between pedestrian mobile users and mmWave APs. In this scenario, a comparison between three different deployments is done based on the performance metrics described in Section 2.2. The objective of this chapter is to evaluate the effect of utilizing UAV-based APs as alternative

coverage providers to the static network in the future wireless network. This chapter contains the scenario description, performance comparison obtained from simulations and a conclusion based on the collected results.

- Chapter 4 explains the second use case, which is a part of a more practical project named Autonomous and Collaborative Offshore Robotics (aColor). The objective of this part is to design and operate the telecommunication system for an autonomous boat used in rescue purposes. This scenario is concentrated on directional backhaul links, for connectivity between GC and the autonomous vessel. The chapter contains a complete description of the mechanical design, electrical design, the steering algorithm developed for mechanical control of directional antennas, together with results obtained from a test run done in Pyhäjärvi lake located in Tampere city[5] and a conclusion based on performed measurements.
- Chapter 5 presents the general conclusions of this work along with future work proposals related to both parts of this thesis. The chapter also contains some discussions on the use of moving APs for providing additional coverage in urban deployments and development of an efficient autonomous maritime ecosystem.

[5]Latitude:61.486574, Longitude:23.757863

2. BACKGROUND

This chapter is focused on presenting the technical background related to this work. In particular, Section 2.1 describes the wireless networks and related technologies especially the ones related to the work of this thesis in detail. Section 2.2 presents the metrics used to evaluate the performance of two different investigated scenarios. Section 2.3 demonstrates the overall network architecture of 4G (LTE) aiming to familiarize the readers with the concept of EPC (Evolved Packet Core) architecture which will also be used in 5G. At last, an overall description of 5G, its use cases, requirements and development proposals are given in Section 2.4.

2.1 Wireless networks

With the world becoming increasingly mobile in recent decades, traditional ways of networking, which are based on wired connectivity are proven to be insufficient. As it was mentioned in Chapter 1, the growing number of mobile devices introduces new challenges to the networking techniques in both mobility and data traffic demand area. As the author of [16] indicated, all wireless technologies regardless of protocol specifications share the same two following features:

- *Mobility*: This is the most unique feature of wireless network technology, the fact that users can move freely without any restriction related to network infrastructure such as cables.
- *Flexibility*: Mobility feature of wireless infrastructure is based on the access network to which users are connecting with one of the access entities called AP or Base Stations (BSs). Once the access entities have been deployed, the connection of users is a matter of capacity, coverage, and security. If these three requirements are satisfied, there is no need to change or add anything new to the deployment, despite the instant variations of the environment and network characteristics. This feature can significantly reduce the deployment and support costs in comparison with wired solutions.

Table 2.1 *Types of wireless networks*

Type	Coverage	Applications	Standards
Personal area network (PAN)	Within a person's reach	Cable replacement for peripherals	Bluetooth (IEEE 802.15.1), ZigBee (802.15.4), NFC
Local area network (LAN)	Within a building	Extension of wired network in wireless	IEEE 802.11 (WiFi), HiperLAN
Metropolitan area network (MAN)	Within a city or block of buildings	Wireless inter-connectivity between homes	IEEE 802.15 (WiMAX)
Wide area network (WAN)	Worldwide	Wireless network access everywhere	Cellular (GSM, UMTS, LTE, etc.)

Wireless network technologies can be categorized based on their coverage range into four categories that are shown in Table 2.1[1][2]. With a different purpose, The writer of [17] categorized the existing wireless systems based on their usage in the year 2005. Between all those systems, the most related ones to this work are the following:

- *Cellular telephone systems*: With the goal to provide duplex voice communication at both pedestrian and vehicle speeds, indoor and outdoor and with regional, national, or in some cases nowadays international coverage.
- *Wireless LANs (WLAN)*: Which is a short-range wireless network with high-speed data rate usable for pedestrian speed users.
- *Satellite networks*: These networks have the same functionality as cellular networks except for their type of base stations being satellites orbiting around the earth. They provide global data coverage for vehicles, pedestrians, and static users. The well known and highly used satellite based system is called Global Positioning System (GPS) which is nowadays widely used for radio-based navigation and localization.
- *Bluetooth*: Provides a short-range wireless connectivity between devices. Its use case is mostly in Wireless Personal Area Network (WPAN) and wearable devices used in the Internet of Things (IoT) development.

Besides the general classification mentioned above, three other particular modern communication technologies, considered in this thesis are as follow:

[1] `https://er.yuvayana.org/types-of-wireless-networking-technology-and-comparison/`
[2] `https://hpbn.co/introduction-to-wireless-networks/`

- *IEEE 802.11 Wi-Fi*[3], which according to [16] is a type of certification program run by Wi-Fi Alliance that includes all the vendors producing equipment based on Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards[4], for example, IEEE 802.11n known as Wi-Fi 4[5] and IEEE 802.11a[6] which both are standards for WLAN technology. Wi-Fi operates in an unlicensed spectrum[7] using an AP as the network's anchor. The AP broadcasts wireless signals that are detectable by other wireless devices in order to form a wireless network. Despite the common belief, Wi-Fi is only a brand name rather than an independent technology itself.
- *3GPP LTE* is another wireless technology, which is a standard for high speed wireless mobile communication[8]. This technology, which is also known as the fourth generation of broadband cellular network technology or 4G, is faster than third generation (3G), has lower complexity, higher throughput, lower latency and is more cost effective.
- *Millimeter-Wave (mmWave)* technology has been introduced recently as the future of wireless communication because of its extremely high data link rate and wide spectrum which is a result of its high frequency (30-300GHz) [18]. Both 3GPP [19] and IEEE [20] standardization groups are aiming to create the appropriate protocols which will enable wireless communications in both licensed and unlicensed parts of the mmWave spectrum.

Due to the fundamental physical limitations, modern wireless networks are facing serious challenges, such as protocol (in)compatibility of the standards working on the same frequency, or growing interference level in the urban deployments [21]. However, the most important challenge that has to be addressed, which at some level unites all other issues, is the limitation of available electromagnetic spectrum in current wireless networks. Assuming finite instantaneous electromagnetic frequency reuse, it becomes hard to design the upcoming technologies, keeping in mind the exponentially growing data traffic demands. The current wireless network technologies can partly handle these demands by using small cell densification [22] concept and physical (PHY) layer techniques, e.g. multiple input multiple output (MIMO) [23]. However, such solutions always lead to the growing control signaling overhead which makes them less and less efficient and more complicated and costly in terms of development, implementation, and support [24]. This will leave

[3] https://www.wi-fi.org/
[4] http://www.ieee802.org/11/
[5] https://standards.ieee.org/standard/802_11n-2009.html
[6] https://standards.ieee.org/standard/802_11a-1999.html
[7] https://www.wi-fi.org/discover-wi-fi/unlicensed-spectrum
[8] http://www.3gpp.org/technologies/keywords-acronyms/98-lte

the researchers and developers with the necessity of improving the wireless network capabilities in terms of latency, bandwidth, and throughput. That is why 5G aims to provide higher throughput and lower latency through utilizing mmWave part of electromagnetic spectrum. In the following sections, these performance metrics are described together with the overall structure of 4G network architecture. Next, 5G wireless network description is given as an example of future communication technology, in order to make the reader familiar with 5G's use cases, requirements and proposed solutions.

2.2 Performance metrics

This work is based on two different scenarios with the objective of investigating the performance of different directional links for moving machines. In this section, the related performance metrics, which describe the performance of the system, are discussed.

2.2.1 Throughput

According to the Oxford Dictionary of Computer Science [25], throughput is "a figure-of-merit for a computer system in which some description of operating rate such as instructions per minute, jobs per day, etc., is used. It is a measure of how much work gets done in a given time interval". In the context of this work, the job that has to be done by the system is to interchange necessary data packets between two parties located in the same network. Thus, throughput is the amount of information passing through the system in a given time period. In the first scenario, the throughput is calculated for the packet data convergence protocol (PDCP) layer using User Datagram Protocol (UDP) data packets. As for the second scenario, this metric is calculated for the application layer using Transmission Control Protocol (TCP) data packets.

2.2.2 Received signal strength

In telecommunications RSS, which for certain technologies is referred to as Received Signal Strength Indicator (RSSI), refers to the power received by a receiver antenna at a known distance from a transmitter antenna. This value is measured in decibels-milliwatts (dBm) and is negative for mobile networks, varying between 0dBm as perfect signal and -110dBm as extremely poor signal[9]. RSS level is affected by

[9] `https://wiki.teltonika.lt/index.php?title=Mobile_Signal_Strength_Recommendations`

the number and type of obstacles between transmitter and receiver, along with the distance between two antennas. Formula 2.1 indicates the general way of calculating this metric at distance r from transmitting antenna in all environments[10]:

$$RSS_{dBm} = (RSS_0)_{dBm} - 10.0\gamma \log_{10} \frac{r}{r_0}, \tag{2.1}$$

where the $(RSS_0)_{dBm}$ refers to the reference signal power at distance r_0 and γ represents the pathloss exponent, which takes into account the operational electromagnetic spectrum carrier frequency, the obstacles presence and their shape in the environment [26] and basically varies for different pathloss models. This formula shows that the reduction of RSS is not linear with respect to the distance and it depends on more than just the distance between two antennas.

2.2.3 Signal-to-interference-plus-noise ratio

The effect of shadowing and fading makes the modeling and performance evaluation of wireless systems more complicated than wired systems. Because of the amount of simultaneous transmission in the typical urban environment, the Signal-to-Interference-plus-Noise Ratio (SINR), which represents the strength of a desired signal over sum of interference from different sources plus background noise, becomes the better metric to evaluate the system performance than Signal-to-Noise Ratio (SNR), which only represents the strength of a desired signal over the background noise [27]. Formula 2.2 shows the SINR definition:

$$SINR = \frac{P_{signal}}{P_{noise} + \sum_{j=1}^{n} (P_{interference})_j}, \tag{2.2}$$

where P_{signal} and P_{noise} are representing the power of desired signal and noise power respectively, n is the number of interference sources which can also indicate the number of adjacent channels which interfere with the desired signal and $P_{interference}$ is the power of each interfering signal. The SINR is usually expressed in decibels (dB). Formula 2.3 shows the SINR calculation in dB:

$$SINR_{dB} = 10 \log_{10} \frac{P_{signal}}{P_{noise} + \sum_{j=1}^{n} (P_{interference})_j} dB. \tag{2.3}$$

[10] `https://pdfs.semanticscholar.org/6bdd/b7d77c2c2bfc061c9e17e212b3abb2172eee.pdf`

2.2.4 Latency, reliability, and security

Although we did not investigate these three performance metrics in our scenarios, they are very important in wireless networks, which makes them worth mentioning here. In the context of wireless networks, latency describes the delay that arises when transmitting or processing network data[11]. It is generally caused by one or multiple slow networking devices, such as routers, in the network.

Reliability is a network's ability to perform a set of requested jobs within a certain period of time under predefined conditions [28]. In other words, reliability refers to the ability of any wireless device in the network to communicate with any other device within the same network at any time using all available means. The other term for reliability can be robustness, in terms of trusting a device to deliver an intended message in a given time to another certain device inside the network.

The portability of wireless network devices leads to the increasing probability of theft and fraud, which makes security an important concept when dealing with wireless networks. there are many security technologies and protocols that deal with different security threats. The authors in [29] provide a full description of these threats and the technologies used to avoid them.

2.3 4G network architecture

To fully understand 5G network architecture, a general view of how 4G network functions and what main components it has is required. Thus, in this section an overview of 4G network architecture is presented [30].

4G architecture consists of three main components:

- The User Equipment (UE), which is the end user that its communication with other devices is of interest.
- The Evolved UMTS Terrestrial Radio Access Network (E-UTRAN).
- The Evolved Packet Core (EPC).

Figure 2.1 shows the overall architecture containing mentioned components. In the following, a small description of the latter two components are given [31].

[11] https://techterms.com/definition/latency

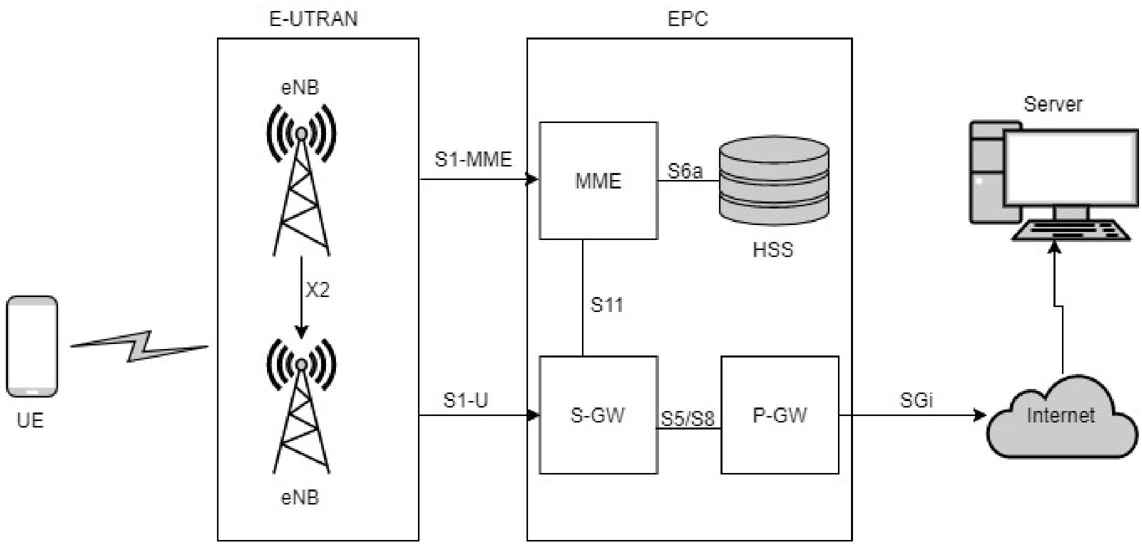


Figure 2.1 *Architecture of 4G network [31].*

2.3.1 E-UTRAN

This component is known as the LTE access network and is responsible for handling the communications between UE and EPC. It is merely a network of BSs called Evolved Node B (eNB). ENBs are connected with each other through X2-interfaces. At any given time, a UE is served by one eNB. eNBs have two main functions: to provide communication access to UE devices and to control the low-level operations of all UE devices by sending signaling messages. E-UTRAN is connected to EPC via S1 interface.

2.3.2 EPC

The EPC is responsible for interconnection of UEs, high-level mobility, security and billing, as well as connection to the other communication networks. The main components of this part of 4G architecture is shown in Figure 2.1. The following provides a small description of each component's functionalities.

- *Mobility Management Entity (MME)*: MME mostly controls the high-level operations of the UE, e.g. idle mode tracking, selecting a Serving Gateway (S-GW) for UE, handover between eNBs, authentication using HSS, the process of activation and deactivation of bearer, paging procedure.
- *Home Subscriber Server (HSS)*: It is the database containing the information (billing, security) of all subscribers.

- *S-GW*: It merely acts as a router and is responsible to forward user data to P-GW.

- *Packet Data Network (PDN) Gateway (P-GW)*: It is a router, connecting mobile networks to the Internet. It also has the role of providing mobility between 3GPP and non-3GPP networks. P-GW is connected to the outside world using SG interface (SGi).

2.4 Fifth generation (5G) of mobile networks

The next generation of wireless networks known as 5G, aims to improve the current wireless network technologies in many aspects such as speed, throughput, latency, reliability, together with covering new applications coming to the market, such as AR/VR, high-resolution streaming, online-gaming, etc. In this section, 5G use cases, requirements and the development solutions are introduced.

2.4.1 Use cases

5G use cases introduced by Nokia [32], [33], Huawei[12], Ericsson[13], and 3GPP (TR 22.891 [34]) research groups can be divided into three main categories as follows:

- *Enhanced mobile broadband*: Refers to the possibility of communicating in crowded areas, which requires both high data rate and low latency. 5G with its high speed, promise of stable connection with real-time response is taking the mobile network systems to the next level. This use case includes VR/AR applications.
- *Massive machine-type communication (or massive IoT)*: It implies the wireless connectivity of over billions of devices in different networks around the world fully automated and without human intervention. It includes concepts such as smart society, where different sensors e.g. temperature, heating controllers, alarms and surveillance cameras, home appliances and wearables, are connected together and the interchanging data is stored and used to manage the distribution of resources (such as power consumption, transmission rate, etc.) in an efficient way. It also allows remote control of different machines covering outdoor (like lawn mower) and indoor (like washing machine) use

[12] `https://www.huawei.com/en/industry-insights/outlook/mobile-broadband/xlabs/use-cases/5g-top-10-use-case`

[13] `https://www.ericsson.com/en/5g/use-cases`

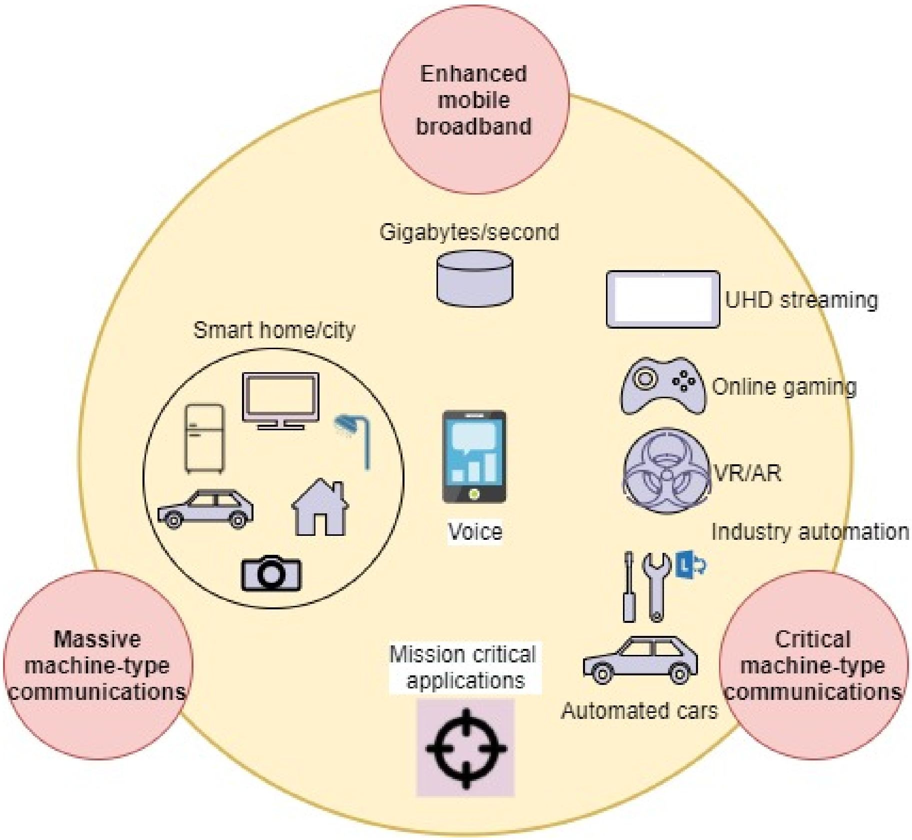


***Figure* 2.2** *5G applications [32], [33]*

cases, and helping to use them autonomously or remotely. The remote control possibility also helps with the smart agriculture, where there is no need of human presence for the machines in the field to work.

- *Critical machine-type communication*: This includes critical applications, such as health-related ones, aiming to eliminate the factor of distance in medical procedures. Examples include tactile Internet [35] and telemedicine [36]. Also smart society applications containing automotive and smart vehicles e.g. planting sensors in the vehicles, roads and all other transport infrastructures, in order to provide traffic control and safety in an automated manner. Another example is smart manufacturing, which aims to provide remote control over machines in a factory with ultra-low response latency that enables reliable and cost effective autonomous operations.

Figure 2.2 summarizes 5G use cases and the opportunities they provide.

2.4.2 Requirements

Based on the use cases mentioned in Subsection 2.4.1 and according to [12–14], 5G requirements can be listed as follows:

- Gigabits per second peak data rates. Edge rate, which refers to the worst available data rate in a wireless network, should be improved by 1000x times in 5G in comparison with 4G solutions [13].
- Ultra-low round trip latency (around 1 ms) and ultra-high reliability [12].
- The ability of control signaling to maintain connectivity of thousands of IoT devices [12].
- Low power consumption and higher battery life for both environmental and economical reasons.
- Low cost end-user equipment. This makes producing millions of IoT devices profitable for companies.

2.4.3 Current state of development

In order to meet 5G requirements, the use of new technologies together with modifying the existing ones are suggested. The following paragraphs are explaining the necessary steps that should be taken towards 5G developments [37].

In order to satisfy the high throughput and low latency requirements of 5G, the use of mmWave band, which refers to the wireless technologies operating in super high frequency (SHF) correspond to 3-30GHz and extremely high frequency (EHF) correspond to 30-300GHz [38] ranges, has been proposed [18]. When the communication systems operate in mmWave band, they will benefit from its wider bandwidth that will lead to a total network capacity improvement. However, the fundamental differences between mmWave and microwave bands along with the limits of mmWave band propagation, such as high pathloss, attenuation caused by macro object blockages, and weather conditions [39] introduces the need for deep research on the benefits of mmWave band usage. Works [40] and [41] provide examples of the researches that have been conducted in this area. Moreover, in [42] and [43] some solutions have been suggested in order to use mmWave band more efficiently.

Another required change for development towards 5G, is an improvement in radio access network (RAN) backbone architecture [37]. Thousands of different interconnected cells (micro, macro, pico) are used to provide wide coverage for the increasing number of mobile devices. Massive MIMO, 3D beamforming, movement from BS-centric network to device-centric network topology [12], increase in use of small cells over big single cell, are only the small changes that are needed in the current architecture to make it sufficient for 5G requirements.

In order to achieve better spectral efficiency, advanced modulation techniques are required. In 4G, Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA) are used as modulation and medium access methods [37]. According to 5GNOW[14], there are four other candidates for 5G PHY modulation schemes:

- Generalized Frequency Division Multiplexing (GFDM) [44]. It is a flexible scheme and reduces the complexity on both transmitter and receiver sides.
- Universal-Filtered Multi-Carrier (UFMC) [45]. This scheme is designed to solve the issue related to loss of orthogonality at the receiver side.
- Filter Bank Multi-Carrier (FBMC) [46]. This scheme uses a preamble burst approach to guarantee a flexible resource allocation in both time and frequency domains.
- Bi-orthogonal Frequency-Division Multiplexing (BFDM) [47]. This scheme uses bi-orthogonality, instead of orthogonality in OFDM, which is a more relax version of orthogonality and does not need the transmitted and received pulses to be individual.

The next generation of mobile networks are all-IP, which means all data and control bits are carried through IP-based communications from network protocol layer up to application layer in Open Systems Interconnection (OSI) protocol stack model [48], while different access technologies are applied in lower layers [49]. That means 5G network is an all-IP network that promised to provide higher data rate with lower latency. Fulfilling these promises requires a change in the protocol stack from network protocol to transport protocol.

Since TCP is the most used transport layer protocol in the Internet, usage of modified TCP might be necessary in the protocol stack in order to meet the expectation of 5G. A lot of solutions were proposed throughout time for changing TCP to meet the requirements of modern networking [50–61]. For example a suggestion for an advanced TCP protocol has been made in [62]. Proposed protocol objectives are providing extremely-high data rates along with efficient congestion control for the backhaul traffic.

[14] http://www.5gnow.eu/wp-content/uploads/2015/04/5GNOW_D3.2_v1.3.pdf

On the other hand, 5G also needs modifications in RAN, which are especially important for boosting performance of inter-cell mobility and overall energy and computation efficiency of the network. For example, the architecture called cloud based RAN-as-a-Service (RANaaS) [63] has been proposed by the iJOIN project [64, 65] in order to move computing responsibility from cell side to a cloud platform. This is expected to help with the network sustainability, energy, and network resource usage efficiency. A review of this technology and other similar backhaul technologies are presented in [66].

3. MMWAVE-ENABLED AERIAL MOBILE ACCESS POINTS IN URBAN-GRID

There are two different scenarios of directional mobile objects communication, which are considered in the scope of this thesis. This chapter will concentrate on directional mmWave access link between pedestrian mobile users and mmWave APs. This scenario uses both static infrastructure APs and UAV driven APs. The research presented in this chapter has been published as the conference paper [67].

To overcome the mmWave limitations mentioned in Subsection 2.4.3, the small cell densification technique [22] is combined with deployment of mmWave AP-equipped UAVs, which could serve as additional network access providers. Because the use of mmWave band in mobile communication is a new subject, and the equipment related to it are fairly expensive and not easily accessible, for the evaluation of this part NS-3 simulator [68] has been used. In what follows, we first describe the capabilities of the used simulator, and then present deployments and assumptions for different setups. At the end of the chapter, the results are shown and discussed.

3.1 Simulator description

NS-3 is an open source discrete-event simulation platform, that has been created and maintained by a vast number of developers around the world. The discrete-event property helps with modeling the system operation as a discrete sequence of events in time, which means that the overall system state changes in respect to the event execution order and is not connected to the particular minimum time step. This allows to skip the “empty” time periods, and improve the computation efficiency of the program.

The core objective of the NS-3 is to simulate complex scenarios and provide the researchers with diverse statistics related to the performance of the system in per-packet basis. There are many modules developed in NS-3, each of them can be used for specific network standard and protocol. The simulator is developed in Python[1]

[1] `https://www.python.org/`

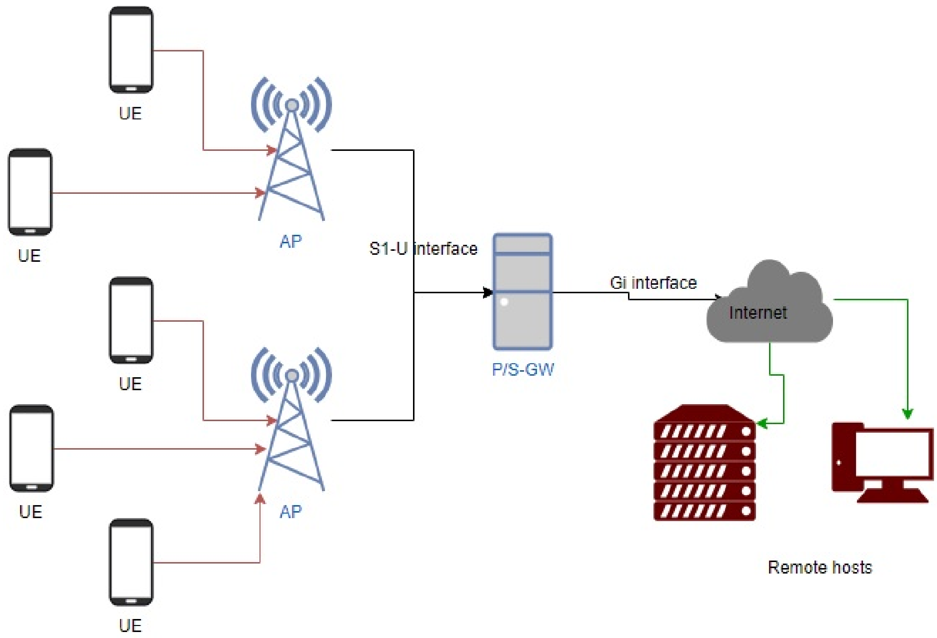


Figure 3.1 *Overall architecture of the mmWave simulation model in NS-3 [69].*

and C++[2]. In this thesis, the following modules are used:

- The mmWave module developed by New York University (NYU) [70]. This module has utilized the mmWave protocol stack physical (PHY) layer and medium access control (MAC) layer and also custom mmWave channel model, while LTE module [71] is used for simulating the upper layers.
- LTE module, which offers a realistic model of LTE radio access and core network. It is developed by the research community.
- The building module [72] for modeling macro objects with different wall materials and size.
- The NS-3 core simulator module for modeling TCP/IP connectivity, and discrete-event simulation functionalities.

Combining all above, it is possible to simulate complex scenarios with mobile users and mmWave access network in an environment featuring macro objects such as streets, buildings, trees and other obstacles.

The simulations related to this section were executed in NS-3 version 3.27, which gives the opportunity to use 3GPP[3] mmWave channel model introduced in [73].

[2] `http://www.cplusplus.com/`
[3] `http://www.3gpp.org/`

The PHY layer structure and frame structure parameters are introduced in [74] and a Time Division Multiple Access (TDMA) with Round-Robin resource distribution procedure is used for MAC layer scheduler [75]. Figure 3.1 shows the overall architecture of the mmWave EPC simulation model in NS-3.

3.2 Simulation methodology

In this section, we investigate the performance of small cell densification technique combined with UAV-assisted AP usage. To do so, three different simulation setups are considered, all featuring similar layout with static ground APs deployment, but varying in user distribution and mobility model. In the following subsections, general and specific assumptions for each setup are described.

3.2.1 Common parameters

The simulation layout (visible in Figures 3.2, 3.3, and 3.4) follows Manhattan grid deployment of a size 165m x 165m (two building blocks) with 15 meters street width and 75m x 75m x 12m concrete buildings [76]. As it can be observed, there are four mmWave APs mounted in the middle of the streets on 3 meters height lampposts, representing the example of ultra-dense cell deployment. All simulation results given in this chapter are developed based on the mmWave-EPC model, which follows the LTE-EPC model architecture and is shown in Figure 3.1. All UEs have the ability for hard handover, meaning they should disconnect fully from the current AP in order to connect to the next one. While the initial cell selection strategy is based on minimum distance, the handover occurs if the difference in SINR from serving cell and target cell exceeds 3dB in the favor of target cell. All users are assumed to be located in the streets (outdoor deployment) and for calculating the penetration loss in buildings, the appropriate 3GPP pathloss model has been used [73]. The parameters, which are mutual to all three scenarios, are displayed in Table 3.1.

3.2.2 Baseline setup

The baseline setup features random waypoint mobility model [77] to simulate users' movement. Initially, users are uniformly distributed around the scenario grid, which means equally distributed load over the considered mmWave APs (on average), thus better response to requests from each user. The objective of this setup is performance evaluation of a basic ultra-dense AP deployment in urban environment. Figure 3.2 shows the user distribution and trajectories in this setup.

Table 3.1 *Common parameters for all simulation scenarios*

Parameter	Value
Building blocks	Manhattan grid
Block dimensions	75m, 75m, 12m [76]
Street width	15m [76]
Number of users	10 per street
User speed	5km/h
User height	1.6m
Infrastructure mmWave AP height	3m
Transmission protocol	UDP
Packet interval	1μs
Input data rate	100Gb/s
MTU (Maximum Transmission Unit) size	1500 bytes
P-GW and remote host link delay	10ms
Propagation scenario	UMi-StreetCanyon
Simulation time	85s

3.2.3 Rush hour setup

The second setup is concentrating on busy-hour case with unequally-distributed traffic load. As it can be seen in Figure 3.3, users are initially deployed in clusters and moving as a group. There are two groups of users, each consist of ten UEs, both groups are moving from the end of the streets towards the crossing, located in the deployment center. The movement of both groups is based on group-reference mobility model introduced in [78].

3.2.4 UAV-assisted APs setup

The third setup aims to evaluate the performance of UAV-assisted APs as additional coverage providers in busy hour. To do so, the same deployment as in Subsection 3.2.3 was considered except in this case, two additional UAV-based APs are also present in the scenario grid, each flying on top of one of the groups. Figure 3.4 shows this deployment.

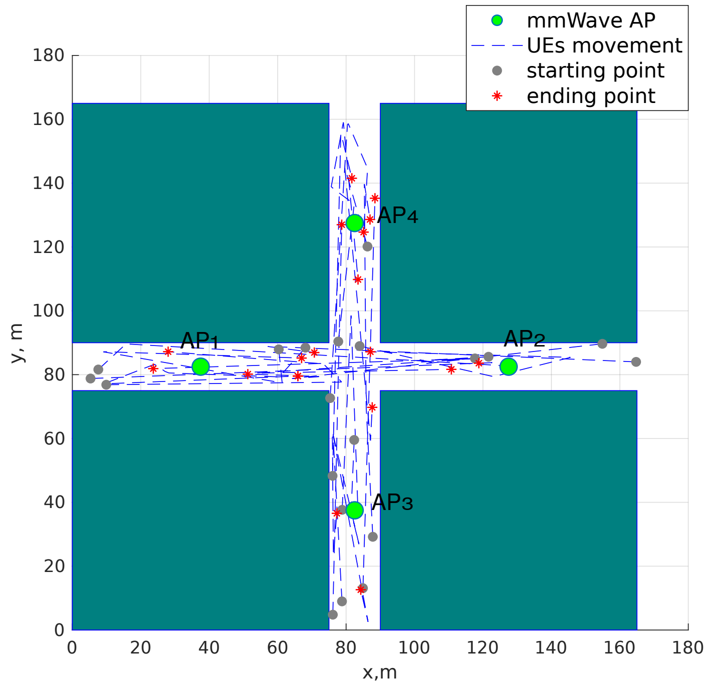


Figure 3.2 *Baseline setup: users and APs distribution.*

3.3 Performance Evaluation

In this section, the details of the performance evaluation approach and statistics collection are explained. Here, the average PDCP layer throughput and SINR are used in all three scenarios as core metrics of interest. NS-3 has the functionality to store traces of received packets by PDCP and RLC layers of each user along with the time and the responsible AP for packet delivery. In the scope of this thesis, we used PDCP layer trace files to compute the average per UE throughput in each scenario. The calculations are done according to the equation 3.1.

$$AverageThroughput = \mathbb{E}(\sum_{i=1}^{Num\_ue} X(rnti = i)), \tag{3.1}$$

where parameter Num_ue indicates the total number of users present in the scenario grid, which in our case is 20, and $X(rnti = i)$ demonstrates the throughput of user i and is calculated using equation 3.2.

$$X(rnti = i) = \frac{(nPacket \cdot sPacket)}{T}. \tag{3.2}$$

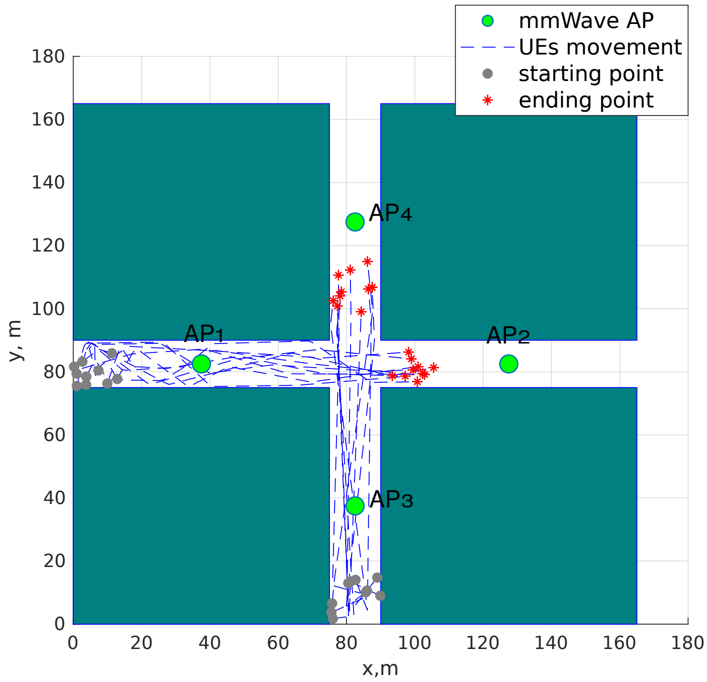


Figure 3.3 *Rush hour setup: users and APs distribution.*

where the $nPacket$ represents the number of packets received by user i over a T seconds time period and $sPacket$ is the size of each received packet. After investigating the results with different time period, T=`0.1` seconds gave more realistic and reliable results so we chose it as the final time period used in equation 3.2. This means the throughput was recalculated every `0.1` second using the mentioned equation.

In addition, the NS-3 simulator captures and records the SINR between each user and all APs in the scenario. This statistics are further used to extract the SINR data between each user and its serving AP.

3.3.1 PDCP layer throughput

The average throughput for all three setups have been calculated and plotted in MATLAB software[4]. Figure 3.5 shows average PDCP layer throughput for all three scenarios. In the following, the detailed explanation of each plot is presented.

Figure 3.5(a) shows the average throughput for the first scenario. As it can be observed, this setup has a better performance than the other two. It is because, as we expect it, the distribution of users around the scenario grid combined with the

[4] `https://se.mathworks.com/products/matlab.html`

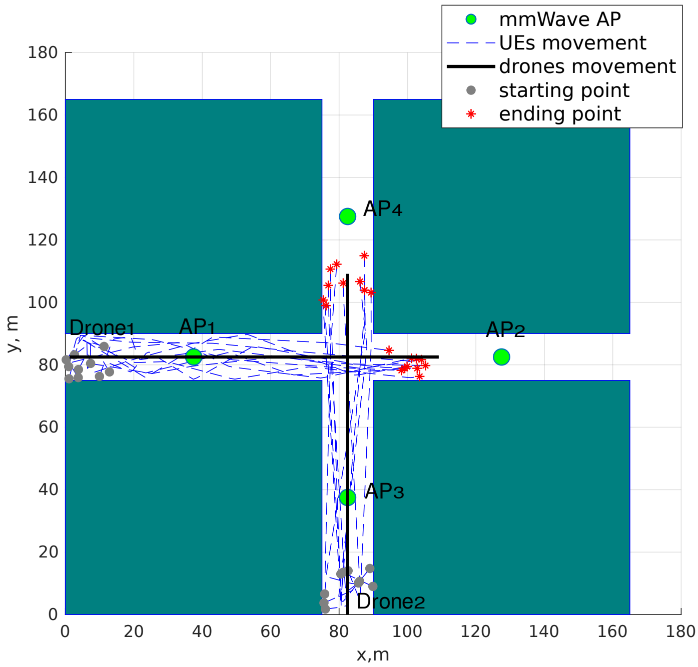
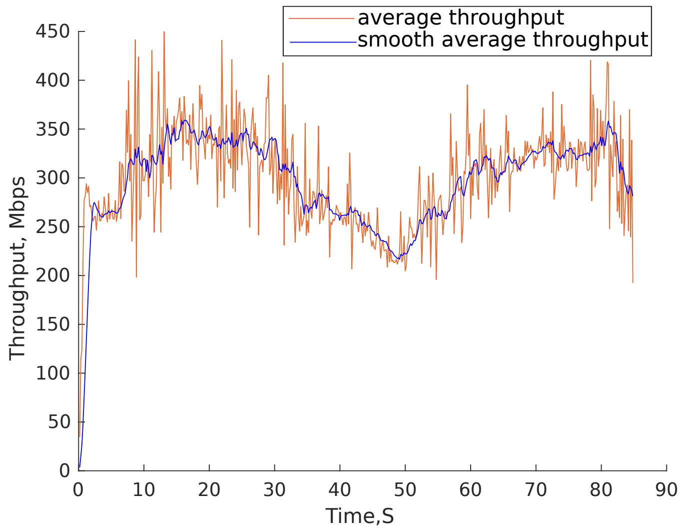


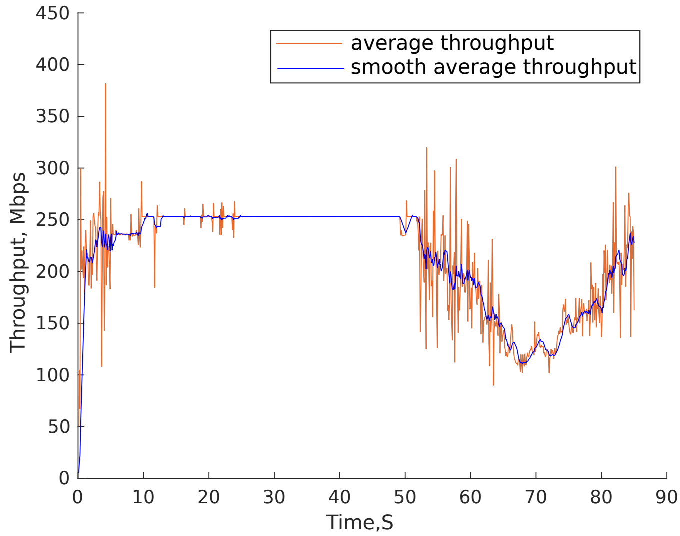
Figure 3.4 *UAV-assisted APs setup: users and APs distribution.*

dense cell deployment in the area leads to an equal load balance on APs, which will cause the better and faster response to each user requests and thus, fair bandwidth distribution and better per UE throughput. The fluctuations seen in all parts of the plot are caused by the handover of users between APs due to their random initial positions and taken route. It is obvious that the plot does not show any major drop, which supports the theory that small cell densification technique may compensate for mmWave band propagation limitations in the urban environment. The coverage probability of 100% is an approve on that as well. The coverage probability is calculated based on the observation of user connectivity and service time.

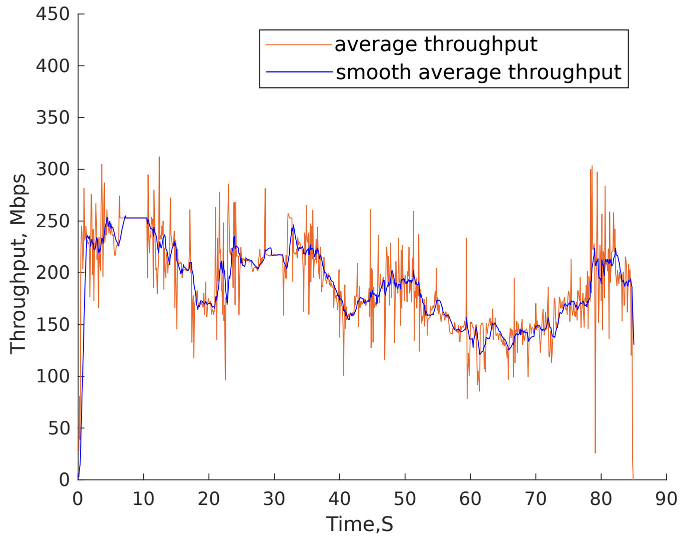
Figure 3.5(b) shows the average throughput for the second setup. The results in this plot show a constant behavior up to the middle of simulation time and after that a significant throughput drop, which happens over time followed by the performance improvement towards the end. The fluctuations at the beginning are caused by initial connection procedures performed by all UEs at the same time. After that, because two groups do not interfere with each other, the average throughput remains constant until the two groups reach the crossroad area of the scenario grid at around 50 seconds after the starting point. Here, the throughput starts to fluctuate and drops down by one hundred Mbps because of the increasing interference level and signal drop along with the handover to the next closest AP. The detailed cell re-selection statistics are shown in Figure 3.6(a). As users are continuing to move



(a) Basic setup: average PDCP throughput

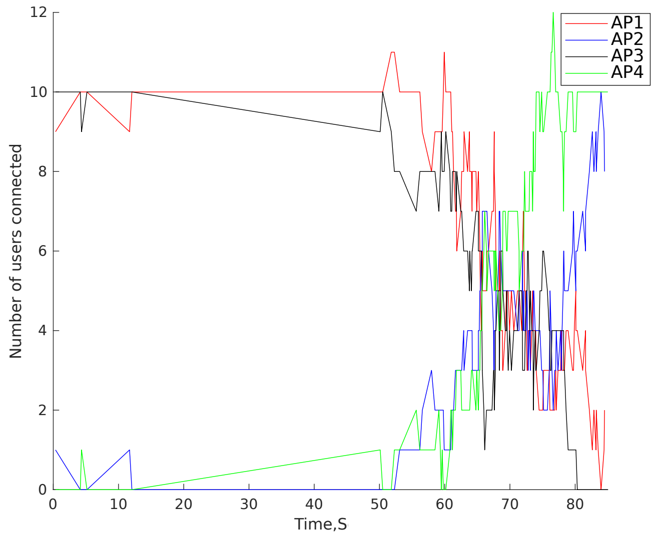


(b) Rush hour setup: average PDCP throughput

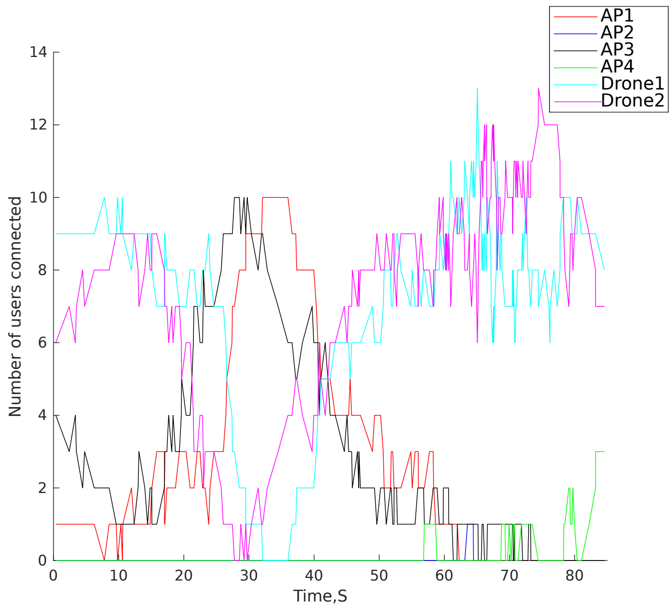


(c) UAV-assisted APs setup: average PDCP throughput

Figure 3.5 *All three setups average PDCP throughput.*



(a) Rush hour setup: handover statistics



(b) UAV-assisted APs setup: handover statistics

Figure 3.6 *Cell re-selection statistics.*

forward and pass the intersection area, the throughput is rising back to the steady state. Except for the intersection area, there is no major drop in performance, which shows the efficiency of small cell densification in urban deployments during busy hour. Using the same idea of calculating coverage probability as the first setup, the coverage probability for the second scenario is equal to 60%.

Figure 3.5(c) shows the average throughput for the third setup. Here, continuous

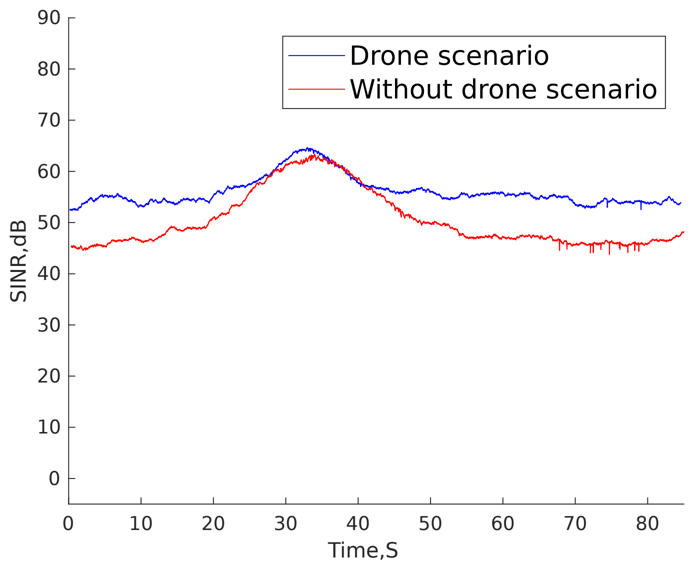


Figure 3.7 *Average SINR for rush hour and UAV-assisted APs scenarios.*

fluctuations are caused by the large number of handovers done by the users between the UAV-based and infrastructure APs, this is called ping-pong effect. The reason behind this ping-pong effect is that at any given time each user is close enough to at least two APs (the UAV on top of it and the infrastructure in its way) to be offered a strong signal. This will cause a constant change of serving AP by the user over a slightly better signal level. Although the presence of UAVs improves the throughput in the intersection area, the negative affect of large number of handovers is not negligible and should be taken into account by introducing additional modifications to the system architecture. Figure 3.6(b) shows the handover statistics for the third setup. As it can be seen, the fluctuations relate to the handover in this plot confirms their effect on throughput degradation. Regardless of the handover margin, it can be observed that utilizing the UAV-based cells in some conditions can cause a degradation in per UE and overall system throughput. Although the coverage probability for this setup is the same as for the second one (60%), no significant drop in the throughput and performance improvement in the intersection area confirms possible benefits of the UAV-assisted mmWave APs in busy hour for urban deployments.

3.3.2 SINR

The SINR statistics is calculated only for the second and third setups. SINR is collected on per user basis, after that the average value was calculated for all users in both setups (Figure 3.7). As it was expected, the overall average SINR in the third setup is higher than in the second one, due to the coverage boost provided by the UAV-based cells. By using the extra coverage provided by the UAV APs, the radio access network architecture can be improved. Assuming the possibility to overcome above-mentioned ping-pong effect, the use of this UAV-assisted APs is a promising solution in the future 5G network.

4. UNMANNED-SURFACE-VESSEL OFF-SHORE COMMUNICATIONS

In this chapter, the second scenario related to the Autonomous and Collaborative Offshore Robotics (aCOLOR) project is described. Here, we concentrate on point-to-point directional backhaul Wi-Fi link between GC and an autonomous boat with mechanically steered directional antennas.

4.1 Project description

The main objective of aCOLOR project is to create collaborative methods for an autonomous robot system with the ability of operating in offshore environment and connecting all three elements (aerial, on the water, and underwater). To do so, an UAV, USV, and Autonomous-Underwater-Vehicle (AUV) have been chosen as connectivity providers between three different environments. From telecommunications point of view, the final goal of this project is to enable the high-speed connection of the vehicles with each other in different conditions and make their operation possible without human presence. Figure 4.1 shows the overall communication setups.

This thesis is only concentrated of aCOLOR's project first phase, consisting of communication between GC and USV. This communication system is consists of the following tasks:

- Deploy communication between GC and USV using 802.11ac (5GHz central frequency) directional antennas.
- Develop and test mechanical beamsteering algorithm for both antennas using GPS on the USV.
- Test LTE as an alternative communication technology between GC and USV, which is used in case of Wi-Fi outage.

The steps towards achieving these goals are to sketch the preliminary system layout and mechanical concept, finalizing the design and choosing the appropriate equipment. The following parts of this chapter focus on these three tasks.

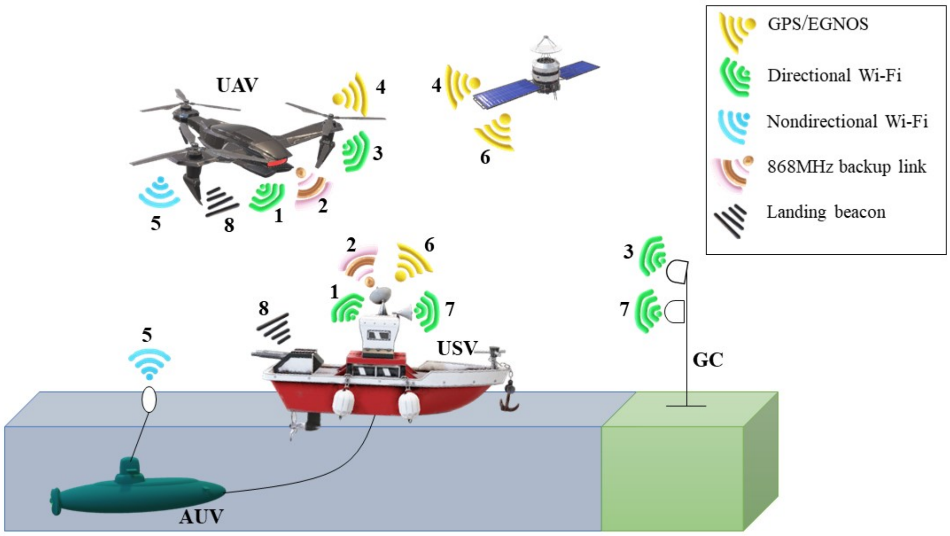
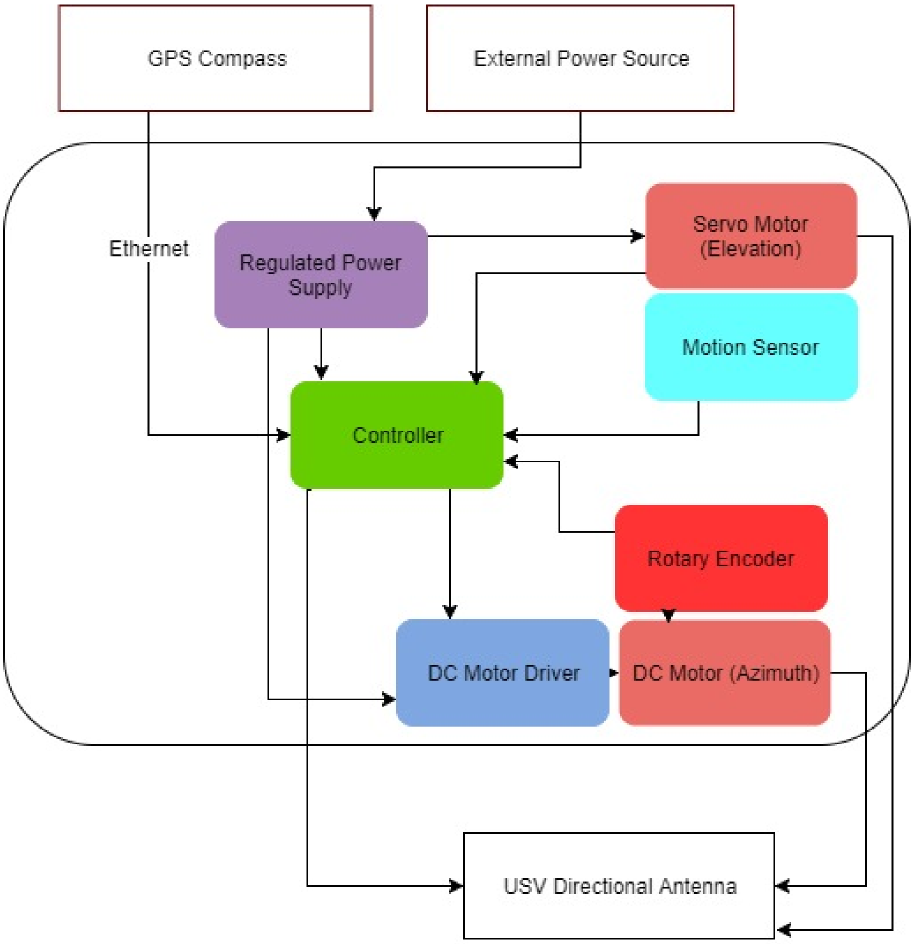


Figure 4.1 *Overall communication schematics of the aColor project. The communication links are as follows: 1. Directional Wi-Fi link between USV and UAV, 2. Backup link between USV and UAV, 3. Directional Wi-Fi link between GC and UAV, 4. GPS link between satellite and UAV, 5. Non-directional Wi-Fi between UAV and AUV, 6. GPS link between satellite and USV, 7. Directional Wi-Fi between GC and USV, 8. Directional link used for landing system between UAV and USV.*

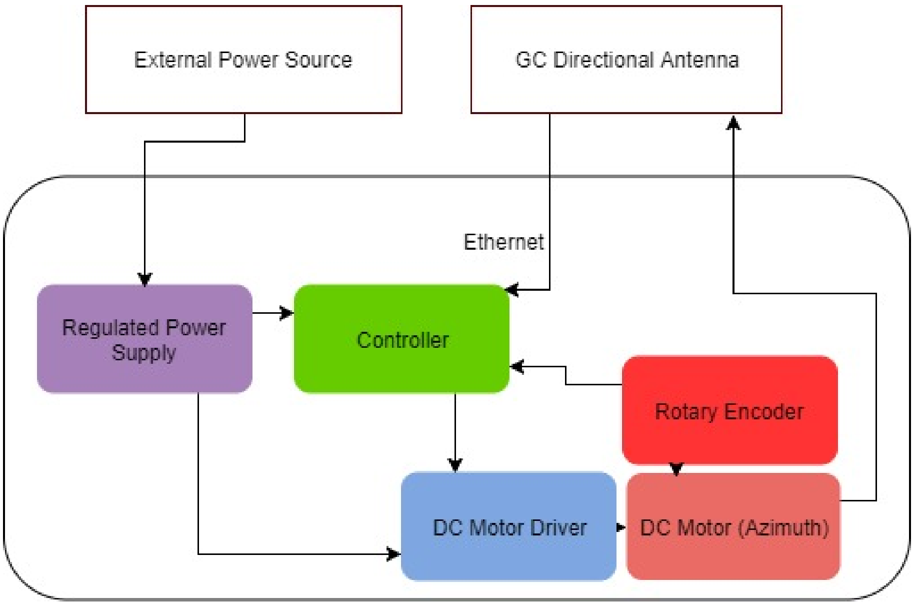
4.2 Conceptual system design

4.2.1 System layout

The communication system between GC and USV with beamsteering capability, consists of an external power source, a controller, motor driver, DC motor and rotary encoder for both GC station and USV. To achieve horizontal beamsteering, the position signals are sent from GPS compass placed in USV to the USV-located controller via Ethernet. The controller is connected to a DC motor, which uses a rotary encoder with a closed-loop feedback to enable precise-position steering. The DC motor receives the control signals from the controller and horizontally steers the directional antenna. It is assumed that the location for GC antenna is known, so controller could rotate the USV antenna towards the GC station by receiving its own GPS coordinates via GPS compass. In continuation, the same GPS coordinates will be send via Wi-Fi link to the GC antenna, which then will be delivered to the controller board placed in GC side via Ethernet. The GC controller governs a DC motor with the same functionalities as the one in the USV, thus it will produce a control signal, which will steer the GC antenna towards USV. In the current



(a) Conceptual layout of the system in USV side



(b) Conceptual layout of the system in GC side

Figure 4.2 *Conceptual system layout for both GC and USV.*

implementation, a vertical steering mechanism is installed only on the USV side, since the vessel might face waves. For this procedure, a 6-axis sensor could be used on USV to define the vertical tilt of the USV in comparison with the ground level. The controller then uses the data received from the sensor to produce a signal, which controls servo motor used for vertical rotation of the antenna. Both sides of the system are powered by external 12V power sources but since each device requires a different input power, a regulated power supply has been installed in both sides.

The overviews of the layouts for USV and GC are shown in Figure 4.2(a) and Figure 4.2(b), respectively.

4.2.2 Mechanical concept

The mechanical design has been created in collaboration with the Mechanical Engineering and Industrial Systems Laboratory (MEI) of Tampere University of Technology. Both GC and USV sides have the same mechanical concept except for the vertical steering that is only present in the USV part. The system consists of the upper housing and the lower housing parts having circular shapes. The lower housing is fixed to the mounting device (tripod for GC and mast for USV) and the upper housing is attached to the lower one by a rotating vertical shaft. The rotation over the vertical axis is done by using a gear mechanism, which contains a DC motor for the rotation of the small gear. The antenna is attached to the upper housing using two aluminum brackets. The servo motor for vertical rotation of the USV antenna is attached to the mounting bracket. Figure 4.3 shows the general mechanical concept for both GC and USV. The GC design lacks the rotation over the horizontal axis, the rest of the design is similar for both parts of the system.

4.3 Final design

The final design of the system consists of electrical and mechanical parts. As it was mentioned before, the design and execution of the mechanical part has been done in collaboration with MEI Laboratory in Tampere University of Technology, while the electrical part was designed by the Electronics and Communications Engineering research group. In this section, the details of chosen equipment for both parts are discussed.

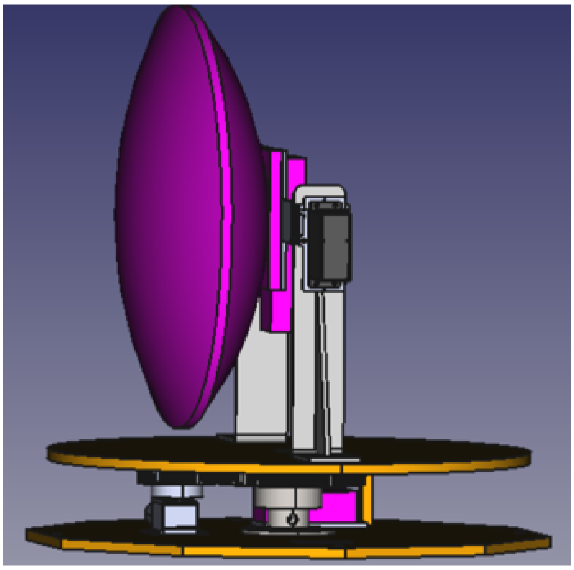


Figure 4.3 *Overall mechanical design for both GC and USV.*

4.3.1 Mechanical components

For the DC motor used in horizontal rotation, CHIHAI GM4632-370 DC motor[1] was chosen. It is a worm geared type motor and has rotary encoder installed. It has a high torque (rated torque of 10kg.cm) and high rotation speed (30 RPM in no load situation) that makes it perfect for the purpose of horizontal beamsteering in real-time. It requires a voltage of 12V, while current should not exceed 60mA.

For vertical steering of the USV system, the HS-805BB servo has been used[2]. It can rotate between 0 to 199.5 degrees, has an acceptable stall torque and requires a power voltage between 4.8V-6V. Its current drain is between 700mA-830mA for mentioned voltages respectively.

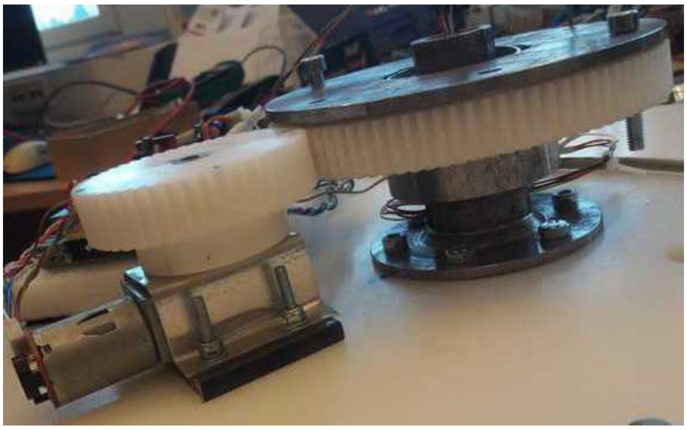
For the mechanical rotation of the upper housing, two gears are used. One installed on the DC motor shaft and the other one installed on the shaft connecting the two housings together, which causes the upper housing to rotate horizontally. Both gears are chosen from Mekanex OY[3]. The small one, which is installed on the motor shaft, has 48 teeth, 75mm diameter (including the teeth). The bigger one is installed on the vertical shaft connecting the two housings together (95 teeth and 145.5mm diameter). Finally, there is a metal bearing under the second gear, which is used to enable the rotation[4]. Figure 4.4(a) shows the final inner mechanical part explained.

[1] https://www.amazon.it/EsportsMJJ-Chihai-Gm4632-370-Encoder-Motoriduttore/dp/B0773JPVFP

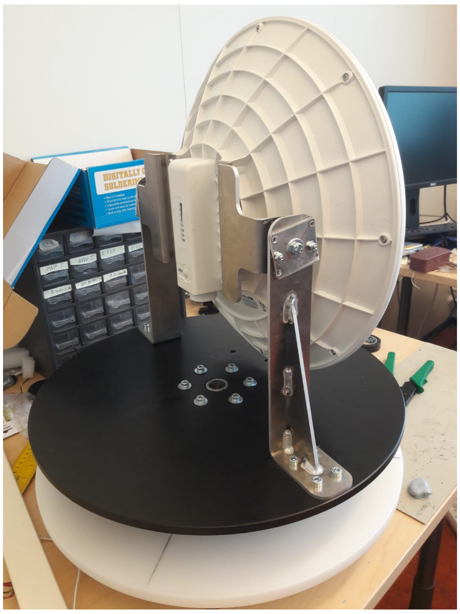
[2] https://www.servocity.com/hs-805bb-servo

[3] https://www.mekanex.se/wp-content/uploads/lieriohammaspyorot-cyl-kugghjul.pdf

[4] https://www.ikh.fi/fi/urakuulalaakeri-30x55x13-16006-2rsk



(a) Detailed placement of the inner mechanical components such as DC motor and gears between two housings



(b) Final state of system's mechanical part consists of two housings and directional antenna

Figure 4.4 *The final mechanical design of the system.*

The upper and lower housings of the mechanical design are made of plastic in a circular shape. The antenna is connected to the upper housing using two metal mounts. The final mechanical design of the system is shown in Figure 4.4(b). The same design has been used for both sides (GC and USV); hence, here we show only one of them.

4.3.2 Networking components

Directional antenna

For the purpose of this project, two Mikrotik DynaDish 5 directional antennas have been chosen[5], one for the USV side and one for the GC. Mikrotik DynaDish 5 offers a reliable point-to-point link in outdoor environment. It is compatible with IEEE 802.11a/n/ac standards and works with Power over Ethernet (PoE) to provide power connection, which will allow to reduce the number of cables in the system.

Router

There are two routers used to interconnect all system components. One should be placed in the USV side and the other one in the GC. Since some equipment (like the directional antennas) can be powered by PoE, the best option is to use routers that provide this ability in their ports. For this project, we chose Mikrotik hEX PoE router[6] with five Gigabit Ethernet ports. The device has a reasonable price for its functionalities, features the compact design and at the same time has a powerful CPU of 800MHz.

LTE router

As it was mentioned before, to guarantee a reliable connection at all times between the USV and the GC, we used LTE as one of the options to support desired link quality. For that reason, two RUT950 LTE routers[7] were installed on the USV and GC sides. This router has been chosen because of its high performance and reliability.

4.3.3 Electrical components

Controller

On both GC and USV sides, we installed Beaglebone green single-board computers[8] to run the algorithms responsible for antenna rotation. Full technical specification

[5] `https://mikrotik.com/product/RBDynaDishG-5HacDr3`
[6] `https://mikrotik.com/product/RB960PGS`
[7] `https://teltonika.lt/product/rut950/`
[8] `https://beagleboard.org/green`

Table 4.1 Technical specifications of the Beaglebone green single-board computer

Item	Value
Processor	AM335x 1GHz ARMR Cortex-A8
RAM	512MB DDR3
On-board Flash Storage	4GB eMMC
CPU Supports	NEON floating-point and 3D graphics accelerator
Micro USB Supports	Powering and communications
USB	Host 1
Grove Connectors	2 (One I2C and One UART)
GPIO	2 x 46 pin headers
Ethernet	1
Operating Temperature	0 - 75 degree Celsius

of Beaglebone green is shown in Table 4.1[9]. The operating system installed on the Beaglebone is Debian Linux[10] released on 05-03-2018 for both Beaglebone green and black models. All other components in mechanical rotation subsystem are controlled by the Beaglebone green using its General Purpose Input/Output (GPIO) pins.

Motor driver

The system is actuated by one DC motor with inner rotary encoder. A motor driver is needed to run this DC motor in the desired speed. The driver chosen for this project is POLOLU-713[11]. This is a dual motor driver, we use one of its two channels for each system[12]. Each channel has two logical inputs and two outputs, which should be connect to Beaglebone green's GPIO pins and motor inputs respectively. It also has a Pulse-Width Modulation (PWM) pin for speed control on each channel, which will be also connected to the Beaglebone PWM pin.

Sensors

In order to actuate the system axis, it is essential to mark the initial position (so-called zero direction) of the system. An easy way for doing this is to use a magnetic

[9] http://wiki.seeedstudio.com/BeagleBone_Green/
[10] Debianhttps://www.debian.org/
[11] https://www.tme.eu/gb/details/pololu-713/motor-control-modules/pololu/
[12] https://www.tme.eu/gb/Document/bb02bd1991e001f7c1ea7dd080a938af/POLOLU-713.pdf

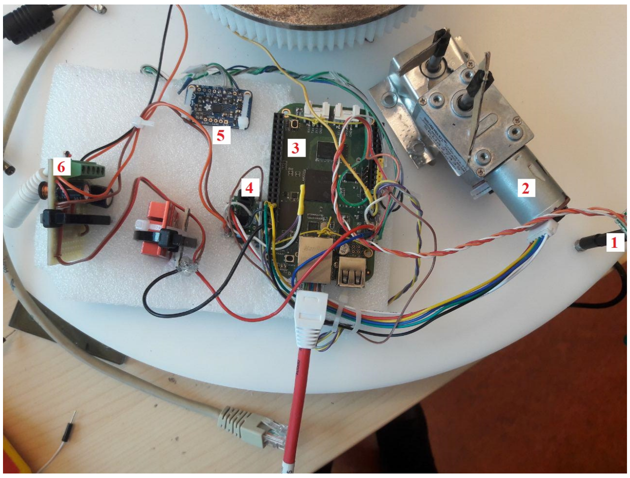


Figure 4.5 *The electrical design of the system. 1:magnetic sensor, 2:DC motor, 3:Beaglebone green, 4:motor driver, 5:LSM9DS0 sensor, 6:voltage regulator.*

sensor. Whenever the system turns on, the rotating calibration sequence is triggered until it reaches a predetermined endpoint, which in our case is the falling edge of a magnet. In this case, the system will assume this point as the zero point and then starts rotating based on the received GPS signals from USV. The sensor is placed on the lower housing of the design but very close to the upper housing. They are two small magnets connected to the bottom of the upper housing. This way when the upper part is rotating the sensor is waiting to detect the magnets and will stop on the falling edge.

The second sensor is Adafruit LSM9DS0[13], which has 3D accelerometer, gyroscope, and magnetometer with indoor navigation use case. In our project, we use this sensor to detect any tilting happened to USV caused by the waves in the lake. The data from this sensor will be used by Beaglebone green to calculate the exact tilt angle of the USV. Then this value will be used in servo controller to tilt the antenna in the vertical axis accordingly. The sensor is placed on the lower housing along with all other electrical components.

Power

To determine the required power supply for the whole system, it is necessary to know the required power for its components. Table 4.2 summarizes all the components used for designing this system, featuring their model, quantity, power consumption and supply voltage.

[13] https://www.adafruit.com/product/2021

Table 4.2 *List of the components used in the system*

Category	Item	Model	Number	Power consumption [mA]	Supply voltage [V]
Mechanical components	DC motor	CHIHAI GM4632-370	2	60	12
	Servo motor	HS-805BB	1	700-830	4.8-6
	Rotary gears	Mekanex OY	2	-	-
	Housing	Build by MEI	2	-	-
Networking components	Directional antenna	Mikrotik DynaDish 5	2	150-820	11-60
	Router	Mikrotik hEX PoE	2	5*1000	12-57
	LTE router	Teltonika RUT950	2	234-778	9-30
Electrical components	Controller	Beaglebone green	2	500	5
	Motor driver	POLOLU-713	2	1000	2.7-5.5
	Sensor	Adafruit LSM9DS0	1	6.45	2.4-3.6
	Magnetic sensor	SS460P HONEY-WELL	1	3.5	3-24

The voltage needed for the sensors and the driver is coming from the Beaglebone green VDD pins, so the only components that should be connected to an external power are the controller, DC and servo motors. To power them we used an external power source with 12V voltage. Finally, we also installed a power supply voltage regulator to regulate the voltage according to each component's needs. The final electrical design of the system is shown in Figure 4.5.

4.4 Beamsteering Algorithm

As it was mentioned before, a GPS-based beamsteering algorithm was developed, in order for both directional antennas (GC and USV) to point towards each other continuously. The program for this algorithm was written in Python language. The program consists of two main parts, the part related to calculation of angular rotation based on GPS data received from USV, and the part related to physical rotation of antenna using encoder data and DC motor. The algorithm related to angle calculation is shown in Program 4.1[14].

```
while True:
      if heading!=0:
          delta_lon = lon[1] - lon[0]
          #lon[0] is the longitude of USV udated by
          #the compass, lon[1] is the longitude of GC
          #lat[0] is the latitude of USV udated by the compass,
          #lat[1] is the latitude of GC
          angle = degrees(atan2(sin(radians(delta_lon)) *
                          cos(radians(lat[1])),
                          cos(radians(lat[0])) *
                          sin(radians(lat[1])) -
                          sin(radians(lat[0])) *
                          cos(radians(lat[1])) *
                          cos(radians(delta_lon))))
          #heading data refers to heading of the USV
          heading_diff = heading - current_heading
          angle_diff = angle - motor.current_angle - heading_diff
          angle_diff = sign(angle_diff)*(abs(angle_diff)%360)
          if abs(angle_diff)>180:
              angle_diff = -sign(angle_diff)*(360-abs(angle_diff))
          if abs(angle_diff)>1:
              current_heading = heading
              motor.turn_by_angle(angle_diff)
              motor.current_angle = angle
          else:
              sleep(0.5)
```

Program 4.1 *The algorithm for rotation angle calculation*

As it can be seen, the core part of the algorithm features a *while* loop, which runs as long as the system is working. First, it calculates the difference between longitude of GC and USV. Then it calculates the angular difference between the point where the USV is placed and GC location. Then it takes into the account the heading

[14] https://www.movable-type.co.uk/scripts/latlong.html?

of the USV, which means that even when USV does not change its geographical position but rather rotates around its center, the antenna should rotate respectively to keep the point-to-point connection with GC. After that, the overall rotation angle considering the rotation of USV and its movements is calculated and sent to a function called *turn_by_angle* at line 23. This function has the responsibility of rotating the DC motor connected to the antenna. The function is mainly using the encoder data to extract motor's current position, by utilizing proportional-integral-derivative (PID) controller logic[15] to modify the speed of the rotation, and stop the rotation when the current position of the motor matches the desired position. Program 4.2 shows the main implementation of this.

```
while True:
        cur_angle = abs(myEncoder.position) * 360 /
encoder_full_rot_ticks
        want_a = pid.update(float(cur_angle))
        duty_cycle = max(70, min(100, abs(want_a)))
        PWM.set_duty_cycle(self.speedPin, duty_cycle)
        if checked_angle==float(cur_angle):
             self.timeout()
             break
        sleep(0.01)
```

Program 4.2 *The main part of the mechanical rotation*

The parameters used in the above algorithm are as follow: *encoder_full_rot_ticks* is the position of the encoder after 360 degrees rotation, PID *update* method uses the formula in Equation 4.1 to calculate the speed in which DC motor should rotate, and the method *timeout* will stop the rotation immediately after being called.

$$u(t) = k_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}. \tag{4.1}$$

where $u(t)$ is the output of the controller at the time t, e_t is the value of the error at the time t, k_p, k_i and k_d are the proportional, integral and derivate gains, which are set using an empirical way with the 1, 0.2, and 0.5 numbers respectively.

4.5 Laukontori test scenario

Once the design of the system was finished, the USV part of the system was installed on the mast of the chosen boat to represent our moving vessel and the GC part was placed on a tripod at Hatanpää harbor located in Tampere, Finland, which has been

[15] http://www.ni.com/white-paper/3782/en/

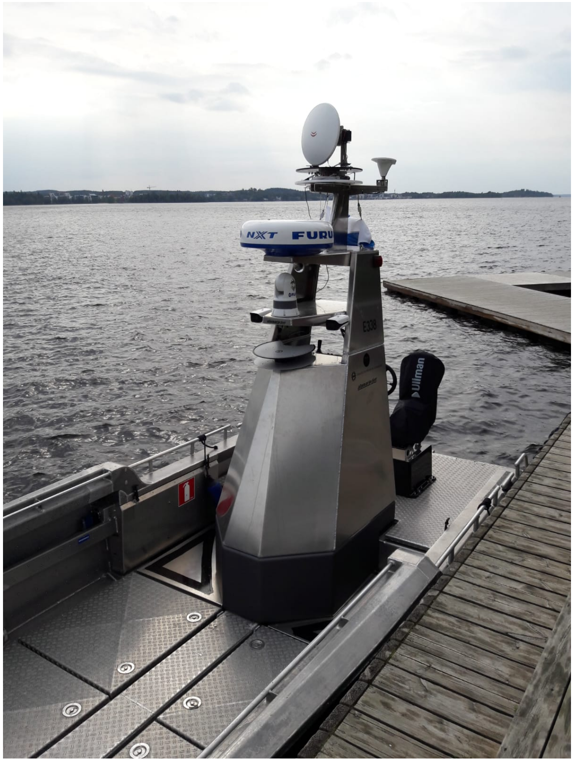


Figure 4.6 *The final state of the USV.*

chosen to be our GC site. Then a predefined route between the ground control and Laukontori in Tampere city center using lake Pyhäjärvi was given to the boat for autonomous traveling.

The final state of the USV is shown in Figure 4.6. For the safety reasons, a dome was installed on top of the USV antenna to keep the system protected from rain and any other moist (not shown in the picture). This picture also shows other components installed on the mast. Besides the directional antenna, there is also an omni-directional Wi-Fi interface and LTE router to maintain the connection between USV and GC at all times. There are also surveillance and thermal cameras installed on the mast used for the other part of the project to enable the unmanned capabilities of the USV. The employed vessel has been assigned to this research project by Alamarin-Jet Oy[16].

The core idea of the scenario was to test how well the designed system works in urban and open lake waters, using directional antennas and proposed antenna steering mechanism. The further results will also show how LTE system works in the similar conditions in terms of RSS and throughput. In the future, the design and implementation of handover mechanism between two communication technologies is planned.

[16] `https://www.alamarinjet.com/`

4.6 Laukontori test results

As it was mentioned before, to collect the throughput and RSS level results for this thesis, a test run with the route from GC to Laukontori and back has been designed. In this section, we discuss the planned route in more details, as well as present and explain the obtained results.

Figure 4.7 shows the route taken for the test run along with the GC position and marks of the steps USV took. The boat starts from The GC[17], moves towards the bridge and then reaches Laukontori harbor area[18], then turns back and takes approximately the same route to come back and at the end stops after the bridge[19] where the connection for USV and GC antennas is in Line Of Sight (LOS). The yellow points are showing the intermediate steps of the boat and its position at the time instants that will be shown in further plots related to throughput and RSS measurements obtained during the test run. The objective of the scenario is to compare the throughput and signal strength level of Wi-Fi connection in case of LOS before the bridge and NLOS (Non-Line Of Sight) after the bridge. Also, we aim to compare these two metrics in Wi-Fi and LTE connections and monitor their changes in LOS and NLOS situations.

Figure 4.8(a) shows and compares the throughput of Wi-Fi and LTE connections. The x-axis shows the equivalent time instants to the yellow points shown in Figure 4.7. As it can be observed, the Wi-Fi throughput is higher than LTE throughput at all times with LOS connection between the boat and GC. However, between the fifth and ninth time instants the LTE throughput becomes higher because in this time period the boat is on the opposite side of the bridge, thus the Wi-Fi connection loses LOS and Wi-Fi throughput at some points reaches zero in the middle of the route. The LTE throughput is following a constant pattern the whole time, which means LOS or NLOS do not have any effect on this connection. This is due to the existence of several LTE BSs, leads to better coverage area for LTE[20]. On the other hand, high level of interference in Wi-Fi connection is caused by more crowded unlicensed spectrum on 5GHz band (such as weather radars in some countries), which leads to degrading of Wi-Fi performance in the urban areas and makes LTE a better alternative option. Regardless of higher bandwidth in Wi-Fi connection, which leads to higher throughput in case of LOS connection (as it is obvious in Figure 4.8(a)), the beamsteering part of our system is not ideal, and depends on the weather conditions and accuracy of the used components. Nevertheless, during

[17] Latitude: 61.493415, Longitude: 23.761406
[18] Latitude: 61.493892, Longitude: 23.762321
[19] Latitude:61.489551, Longitude: 23.756098
[20] `https://elisa.fi/kuuluvuus/`

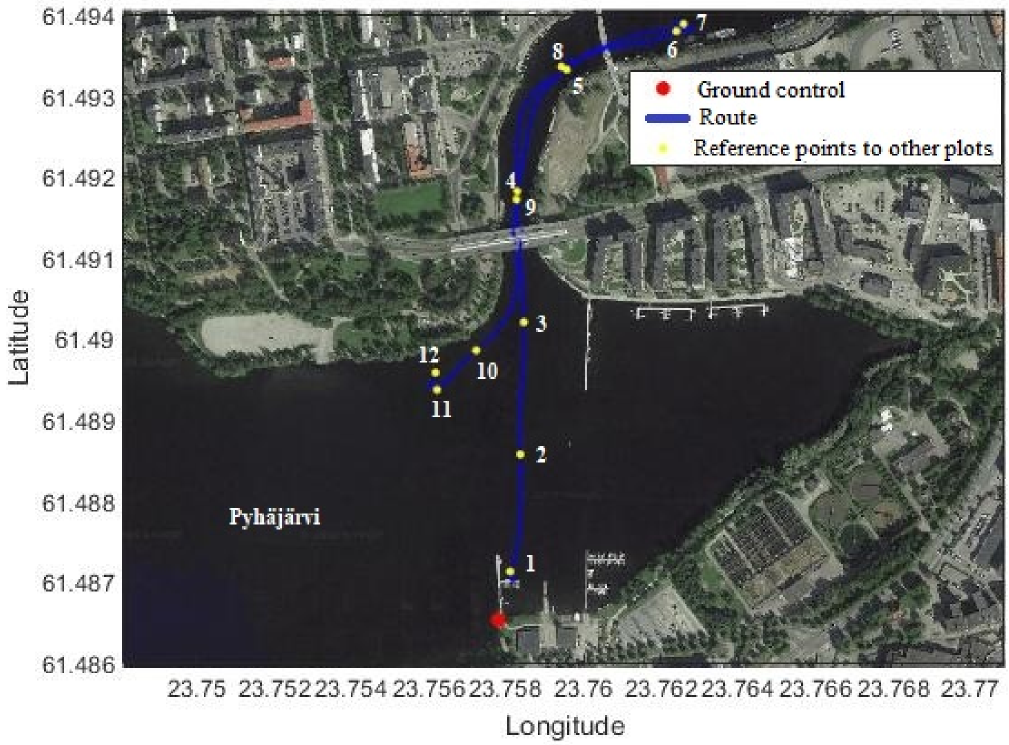
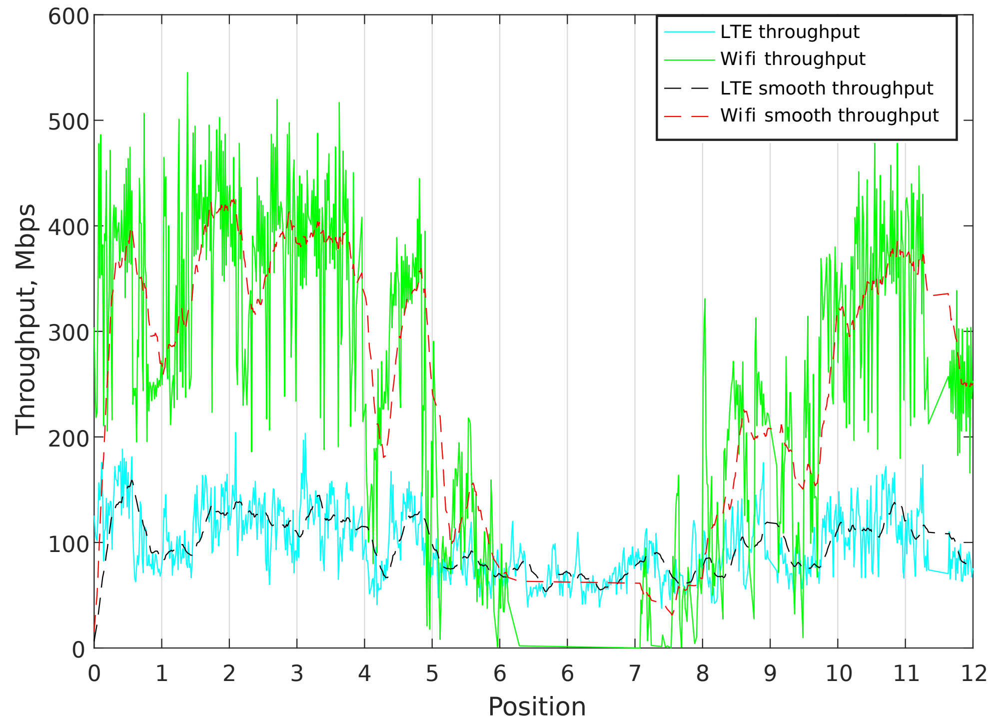


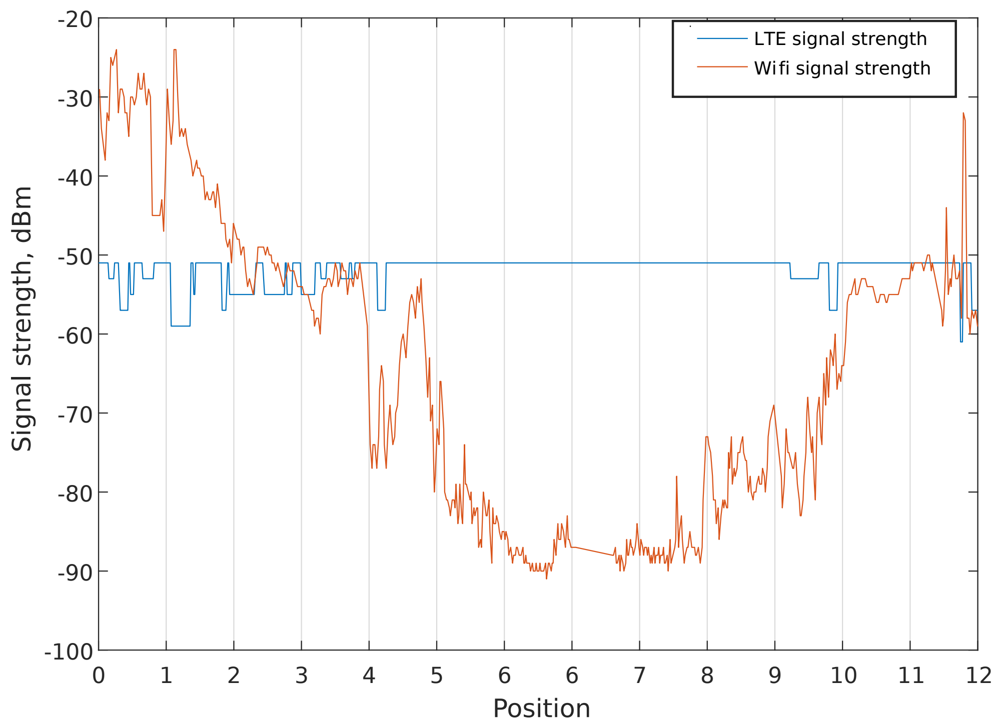
Figure 4.7 *Laukontori test run route.*

the Wi-Fi outage time, LTE will be an appropriate alternative for keeping the connection between the boat and GC alive. Thus, future communication architecture can feature inter-system handover mechanism, in which points five and nine can be used as suitable time moments to perform handover from LTE to Wi-Fi and from Wi-Fi to LTE respectively.

Figure 4.8(b) shows and compares the signal strength level for Wi-Fi and LTE as a function of time for this test run. As it can be seen, the RSS of LTE is nearly constant with small level of variation as compared to the one of Wi-Fi. Clear 30dB drop in signal level between points three and four is caused by the switch between LOS and NLOS states. At the drop moment, the boat is going under the bridge, thus there is no GPS data received at that moment. The strategy in no-GPS situation for our system is to keep the antenna in the last known position before GPS loss until further data arrives. Comparing this figure with Figure 4.8(a), one can easily observe that during the time when Wi-Fi throughput is lower than LTE throughput, the signal strength level of Wi-Fi is also much lower than similar metric in the LTE. Generally, assuming similar bandwidth and modulation and coding schemes, the connection with stronger signal level has better throughput and thus should be used for throughput-demanding applications such as HD video transmission, radar and



(a) Laukontori test run throughput. The time instants shown on the x-axis are equivalent to the yellow reference points on the Laukontori route map



(b) Laukontori test run signal strength level. The time instants shown on the x-axis are equivalent to the yellow reference points on the Laukontori route map

Figure 4.8 *Conducted results from Laukontori test run.*

positioning data. However, the applications that require reliability and low (and stable) latency, such as telemetry (if the USV is controlled by the GC operator), should anyhow utilize LTE, at least in the urban Wi-Fi NLOS environments.

In conclusion, this test run confirms that there is a direct relation between the type of communication (LOS or NLOS) with signal level and thus the performance in terms of throughput for the Wi-Fi link, but the commercial LTE link does not suffer from the outage problems in the test area, which makes it a suitable backup link in case of Wi-Fi outage.

5. CONCLUSIONS

This chapter concludes the thesis, summarizing each of the scenarios evaluated in this work. The chapter is logically divided into two parts, each summarizing the motivation and evaluating the results obtained from one of the lines of work that has been done as well as discussing their future work requirements.

5.1 MmWave APs in urban grid scenario

The number of mobile devices and the associated user traffic demands are increasing exponentially and the current wireless technologies can not support them by introducing minor modifications in their architecture. This trend has caused the need for a new technology and the appropriate studies have been conducted by research community and corporations around the world for several years to finalize the concept of 5G in terms of its use cases and architecture. One of the main use cases of 5G implies enhanced mobile broadband, and for that additional spectral resources are needed. As it was mentioned before, eventually industry proposed to use mmWave band as the main solution towards this problem. Although mmWave band will offer wider spectrum, it has some propagation limitations.

One way to improve performance and overcome the propagation limitations of mmWave band is combining small cell densification technique with mmWave AP-equipped UAVs. This solution, theoretically, ensures LOS for all users at any given time, thus achieveing higher capacity, coverage and average user performance. To test this theory, in this thesis three different scenarios have been evaluated using NS-3 simulator.

The results showed that the usage of dense mmWave deployment may guarantee LOS connection at any given time for all users in urban environments. However, it will not perform well in crowded areas during busy hour in scenarios with high interference and uneven user distribution. The results also proved that although combining this technique with mmWave AP-equipped UAVs can improve the performance in busy hour, it will cause higher interference and ping-pong effect, which will decrease the overall performance level. Hence, this will raise a question of which modifications can be applied to the network architecture and/or appropriate mobility procedures that can decrease the negative impact of ping-pong effect. One possible solution is to introduce a more intelligent dynamic coverage planning scheme, in such a way that mobile APs and static APs do not interfere with each other and introduce a more appropriate handover margin.

Nevertheless, the idea of using mmWave-assisted UAVs as mobile APs in large-scale scenario has some other limitations. It brings out the need for an elaborated regulation of air traffics, which should prevent UAVs from colliding. It also makes it harder to measure and control interference between cells of different operators. There is also a problem with the UAV batteries – currently it is unclear how it is possible to charge them without halting the network [79] and many other limitations that should be addressed when planning the usage of such technology in long-term.

5.2 Off-shore communications scenario

Another important 5G use case is MTC, which has been outlined in Section 2.4. One of the interesting scenarios of MTC is enabling high-speed long-range communications that can be used for autonomous robotics. Since certain applications of the autonomous robotics aim to decrease, and eventually eliminate human interactions on offshore operations, a combined research project between industry and academia has been conducted. This project aims to take the lead on implementing the first prototype of aCOLOR system. This thesis describes part of this research related to communications, with the final goal of implementing such system that can connect all three automotive subsystems: air-based, water surface, and underwater. The corresponding chapter in this thesis describes the communication system enabled between the GC site and the USV moving across the lake.

To make such communication system possible, two modules, each for one end of the communication link, utilizing directional Wi-Fi interfaces have been designed and implemented. Both modules (installed in GC and USV) are featuring mechanical beamsteering to keep high-speed connection over large distances as long as possible. A detailed explanation of how the system is designed and implemented along with the beamsteering algorithm and how the system works is given in Chapter 4. As it was mentioned there, two LTE routers are also on both sides of the system, working as an alternative link between the GC and the USV in case of NLOS for Wi-Fi connection. After finishing the implementation, both systems were planted in their positions and several test runs were completed to evaluate the system's performance in terms of signal strength level and throughput for both Wi-Fi and LTE. The final test run together with results evaluation are discussed in Section 4.8.

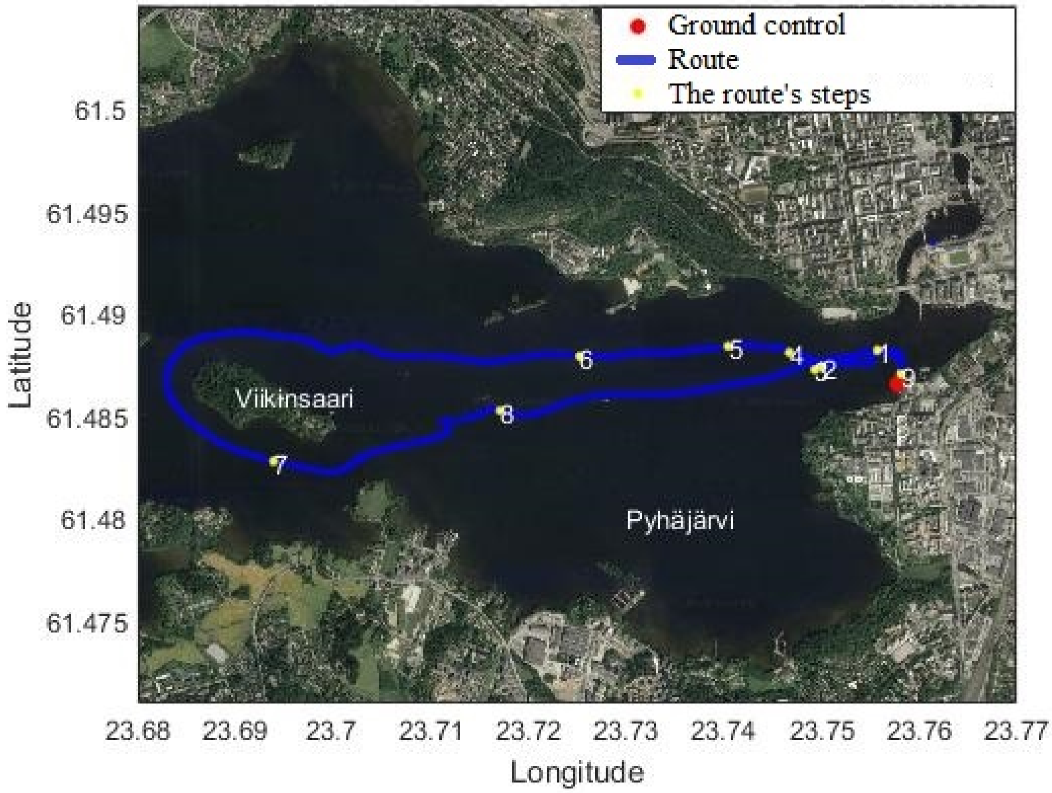


Figure 5.1 *Viikinsaari test run route.*

As the results show, the system performs satisfactorily if certain conditions are met, and as it was mentioned, this is only the beginning of a bigger project during which we suppose to connect all elements to enable autonomous offshore operations. The next step of this work will target measurements of the maximum distance between the GC and USV, in which the connection stays active and what should be done in case of no LOS for neither Wi-Fi nor LTE. To do that, a test will be done where USV starts in the harbor and comes back to the GC station after bypassing an island. The route for this test is shown in Figure 5.1.

The idea here is to find a solution for keeping the connection alive at all times, even in case of NLOS for both radio technologies. One possible solution is to use an aerial vehicle, which will relay the Wi-Fi connection – in order to test this scenario, we will need to equip UAV with two (directional) Wi-Fi interfaces. Because of UAV's ability to fly higher than the obstacles, such as islands or buildings, we can guarantee indirect Wi-Fi connection, limited only by transmission range and weather conditions. Another option for assuring the presence of connection is to have multiple GC sites installed across the lake shore to decrease the probability of losing the LOS. However, this solution requires to implement a handover mechanism between GCs, and also significantly increases the overall system cost.

Nevertheless, the study in this project is ongoing and hopefully it will become an innovation in automating offshore operations eventually. As the next step, we are aiming to design and implement USV-to-air and USV-to-underwater communication interfaces, in order to interconnect all three types of vehicles together and enable the fully autonomous offshore operations.

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