Toby Clifford

Applications of 5G in Offshore Communication

Master's thesis in Communication Technology
Supervisor: Steinar Bjørnstad
June 2023

Master's thesis

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Title: Applications of 5G in Offshore Communication
Student: Clifford, Toby

Problem description:

The IMT-2020 standard specifies improved technical performance requirements for 5G networks when compared to the IMT-Advanced standard for 4G networks [31]. 4G networks have already been deployed on offshore installations to provide coverage for devices on or in the vicinity of the installations. The Internet of Things (IoT) has made it possible for sensors to transmit data over the internet, and such sensors have already been deployed in offshore environments where there is 4G coverage [53].

5G networks offer lower latency, higher capacity, and higher reliability when compared to 4G networks. Improved performance in these areas opens up the possibility to explore new use cases which previously weren't possible when using a 4G network.

The main tasks of this thesis will be to conduct a literature study and an experiment. The literature study will aim to identify new use cases for 5G in an offshore environment, and the experiment will aim to emulate an offshore use case scenario and obtain performance metrics for a best case scenario. The goal is to gather real world data from an onshore commercial 5G network and compare it with the findings from the literature study to determine whether the identified use cases are feasible.

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Main supervisor: Bjørnstad, Steinar, NTNU

Abstract

Non-standalone 5G networks are being rolled out across Norway as a stepping stone in transitioning from standalone LTE to standalone 5G. We explore how 5G can be used in an offshore environment, such as on oil and gas platforms, to enable new use cases with performance requirements that LTE is unable to fulfil. We discuss three classes of use cases for 5G: Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC), and Ultra-Reliable Low Latency Communications (URLLC) and explore how they are enabled by changes in the 5G specifications including millimetre wave transmissions, massive MIMO and beamforming, and a flexible frame structure.

We present a use case which involves AR and VR solutions to improve the maintenance process of offshore platforms. The use case consists of three parts. The first part involves overlaying graphics onto the user's field of view including information about the machine the user is looking at, as well as safety and maintenance manuals. The second part provides a more interactive two-way communications experience with experts onshore. The third part compliments the employee training process with the use of VR models. The use case offers multiple Quality-of-Experience (QoE) levels, each with its own performance requirements.

We perform an experiment to measure the bandwidth and latency of a standalone and a non-standalone 5G network to determine whether current 5G networks can meet the performance requirements of the AR/VR use case. Results show that the downlink throughput requirement was met for a low QoE level, however, the measured uplink throughput was not high enough. There were large variations in downlink throughput between the base stations tested and between the standalone and non-standalone networks. None of the 5G networks tested met the latency requirements for the AR/VR use case. The results showed that the lowest latency was achieved when using a standalone network and a local server located in the 5G core.

Furthermore, we acknowledge that the current frequency allocation for mobile communication networks in Norway limits the full potential of 5G offshore. However, the Norwegian Communications Authority (NKOM) plans to allocate the 26 GHz frequency band to mobile network operators at the end of 2023, as well as allow for local 5G networks with custom frame structures. Both developments can enable higher throughput and lower latency in future 5G networks.

Sammendrag

Det lanseres non-standalone 5G-nettverk i Norge som neste steg i overgangsperioden fra standalone LTE til standalone 5G. Vi analyserer hvordan 5G kan brukes offshore – for eksempel på olje- og gassplattformer, for å tilrettelegge nye brukstilfeller hvor ytelseskravene ikke oppfylles av LTE. Vi drøfter tre applikasjonsområder innen 5G; Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC), og Ultra-Reliable Low Latency Communications (URLLC). Endringer i 5G-spesifikajsonene – som spesifiseringen av bruk av millimetre wave for overføring, massive MIMO og beamforming og en fleksibel rammestruktur, fører til at disse applikasjonsområdene kan bli realisert.

Vi presenterer et brukstilfelle som bruker AR og VR til å forbedre vedlikeholdsprosessen av offshore-plattformer. Brukstilfellet består av tre deler. Den første delen består av et ekstra lag av grafikk over brukerens synsfelt som kan gi brukeren informasjonen om og manualen til en maskin som brukeren har i synsfeltet. Den andre delen innebærer å skape en mer interaktiv opplevelse av toveiskommunikasjonen mellom brukeren og eksperter som befinner seg onshore. Den siste delen handler om opplæring av nye brukere ved hjelp av VR-modeller. Dette brukstilfellet tilbyr flere Quality-of-Experience (QoE) nivåer, hvert med sine ytelseskrav.

Vi gjennomfører et eksperiment for å måle båndbredden og forsinkelsen i et standalone og et non-standalone nettverk for å finne ut om dagens 5G-nettverk oppfyller ytelseskravene av AR/VR- brukstilfellet. Resultatene viser at gjennomstrømmingskravet for nedlink ble oppfylt for et lavt QoE nivå, men den målte opplink-gjennomstrømningen ble imidlertid ikke høy nok. Det var store forskjeller på den målte nedlink-gjennomstrømningen mellom de ulike basestasjonene og mellom standalone-nettverket og non-standalone-nettverket. Ingen av nettverkene oppfylte forsinkelseskravene til AR/VR-brukstilfellet. Resultatene viste at den laveste forsinkelsen ble oppnådd ved bruk av et standalone nettverk og en lokal server plassert i 5G-kjernen.

Videre anerkjenner vi at gjeldende tildeling av frekvensbånd til mobilkommunikasjon i Norge begrenser det fulle potensialet av 5G offshore. Nasjonal kommunikasjonsmyndighet (NKOM) planlegger imidlertid å tildele 26 GHz-båndet til mobilnettoperatører i slutten av 2023. I tillegg tilrettelegger NKOM for lokale mobilnett med tilpassede rammestrukturer. Disse endringene kan føre til økt gjennomstrømning og lavere forsinkelse i 5G-nettverk i fremtiden.

Preface

This thesis was written in the spring of 2023. It concludes my two-year master's programme in Communication Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim. This thesis is intended for an audience with a technical understanding of mobile networks.

Acknowledgements

I would like to thank my supervisor, Steinar Bjørnstad, for his constant support and guidance. I am very grateful to Steinar for providing thorough feedback throughout the duration of this project. I would also like to thank Ergys Puka for helping me to understand the tools which I would be using during the experiments conducted as part of this thesis.

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List of Acronyms

3GPP 3rd Generation Partnership Project.

5GC 5G Core.

AAS Active Antenna System.

API Application Programming Interface.

AR Augmented Reality.

AR/VR Augmented Reality/Virtual Reality.

ATEX Equipment for Potentially Explosive Atmospheres.

CP Cyclic Prefix.

CRC Cyclic Redundancy Check.

DRX Discontinuous reception.

eMBB Enhanced Mobile Broadband.

eNB eNodeB.

EPC Evolved Packet Core.

eSIM Embedded Subscriber Identity Module.

FR1 Frequency Range 1.

FR2 Frequency Range 2.

gNB gNodeB.

GSMA GSM Association.

IECEx International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres.

IoT Internet of Things.

IQR Interquartile Range.

ISP Internet Service Provider.

ITU International Telecommunication Union.

IXP Internet Exchange Point.

KPI Key Performance Indicator.

LTE Long-Term Evolution.

MCPTT Mission Critical Push-to-Talk.

MIMO Multiple Input Multiple Output.

mMTC Massive Machine-Type Communications.

mmWave Millimetre Wave.

MR Mixed Reality.

MTC Machine-Type Communication.

MU-MIMO Multi User MIMO.

NFV Network Function Virtualisation.

NIX Norwegian Internet Exchange.

NKOM Norwegian Communications Authority.

NR New Radio.

NSA Non-Standalone Architecture.

NTNU Norwegian University of Science and Technology.

OFDM Orthogonal Frequency-Division Multiplexing.

PDN Packet Data Network.

QoE Quality-of-Experience.

QoS Quality-of-Service.

RAN Radio Access Network.

RRC Radio Resource Control.

RRH Remote Radio Head.

RTT Round Trip Time.

SA Standalone Architecture.

SBA Service-Based Architecture.

SINR Signal-to-Interference-plus-Noise Ratio.

SNR Signal-to-Noise Ratio.

SU-MIMO Single User MIMO.

TDD Time Division Duplex.

TTI Transmission Time Interval.

UDP User Datagram Protocol.

UE User Equipment.

UPF User Plane Function.

URLLC Ultra-Reliable Low Latency Communications.

VR Virtual Reality.

VSAT Very Small Aperture Terminal.

Chapter 1
Introduction

1.1 Background and Motivation

Offshore networks exist today with the goal of providing general connectivity for people working in the oil and gas, maritime, and wind energy sectors. The largest offshore communication network is operated by Tampnet which provides vast 4G coverage in the North Sea and the Gulf of Mexico [52]. Such networks also provide companies with the opportunity to remotely monitor devices such as sensors, and automate previously manual tasks [10].

Long-Term Evolution (LTE) was initially designed for one universal use case - high-speed internet access [47]. After the initial LTE specification, 3GPP specified some modifications to the standard aimed at supporting IoT use cases. This class of use cases is referred to as Machine-Type Communication (MTC).

While 4G networks such as the one operated by Tampnet currently support use cases such as monitoring of IoT sensors on oil and gas platforms, 5G poses the question as to whether a more enhanced interaction with devices and people offshore can be achieved.

From the start, 5G was specified to support three new generic usage scenarios:

- Enhanced Mobile Broadband (eMBB) for data-driven applications which require very high data rates.
- Massive Machine-Type Communications (mMTC) to enable a large volume of devices to communicate in a single cell.
- Ultra-Reliable Low Latency Communications (URLLC) for safety and mission-critical systems.

5G networks are being continuously deployed onshore around the world today, with most in the form of Non-Standalone Architecture (NSA). This architecture consists of a 5G Radio Access Network (RAN) connected to LTE's Evolved Packet Core (EPC). Utilising the existing EPC makes deployment of a 5G network cheaper and quicker. 5G Standalone Architecture (SA) refers to a 5G network in which the 5G RAN is connected to a 5G Core (5GC), i.e. a full 5G implementation. The three generic usage scenarios described above are specified to work with 5G SA.

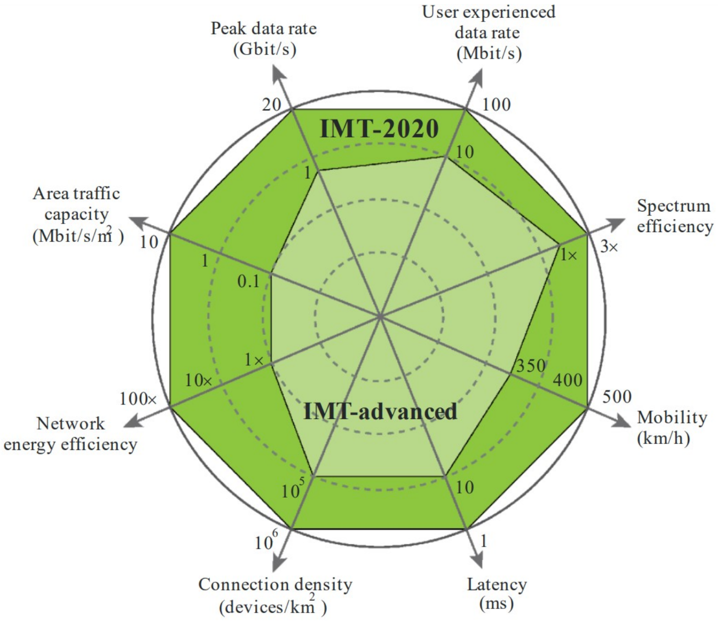

Figure 1.1: Comparison of IMT-Advanced and IMT-2020 according to ITU-R M.2083-0 [31]

1.2 Methodology

This thesis will consist of two phases; a further research (literature study) phase, and an experimentation phase. The further research phase will aim to:

- Identify existing offshore mobile networks and their purpose.
- Identify changes in the 5G specification which enable the new generic usage scenarios (eMBB, mMTC, URLLC).
- Identify offshore use cases which require 5G and evaluate a key use case in depth.

The experimentation phase will aim to determine the real-world capabilities of 5G. The network performance data obtained from the experiment will be compared with the performance requirements of a key 5G offshore use case.

The idea is to compare results from the experimentation phase with the findings from the literature study to determine whether potential offshore use cases would be feasible. For example, consider a use case which requires a latency of x ms to guarantee a certain Quality-of-Service (QoS). The experiment will determine whether current 5G networks can support this use case.

1.3 Scope and Limitations

The scope of this thesis encompasses potential offshore use cases which possess requirements that the IMT-2020 standard aims to address. The experimental phase will be conducted onshore in Trondheim using a public 5G network and a private 5G network. The conclusions from the experiment will only be based on the parameters to be measured. These parameters are throughput and latency. Specific limitations regarding the experimental phase are described separately in section 4.5.

1.4 Existing offshore networks

This section will look into current offshore networks and the services they provide.

1.4.1 Tampnet 4G Network

Tampnet's network in the North Sea provides over 250,000 square km of coverage [54]. The network serves oil and gas platforms, wind farms, and service and commercial vessels. Supported use cases include voice, Mission Critical Push-to-Talk (MCPTT), autonomous machines, remote control, predictive maintenance, and environmental sensing [10].

The backbone of Tampnet's network consists of fibre and radio links. Fibre cables connected to sites located along the coastlines of countries bordering the North Sea extend out to fixed platforms at sea. For situations in which it is too costly or too complicated to lay fibre cables, point-to-point radio links are used to connect base stations to the network. Figure 1.2 gives an overview of the network infrastructure in the North Sea. The cellular network uses a GSM and 4G/LTE RAN, and a virtual EPC. Tampnet state that 4G coverage often penetrates structures so that devices inside can connect to the network. In cases where signal penetration is not achieved, internal inward-pointing antennas are installed on the structures.

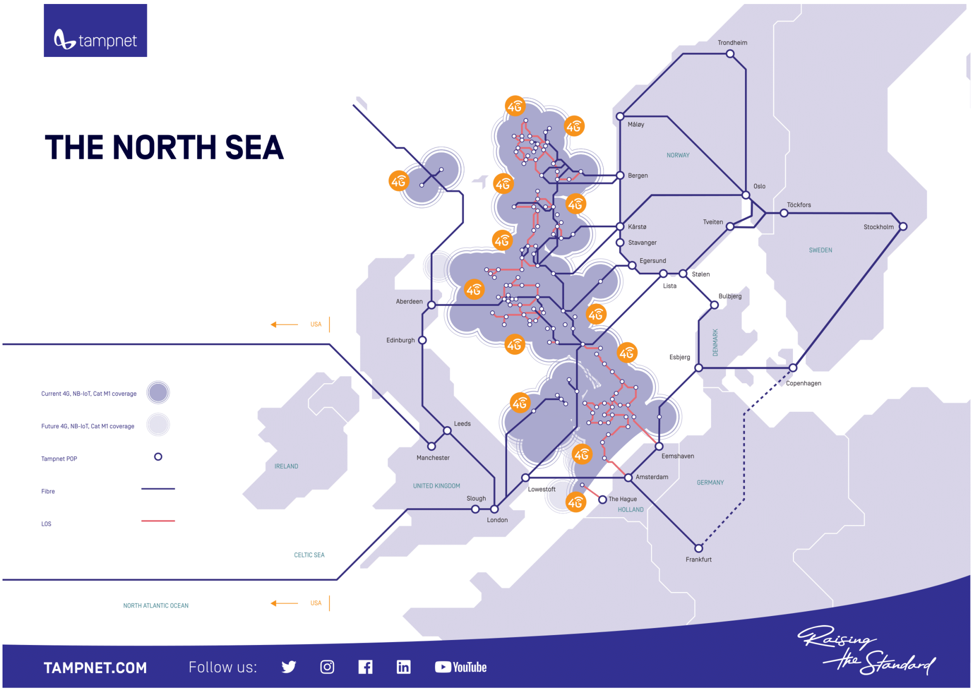

Figure 1.2: Tampnet North Sea coverage map. Image source: Tampnet [51]

The initial need for an offshore network was to provide general coverage for people working offshore. Since the growth of IoT devices, other use cases have been identified for the offshore network which provide more than just general coverage. The Tampnet network is also open for public use through roaming agreements set up with various mobile network operators. Devices supporting an Embedded Subscriber Identity Module (eSIM) can also purchase a data subscription regardless of whether the user's home operator has a roaming agreement with Tampnet.

A current use case for Tampnet's 4G network is corrosion monitoring [10]. IoT sensors are placed on metal surfaces, such as beams and pipes, which then use the network to transmit data about the condition of the metal to a central database. Analysts then use the data to determine the extent of corrosion and whether maintenance is required. The benefits of this are that it allows the monitoring of pipes and metal structures to be conducted from onshore, meaning that fewer people are needed to be transported to the offshore platform. It also allows the people who are offshore to focus their attention on problems which occur rather than having to carry out periodic manual inspections of pipes and structures.

Another supported use case is remote-controlled drones for measuring greenhouse gas levels around a platform. Air quality data is analysed to determine whether emission reduction measures should be implemented. Drones are also used for visual inspection of parts of a platform which are hard to reach or dangerous for a human to approach. Drone inspection removes the need for companies to employ specialised teams to set up scaffolding or climbing ropes to manually inspect parts of the platform. Additionally, a drone can be instantly deployed on the platform instead of having to wait for experts to travel offshore.

1.4.2 Telenor Maritime 4G Netowrk

Telenor Maritime operates a 4G network on the Norwegian Continental Shelf. This service is aimed at companies operating in the cruise and ferry, offshore oil and gas, offshore wind, and fisheries industries. LTE base stations are installed on oil and gas platforms to provide coverage for devices on the platform and for vessels in its vicinity. Telenor Maritime provide a dedicated network for Equinor's operations as well as a public 4G network, with both networks operating on different frequencies [55]. A dedicated network for Equinor allows the company to define its own QoS requirements, as well as making it easier to ensure that they are met thanks to the absence of external traffic.

A current use case for Telenor Maritime's network is remote vehicle operations. Telenor Maritime, in conjunction with Oceaneering, have launched a remotely operated underwater vehicle [45]. The vehicle uses a surface floating buoy which contains a 4G and a satellite transceiver. This transceiver connects to offshore LTE eNodeBs (eNBs) and thus enables remote control of the underwater vehicle from on land. In cases where the underwater vehicle needs to operate outside of LTE coverage, the satellite connection can be used. When using the 4G network, the vehicle can transmit a high-resolution video feed. The benefits of this system are that the vehicle does not need to be tethered to a surface ship and the people controlling it can be based onshore.

1.4.3 Starlink Maritime Satellite Network

Using a network of low earth orbit satellites, Starlink Maritime offers download speeds of up to 350 Mbps [49], upload speeds of up to 40 Mbps [50] and a latency of 50ms. A use case for this service is to provide general connectivity to offshore workers. SpaceX, the parent company of Starlink, provide this service to their employees when working offshore. During their free time, employees can stream movies and play online latency-sensitive multiplayer games [50]. Satellite connectivity can provide seamless coverage for vessels at sea since there is no requirement for the vessel to be in the coverage area of a base station.

Low latency is one of the main advantages of a low earth orbit satellite system in comparison to traditional Very Small Aperture Terminal (VSAT) systems. VSAT systems communicate with geostationary satellites orbiting the earth at 35800 km. This large distance results in a latency of at least 250 ms with protocol processing taking another 300ms to 500 ms [28]. In contrast, low earth orbit satellites such as Starlink operate at a maximum altitude of 2000 km, thus enabling lower latency communications.

Chapter 2
5G Background

2.1 Key Changes in the 5G Specification

2.1.1 Millimetre Wave (mmWave)

5G New Radio (NR) specifies the use of much shorter wavelengths than used in LTE. The 5G frequency spectrum is divided into two ranges, Frequency Range 1 (FR1) encompassing wavelengths between 410 MHz and 7125 MHz, and Frequency Range 2 (FR2) encompassing wavelengths between 24250 MHz and 71000 MHz [16]. It was originally specified that FR2 would encompass frequencies up to 52600 MHz. However, as of 3GPP Release 17, it was decided that this upper bound would be increased to encompass the 60000 MHz globally unlicensed band. At the higher frequencies encompassed in FR2, more spectrum is available and thus Millimetre Wave (mmWave) spectrum allocations are often extremely wide, with 800 MHz or more per service provider [11]. 5G takes advantage of this by supporting a maximum channel bandwidth of 400 MHz in FR2, compared to 100 MHz in FR1 and 20 MHz in LTE-Advanced. This enables a much higher capacity and better handling of peak data rates than what is possible with LTE. An overview of FR1 and FR2 is presented in table 2.1.

	FR1	**FR2 (includes mmWave)**	
		FR2-1	**FR2-2**
Frequency range	410 - 7125 MHz	24250 - 52600 MHz	52600 - 71000 MHz
Max. channel bandwidth	100 MHz	400 MHz	2000 MHz
Subcarrier spacing	15, 30, 60 kHz	60, 120, 240 kHz	120, 480, 960 kHz
Duplex Mode	FDD, TDD	TDD	
Max. number of subcarriers	3300 (4096 if using Fast Fourier Transform (FFT))		
Carrier aggregation	Up to 16 component carriers		
Radio frame length	10 ms		
Subframe length	1 ms		

Table 2.1: FR1 and FR2 specifications as of 3GPP Release 17

Using mmWave 5G, Telia has recorded download speeds of up to 4 Gbit/s in a lab. A pilot project is also in operation in which a floating buoy located 1.6 km off the coast of Trondheim equipped with a 5G mmWave transceiver recorded download speeds of 2.6 Gbit/s [56].

2.1.2 Massive MIMO

MIMO makes use of multiple antennas at the transmitter and receiver to improve the quality of a received signal for a user or group of users. Conventional MIMO systems, as used by LTE-Advanced, operate with an antenna configuration of up to 8 transmitters and 8 receivers (8x8). Massive MIMO supports up to 256 transmitters and receivers (256x256) at the base station and 32 transmitters and receivers at the User Equipment (UE) [34]. With more transmitters and receivers, a 5G base station will be able to transmit more simultaneous data streams than an LTE base station.

Conventional MIMO was introduced in 3GPP release 8 for LTE and focused on two main techniques: spatial diversity and spatial multiplexing. Spatial diversity involves a base station transmitting the same data stream from multiple transmitters in order to improve the Signal-to-Noise Ratio (SNR) at the receiver [34]. Each data stream sent from a spatially separated transmitter will propagate along a different path to the UE. The negative effects of multipath fading are reduced as the UE can use the multiple data streams it receives to reconstruct the original signal. Spatial multiplexing involves a base station transmitting a payload across different streams in parallel. The original payload is split up at the base station, and each spatially separated antenna in the MIMO array transmits a different part of the payload using the same time-frequency resource. Each data stream acts as an individual channel between the base station and the UE. The data streams, having travelled different paths to reach the UE, are received by multiple antennas and combined into their original sequence. When multiplexing data streams which are destined for the same UE, this is referred to as Single User MIMO (SU-MIMO). When multiplexing data streams which are destined for multiple UEs, this is referred to as Multi User MIMO (MU-MIMO). Spatial multiplexing can increase spectral efficiency which results in increased network capacity and user throughput [3]. These techniques are not new to 5G, however, massive MIMO provides much larger antenna configurations through the use of an AAS (as shown in figure 2.1) and thus the effects of these techniques become greater.

Beamforming is a technique used to amplify a signal in certain directions rather than others. It is done by adjusting the phase and amplitude of transmitted signals so that the signals add constructively in the direction of the UE. The goal is to ensure that the UE receives a high beamforming gain which improves the Signal-to-Interference-plus-Noise Ratio (SINR). Improved signal quality results in greater

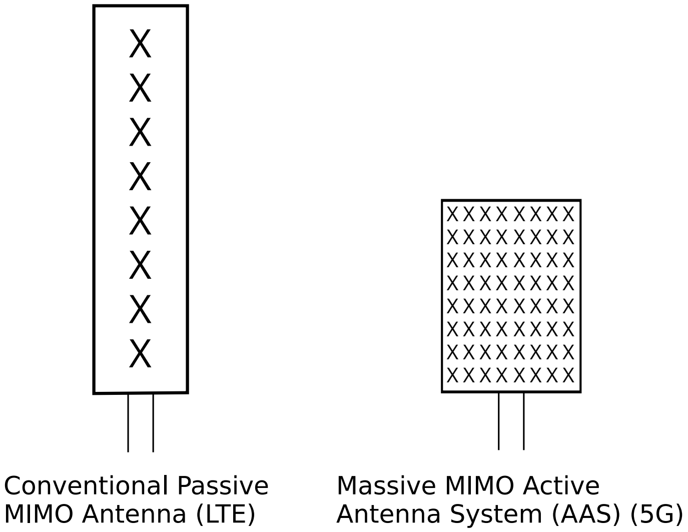

Figure 2.1: Conventional MIMO antenna vs Massive MIMO antenna

network coverage, capacity and improved user throughput [2]. Massive MIMO in 5G makes beamforming possible as a result of the large number of transceivers contained within the AAS.

The configuration of the AAS impacts the beamforming ability. The antenna array contains a number of dual-polarised antenna element pairs. Instead of connecting each dual-polarised antenna element pair to a pair of radio chains, the array is divided into sub-arrays as shown in Figure 2.2. A 2x1 sub-array contains two dual-polarised antenna element pairs. Each sub-array is then connected to one pair of radio chains. A radio chain consists of the resources (transmitters and receivers) required to transform a digital signal into an analogue signal and vice versa [2]. The more radio chains the system uses, the wider the range of angles through which beamforming can be performed. However, using more radio chains increases the complexity and cost of the system [2]. Therefore, a compromise must be made between ensuring that the majority of UEs are in the main lobe of the array and keeping the sub-array size as large as possible to reduce complexity and cost. Figure 2.3 shows the effect of changing the size of the sub-arrays on the range of angles through which the beam can be directed.

Another technique used in massive MIMO is null forming. Null forming aims to reduce the beamforming gain in certain directions so as to not cause inter-cell interference and intra-cell interference. The antenna beam is designed to have low or zero gain in the directions of the UEs which are not the intended target of the signal.

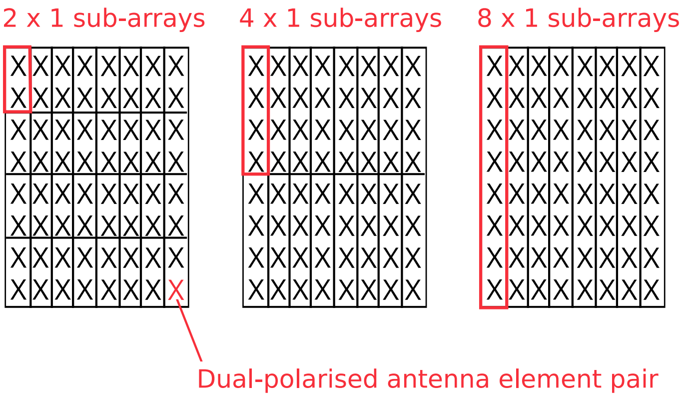

Figure 2.2: AAS array configuration example

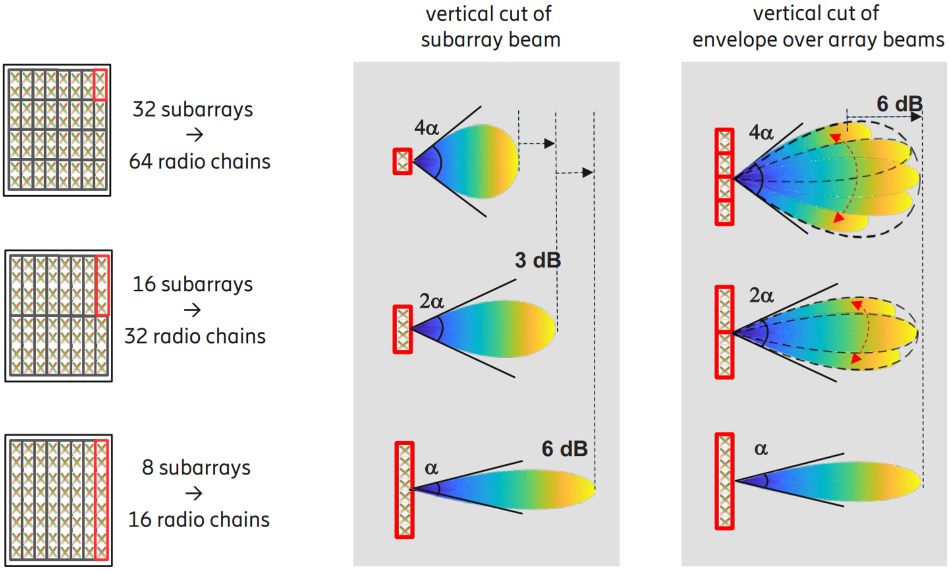

Figure 2.3: Effect of sub-array size on the beamforming ability of an AAS. Image source: Ericsson [2]

2.2 Generic Usage Scenarios

As identified in the preparatory work for this thesis [8], 5G specifies three classes of use cases: eMBB, mMTC, and URLLC. This section will take a deeper look into these classes and identify the technology which makes them possible.

2.2.1 Enhanced Mobile Broadband (eMBB)

eMBB focuses on human-centric use cases requiring large data volumes and very high data rates. It also specifies support for greater user mobility than in LTE. The eMBB scenario covers use cases requiring wide area coverage down to hotspot coverage. The performance requirements for eMBB, as specified in ITU-R M.2410-0, are listed in table 2.2.

As 5G is expected to offer a wide range of performance in a wide range of environments, the International Telecommunication Union (ITU) have defined multiple test environments in which to evaluate the performance of 5G against its requirements [30]. These environments reflect a combination of geographic environment and usage scenario. For the eMBB usage scenario, the following three test environments are defined:

- Indoor Hotspot - An isolated indoor environment such as in offices or shopping centres. User density is very high and user mobility is stationary or pedestrian.
- Dense Urban - An urban environment where user density and traffic loads are high. User mobility focuses on pedestrian and vehicular users.
- Rural - A rural environment with continuous wide area coverage. User mobility focuses on pedestrians, vehicular users and high-speed vehicular users.

Requirement	**Value**	**Note**
Peak data rate	20 Gbit/s DL 10 Gbit/s UL	
User experienced data rate	100 Mbit/s DL 50 Mbit/s UL	Defined for the Dense Urban environment
Peak spectral efficiency	30 bit/s/Hz DL 15 bit/s/Hz UL	
Area traffic capacity	10 Mbit/s/m^2	Defined for the Indoor Hotspot environment
User plane latency	4 ms	
Control plane latency	20 ms	
Mobility	500 km/h	Defined for the Rural environment
Mobility interruption time	0 ms	

Table 2.2: Minimum eMBB requirements for IMT-2020 radio interfaces. Data from ITU-R M.2410-0 report[32]

Enablers of eMBB
5G eMBB supports much higher data rates than LTE networks due to the use of higher frequency bands. To reach the very high data rates proposed in IMT-2020, mmWave, as described in section 2.1.1, enables large channel bandwidths to be used which can carry large amounts of data. Massive MIMO, as described in section 2.1.2, is another enabler of eMBB helping to improve spectral efficiency by 10 times that of conventional MIMO [38]. Beamforming contributes to improving the received signal quality at the UE which is crucial for obtaining high throughput via spatial multiplexing. Another enabler of eMBB is the flexible carrier aggregation scheme. Carrier aggregation involves aggregating two or more component carriers in order to provide a wider transmission bandwidth than would be possible by using a single carrier. Carrier aggregation was introduced in LTE with support for aggregating a maximum of 5 component carriers. In 5G, up to 16 component carriers can be aggregated. Carrier aggregation in 5G is flexible because carriers can be aggregated across FR1 and FR2, and each aggregated carrier can be of a different numerology.

2.2.2 Massive Machine-Type Communications (mMTC)

mMTC focuses on supporting a large number of simultaneously connected devices. The devices supported by this use case will typically transmit low volumes of non-delay-sensitive data. Devices such as IoT sensors with a long battery life fall into this category.

One test environment defined in ITU-R M.2412-0 [30] is specified for mMTC:

- Urban Macro - An environment targeting continuous coverage to support a large number of connected machine-type devices.

The only radio requirement defined for the mMTC use case is the connection density. This is the total number of devices for which the network can guarantee a specific QoS per unit area. The minimum connection density should be 1 000 000 devices per km^2 [32]. The specific QoS to be achieved is that 99% of packets are transmitted with a latency of 10 seconds or less.

Enablers of mMTC
A new Radio Resource Control (RRC) state, RRC inactive, is introduced in order to save power consumption when a device is not transmitting data. As of 3GPP Release 17, a scheme named small data transmission allows a UE to send data in the RRC inactive state without having to transition to the RRC connected state [15]. This reduces the control plane signalling overhead. Additionally, 5G introduces an enhanced Discontinuous reception (DRX) scheme [9]. DRX enables the UE to enter sleep mode for a certain period of time in which the network does not send any data.

Once this time period is over, the UE wakes up and checks with the network if there is any data to receive. The UE will then enter sleep mode for the set period of time again.

2.2.3 Ultra-Reliable Low Latency Communications (URLLC)

URLLC focuses on providing ultra-high network reliability and ultra-low latency. Application areas for URLLC are safety and mission-critical systems which require a guaranteed QoS in order to function correctly. The performance requirements for URLLC, as defined by ITU-R M.2410-0, are presented in table 2.3.

One test environment defined in ITU-R M.2412-0 [30] is specified for URLLC:

- Urban Macro - An environment targeting continuous ultra-reliable and low latency communications.

Requirement	**Value**
User plane latency	1 ms
Control plane latency	20ms
Reliability	1 packet loss in 10^5 packets
Mobility interruption time	0 ms

Table 2.3: Minimum URLLC requirements for IMT-2020 radio interfaces. Data from ITU-R M.2410-0 report[32]

Enablers of URLLC

A key enabler of ultra-low latency in 5G is a much shorter, and more flexible frame structure. In 5G NR, downlink and uplink transmissions are organised into frames with a 10 ms duration. Each frame consists of ten subframes with a 1 ms duration. Each subframe consists of one or more slots with each slot consisting of 14 Orthogonal Frequency-Division Multiplexing (OFDM) symbols. Resources in 5G are scheduled in units of OFDM symbols in comparison to LTE in which resources are scheduled in units of subframes [18]. As of 3GPP release 17 [14], seven transmission numerologies (μ) have been defined. These numerologies define the structure of NR data frames. Figure 2.4 illustrates three numerologies: $\mu = 0$, $\mu = 1$, and $\mu = 2$. The case where $\mu = 0$ corresponds to the same frame structure as used in LTE. Details for the specific numerologies are shown in table 2.4. Each rectangle containing an 's' in figure 2.4 represents an OFDM symbol and each coloured block of OFDM symbols represents a slot. Each slot can be classified as a downlink slot in which all symbols are used for downlink transmission, an uplink slot in which all symbols are used for uplink transmission or a special slot which can consist of downlink, uplink, or guard symbols.

The Transmission Time Interval (TTI) represents the minimum data transmission time. In LTE, the TTI is fixed at 1 ms for all transmissions, whereas in 5G, the TTI is dependent upon the number and length of OFDM symbols. Reducing the TTI has the effect of reducing the time-to-transmit latency, processing latency, and propagation latency as described in section 4.3.1.

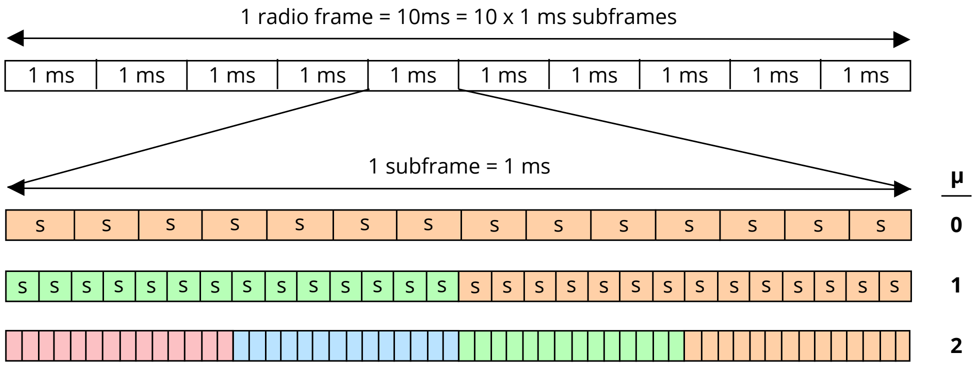

Figure 2.4: 5G frame structure

Numerology (μ)	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Subcarrier spacing (kHz) = $2^{\mu} \times 15$	15	30	60	120	240	480	960
Number of slots per subframe	1	2	4	8	16	32	64
Slot duration (ms)	1000	500	250	125	62.5	31.25	15.625
Number of OFDM symbols per slot	14						
Length of an OFDM symbol (μs)	66.67	33.33	16.67	8.33	4.17	2.08	1.04
Length of a Cyclic Prefix (CP) (μs)	4.69	2.34	1.17	0.59	0.29	0.15	0.07
TTI (length of an OFDM symbol including CP) (μs)	71.35	35.68	17.84	8.92	4.46	2.23	1.11

Table 2.4: 5G transmission numerologies. Data from [14] and [18]

Another enabler of ultra-low latency is the use of mini-slot transmissions. 3GPP TR 38.912 [1] states that mini-slots provide support of very low latency including URLLC for certain slot lengths. A mini-slot consists of a number of OFDM symbols and is the minimum supported scheduling unit in 5G NR. For URLLC, mini-slots can consist of as few as two OFDM symbols [1]. Mini-slot data can also be inserted at the front of a transmission queue, ahead of other conventional slot data, which ensures that it is transmitted as soon as possible, thus reducing queuing latency [18].

The architecture of the 5G core also contributes to low latency. The 5GC uses a Service-Based Architecture (SBA) which enables the use of Network Function Virtualisation (NFV). NFV is a concept which decouples network functions from physical hardware devices by implementing them as virtual network functions. As the network functions of the 5GC are implemented in software, there is more flexibility about where in the network these functions are implemented. To achieve lower latency, the User Plane Function (UPF) can be deployed on edge computing nodes closer to the user. To achieve latency of less than 1 ms, it is mandatory that the UPF is placed at the network edge [35]. This has the effect of reducing the transmission latency of the backhaul network as communication through the core network is reduced. Additionally, this contributes to reduced forwarding latency due to a flatter network architecture with fewer hops [18].

Edge computing can also be used for storing and caching user applications and data. Edge computing nodes deployed close to the RAN will enable users served by those base stations to access content stored and cached on the edge node instead of retrieving the content through the core network and the wider internet. This results in reduced propagation latency due to shorter distances between where the data is stored and the UE.

2.3 Architecture

5G networks can be characterised by their architecture type. Architectures which use dual connectivity, where NR and LTE are used simultaneously, are referred to as non-standalone. Architectures which only use one radio access technology are referred to as standalone. Both NSA and SA are further split up into different deployment options. 5G option 2 (SA) is the goal of future deployments, however, initial public 5G networks have been deployed as option 3 networks (NSA) [47]. This section will therefore consider option 2 and option 3 architectures.

2.3.1 Non-Standalone Architecture (NSA) - Option 3x

This architecture consists of an EPC and LTE RAN alongside a 5G RAN. Control plane data is handled by the EPC, and a 5GC is not used. Only user plane data is handled by the 5G RAN which acts as a secondary serving cell alongside the 4G RAN to increase throughput for the user and capacity of the cell. This option allows mobile network operators to deploy the NR technology quicker than having to wait to configure a 5GC. Therefore, most early implementations of 5G networks have used NSA architecture [37]. Option 3x is the industry mainstream when it comes to NSA, as it routes user plane data directly to the 5G gNodeB (gNB) to avoid excessive load on the LTE eNB [19].

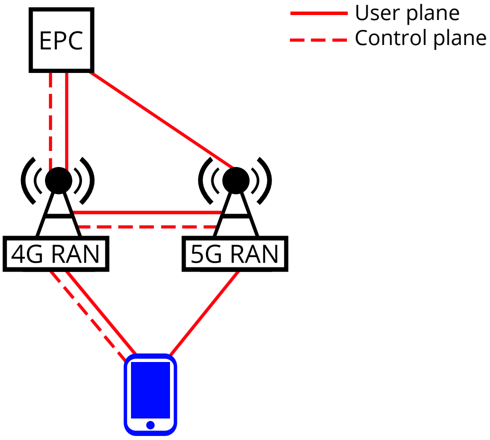

Figure 2.5: NSA option 3x architecture

NSA focuses on the eMBB use case [25]. As most early implementations of 5G networks are of the NSA type, the benefits of eMBB have been more publicly visible than those of mMTC and URLLC.

2.3.2 Standalone Architecture (SA) - Option 2

Standalone 5G architecture uses a 5GC connected to a 5G RAN (see figure 2.6). Unlike NSA, SA supports all three generic usage scenarios for 5G (eMBB, mMTC, and URLLC) [25]. Additionally, an option 2 network offers improvements related to the eMBB use case when compared to option 3 networks [20]. Namely, decreased end-to-end latency and edge computing could benefit real-time interactive services, such as 3D Augmented Reality/Virtual Reality (AR/VR). 5G SA also opens up a range of new use cases which utilise SBA and network slicing.

5G Core

The 5GC is a cloud-based system which uses SBA. This allows network functions to provide one or more services to other network functions via an Application Programming Interface (API). By using SBA, network functions can be rapidly implemented and scaled as well as moved to the edge of the network to reduce end-to-end latency [39].

Network Slicing

With a 5GC in place, network operators are able to take advantage of network slicing to offer a guaranteed QoS to customers. Each network slice is an isolated, end-to-end logical network which uses the 5GC and 5G RAN. Network slices can be deployed across the core network, the access network, and the transport network. A separate network slice could be deployed for each of the three generic 5G usage scenarios. A device can be connected to up to 8 different core network slices simultaneously, thus allowing for different applications on a single device to use different network slices.

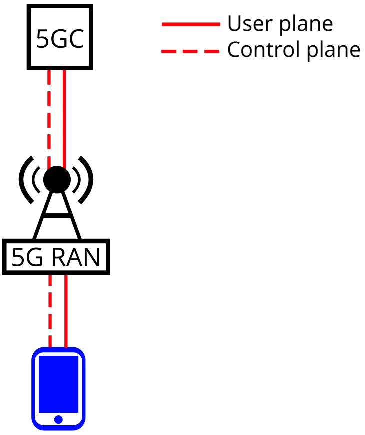

Figure 2.6: SA option 2 architecture

2.4 Challenges of Using 5G Offshore

Preliminary work carried out in the pre-project [8] identified that electrical equipment used in potentially explosive atmospheres, such as in certain areas of offshore platforms, is subject to restrictions as defined under the EU's Equipment for Potentially Explosive Atmospheres (ATEX) directive. A similar non-mandatory but widely used international scheme also exists - International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres (IECEx), through which over 30 nations including Norway participate [7]. Offshore network operators must take into consideration the restrictions outlined in the IECEx scheme and/or ATEX directive when deploying an offshore network.

Chapter 3
Offshore Use Cases

This chapter will explore in depth a possible use case for 5G. A structured approach will be followed to ensure that the use case description adheres to the following structure:

- Problem description and motivation - A description of what the use case is addressing.
- Current status and challenges - The problems which the use case aims to solve.
- New features - The new technology or services that the use case takes advantage of in comparison to what is already in place.
- Technical requirements - The technical requirements to enable the use case.
- Role of 5G - Why 5G is useful for the use case. The role of 5G in enabling the use case will be characterised by one of three categories (as defined by the 5G-Solutions for European Citizens project [36]):
  - Category A: 5G is essential to the use case. I.e. one or more Key Performance Indicators (KPIs) (latency/bandwidth etc.) will not be met without the use of 5G.
  - Category B: The use case does not contain any KPIs which strictly require 5G. However, the use case will benefit from 5G performances or 5G will enable a wider uptake of the use case.
  - Category C: The use case does not contain any KPIs which strictly require 5G. It is possible to use 4G or 4.5G for the use case.

Six potential offshore use cases proposed by Hajri et al.[24] were already identified from a literature study during the pre-project phase [8]. These use cases are listed below.

- Multi-Vision Smart Surveillance
- Body Worn Camera
- Real-Time Vehicle Surveillance
- 3D AR/VR for Maintenance and Troubleshooting
- UAV Inspection and Video Surveillance
- Scaffolding and PPE Compliance Detection

The GSM Association (GSMA) have identified several potential 5G use cases (not offshore-specific) and their bandwidth and latency requirements which can be seen in figure 3.1. Of the six use cases identified in the pre-project, the AR/VR use case is subject to the strictest latency and throughput requirements according to GSMA. Therefore, we have chosen to analyse this use case in this chapter.

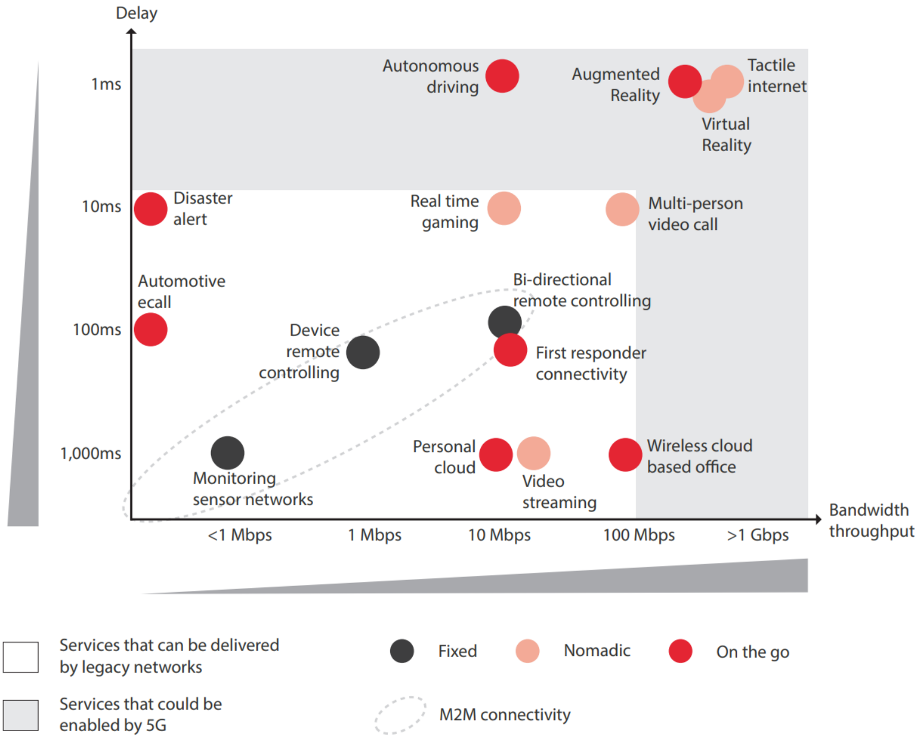

Figure 3.1: Bandwidth and latency requirements for potential 5G use cases. Image source: GSMA Intelligence [23]

3.1 Augmented and Virtual Reality for Platform Maintenance

3.1.1 Problem Description and Motivation

The use of Augmented Reality (AR)/Virtual Reality (VR) is not a new concept, however, the computing power required to facilitate a seamless and immersive experience is very high. VR and AR are often talked about in the same sentence however they are both in fact two different technologies. VR creates a fully virtual environment in which the user becomes totally immersed with the help of specific hardware such as a VR headset. This can be thought of as a computer simulation in which the user is separated from interacting with the real world. AR on the other hand combines digital elements with the real world. The user is fully aware of their presence in the real world while at the same time being able to see digital elements overlaid on top of real world objects. Mixed Reality (MR) is a combination of AR and VR.

AR/VR has the potential to provide the user with easy-to-access, hands-free information while the user is performing a task. This use case will explore the possibility of using 5G with an AR/VR system to improve maintenance operations on oil and gas platforms.

3.1.2 Current Status and Challenges

Existing 4G networks on oil and gas platforms allow IoT sensors to be connected to the network. These sensors make it possible to transmit data related to the condition of machines over an internet connection. This data can then be viewed on a screen in a control room or via a mobile device on the platform. This solution is limited by the fact that it is difficult for the user to simultaneously engage with the digital information and perform a maintenance task. For example, a user must pick up a tablet, read the information on the tablet, put the tablet down, and then perform a maintenance task on a machine.

The main challenges of AR/VR as identified in a consumer survey are lack of mobility, bulky headsets and network lag [12]. According to the survey, half of early adopters of VR headsets believe that the current headsets limit their mobility. Offshore workers on oil and gas platforms require full mobility in order to reach all areas of the platform. Network latency is a key factor in providing a smooth experience for the user. If latency is too high, a lag can occur between when an action is performed by a user and when the AR/VR device updates the view for the user. This can cause nausea and motion sickness and thus become counter-productive for the user.

Another challenge is that synchronising the real-world actions of a user with a digital environment is a compute-heavy process. Many VR applications run on local devices because the latency and bandwidth of 4G networks are not at the required level in order to host AR/VR applications on the cloud. The relatively low processing power of mobile devices compared to cloud computing servers limits the current use cases for this technology.

3.1.3 New Features

The features described below are assumed to be implementable through a pair of AR/VR glasses worn by the user. Unlike current VR headsets, in order for the glasses to not prohibit mobility, a mixed reality solution in the form of AR glasses with built-in VR capabilities would allow the user to interact with both real world and digital objects.

Graphics overlay: AR/VR glasses could overlay graphics onto the users' field of view and display information such as efficiency rates of the machine which the user is looking at, or show the location of a faulty component or machine. This would allow the fault zone to be identified quicker, and the glasses could guide the maintenance technician to its location on the platform. This would be of great use to technicians who have recently arrived on the platform and do not know their way around. AR/VR glasses could also overlay safety data onto the users' field of view. Data could include safety manuals and procedures, as well as overlaying a colour onto a machine or pipe to indicate its temperature so that the user does not unknowingly touch a hot surface. This has the potential to increase the safety of employees working on the platform, and it would allow faster training on the job thanks to instant access to hands-free training and safety manuals. This feature makes use of data from sensors attached to machines or other parts of an oil and gas platform. The use of AR/VR allows this already existing data to be displayed in a more convenient and interactive manner. Adding more IoT sensors to different parts of the platform will increase the level of detail available to the user.

Two-way communications: AR/VR glasses equipped with two-way communications can enable the user's field of view to be streamed over the internet to an onshore location where it can be viewed by an expert. The expert will be able to see what the technician on the platform sees and give them instructions. This will allow experts to be situated in a centralised location onshore and interact with technicians spread across a range of offshore installations. Such a solution will save time and money for the company employing the experts as they will not be required to travel offshore as frequently as before.

Training: An oil and gas company can use VR to create virtual representations of their own oil and gas platforms which they can use to train their workers without having to go offshore. Training tasks could include the assembly and disassembly of machines and the repair and maintenance of equipment. This can help the workers to develop situational awareness in a safe onshore environment. The company also will benefit from improved efficiency and productivity [48].

3.1.4 Technical Requirements

VR services can be classified into weak-interaction services and strong-interaction services [26]. Weak-interaction services encompass VR videos and VR live broadcasts. The user has limited freedom and interactivity with weak-interaction services. Strong-interaction services support enhanced interaction with hand gesture recognition, eye tracking and touch feedback. Strong-interaction services encompass full user immersion and real-time responses from entities in the virtual world in response to interactions with the user.

AR/VR for platform maintenance is an example of a strong-interaction service. Entities in the virtual environment such as training and safety manuals overlaid onto the user's field of view need to respond to interactions from the user in real time. Such interactions could include the user navigating through the information by using hand gestures or eye movement tracking. Overlaying a colour onto objects to reflect their temperature requires low latency to minimise the lag between a user turning their head and the colour staying overlaid on the correct object as it moves across the user's field of view. The same requirement of minimal lag also applies when the AR/VR device is used for training purposes.

The GSMA defines three sets of requirements for strong-interaction services with the following content resolutions: 2K, 4K and 8K. We will only consider the requirements for 4K and 8K content as they provide a better visual experience [22]. The requirements are presented in table 3.1. Huawei also defines a set of requirements for strong-interaction services. The requirements are split into three VR Quality-of-Experience (QoE) levels with each increase in level resulting in an increase in video quality and frame rate. The QoE levels are named fair, comfortable, and ideal [27], with the ideal level consisting of two sets of requirements thus allowing us to split this level into 'ideal' and 'ideal plus'. The fair QoE level will not be considered in this evaluation as the resolution is very low (equivalent to that of a 240p video on a traditional TV screen). The specifications for the QoE levels and their corresponding network requirements are displayed in table 3.2.

Bandwidth

AR/VR requires high bandwidth in order to transmit data to and receive data from a remote server on which the data is processed. This is due to the need for AR/VR terminals to be lightweight enough for the user to comfortably wear. The compromise is that the AR/VR terminals possess low computing power, and instead, the data

Content resolution	**4K**	**8K**
Frame rate (FPS)	90	120
Bandwidth requirement	50 - 200 Mbit/s	200 - 800 Mbit/s
RTT requirement	$\leq$ 16 ms	$\leq$ 10 ms

Table 3.1: Network requirements for cloud-based VR. Data from GSM Association (GSMA) [22]

QoE Level	**Comfortable**	**Ideal**	**Ideal Plus**
Content resolution	4K	8K	16K
Approx. TV resolution (equivalent pixels per degree)	480p	720p	4K
Frame rate (FPS)	90	120	200
Bandwidth requirement	$\geq$ 260 Mbit/s	$\geq$ 1 Gbit/s	$\geq$ 1.5 Gbit/s
RTT requirement	$\leq$ 15 ms	$\leq$ 8 ms	$\leq$ 8 ms
Packet loss requirement	$\leq$ 1e-5	$\leq$ 1e-6	$\leq$ 1e-6

Table 3.2: Network requirements for cloud-based VR. Data from Huawei [26] [27]

must be transmitted to a server with high computing power. In this case, the mobile network is responsible for the data transmission.

The GSMA state that when compared to VR-only applications, AR/VR applications can require an uplink bandwidth equal to or in some cases higher than the downlink bandwidth. This high uplink requirement is a result of the vast amount of sensor data which must be transmitted to the processing server in order to "understand the real world" [22]. For this use case, we assume that the downlink and uplink bandwidth requirements are the same. The bandwidth requirements for AR/VR for platform maintenance are shown in tables 3.2 and 3.1.

Latency

End-to-end latency for an AR/VR system can be split into three main components: on-device processing latency, network transmission latency, and cloud/edge processing latency. The latency requirements presented in tables 3.1 and 3.2 only refer to the network transmission latency. Figure 3.2 illustrates the latency components of an AR/VR system. To put the network transmission latency requirement into perspective, we also present the on-device processing latency requirement and the cloud/edge processing latency requirement. According to Huawei [27], on-device processing latency should not exceed 30 ms for a comfortable QoE, and 26 ms for an ideal and ideal plus QoE. Similarly, cloud or edge server processing latency should not exceed 25 ms for a comfortable QoE, and 16 ms for an ideal or ideal plus QoE. Combining the latency requirements for all three components results in a total maximum end-to-end latency of 70 ms for a comfortable QoE and 50 ms for an ideal and ideal plus QoE.

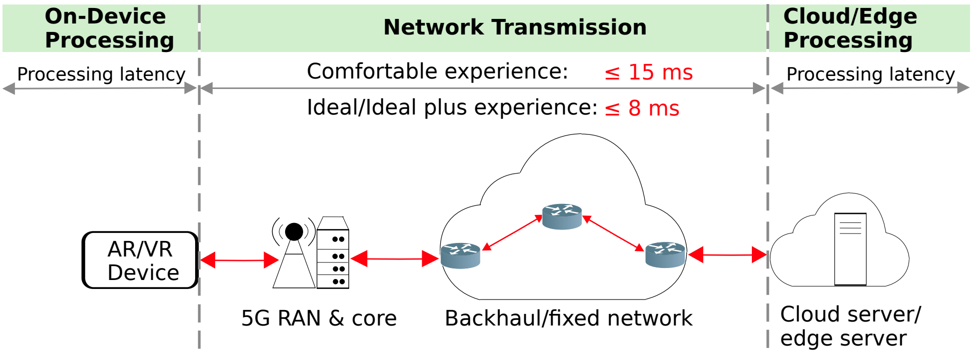

Figure 3.2: Latency components of an AR/VR system

Packet Loss
As previously stated, AR/VR for platform maintenance is a strong interaction service. This places stricter requirements on packet loss due to high user interaction with the service. User Datagram Protocol (UDP) is the recommended transport protocol for strong interaction services [27], however, due to it being a connectionless protocol, there are no guarantees against packet loss. Data from an experiment conducted by Huawei revealed that packet loss in 1e-5 slightly affects user experience, whereas packet loss in 1e-6 does not affect the user experience [27]. These differences are reflected in the different QoE levels shown in table 3.2.

3.1.5 Role of 5G

LTE-Advanced which implements the IMT-Advanced standard as shown in figure 1.1, is specified to support a peak data rate of 1 Gbps and support a one-way user plane latency of 10ms in unloaded conditions (a single user with a single data stream) for small IP packets [33]. This results in a Round Trip Time (RTT) of at least 20 ms (if we assume negligible processing delay on the device). Therefore, even in peak conditions, LTE-Advanced cannot support this use case.

A 5G SA network can theoretically support the requirements for the ideal plus QoE level. The minimum acceptable packet loss for 5G is specified to be 1e-5. As strong interaction services have a low tolerance for packet loss [26], the network must ensure that this value is never reached and that packet loss stays below 1e-6. The role of 5G for this use case can be classed as category A - 5G is essential for this use case.

Edge Computing
The latency requirements presented in table 3.2 will be difficult to guarantee if the

user is connected to the application server via a geographically long link. If we consider the Heimdal gas field in the North Sea which lies 212 km off the coast of Stavanger, we have a total straight-line round trip distance of 424 km. Given that the latency per 1 km of optical fibre is 5μs (from table 4.4), this results in a minimum propagation latency of 2.1 ms to a server located in Stavanger. For the ideal and ideal plus QoE levels with a latency requirement of 8 ms, this propagation latency contributes just over 25% to the 8 ms limit. For offshore platforms closer to shore than the one used in the example, it might be feasible to use onshore servers. However, for platforms further from the shore, the propagation latency will be greater than the 2.1 ms already calculated. Edge servers on the platforms will therefore be required to minimise the propagation latency and perform as much local data processing as possible. Two key uses of edge servers to minimise latency are as follows:

- 5G allows the UPF, which is responsible for packet routing and forwarding amongst other things, to be placed close to the RAN. This allows packet processing and aggregation to be performed at the network edge. To achieve ultra-low latency, the UPF must be placed on an edge node on the offshore platform [35].
- Edge servers can host the compute-heavy applications required for AR/VR. To ensure that AR/VR headsets are light enough to enable the user to move freely, the headsets should only possess basic capabilities such as network connectivity, video and audio encoding and image display [26]. This necessitates the use of remote computing and rendering capabilities. The outputs of the remote computation and rendering can be streamed to the AR/VR headset via an ultra-low latency 5G network. Figure 3.3 illustrates the use of edge servers on an offshore platform.

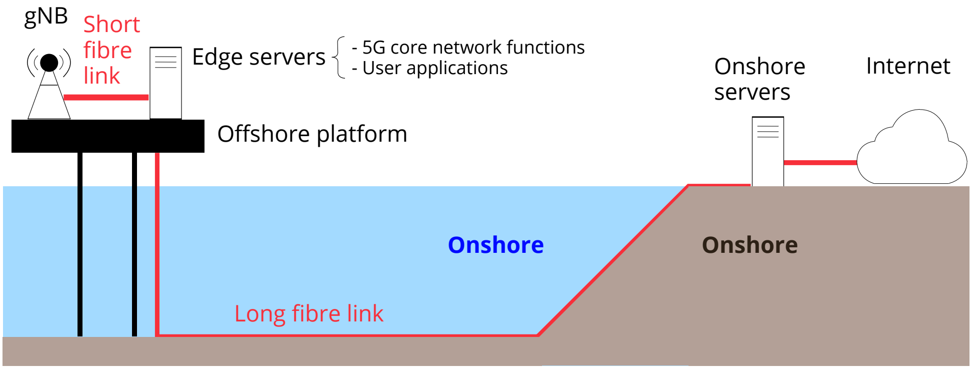

Figure 3.3: Edge server on an offshore platform

Chapter 4

Experimentation

The aim of the experimental phase is to emulate an offshore 5G network setup with short distances and line-of-sight to the base station. The requirements specified for IMT-2020 radio interfaces (as illustrated in figure 1.1) specify the minimum performance of 5G radio networks. While all 5G networks should meet these requirements, different use cases have their own requirements in order to guarantee a certain QoS. It is, therefore, necessary to determine whether 5G networks can, in practice, support the AR/VR for platform maintenance use case described in section 3.

As previously stated, most current implementations of 5G networks use NSA. NTNU has deployed a private 5G SA network using Nokia Digital Automation Cloud on its Trondheim campus. The NTNU 5G network also contains a local server. The experiment was conducted on both a Telia public 5G network and the NTNU private 5G network. This allowed a comparison to be made between NSA and SA networks. As 5G SA is the goal for future 5G network deployments, this experiment provides data related to whether a use case can operate on current NSA networks, or whether it requires an SA network.

The network parameters measured in this experiment were decided to be uplink throughput, downlink throughput and latency. These parameters directly correspond to the network requirements identified in chapter 3 for the offshore use case. Measuring these parameters allows a comparison to be made between the requirements for a use case and the achievable performance of current 5G networks.

4.1 Tools and Equipment

The experiment was conducted using a Nokia XR20 5G phone running Android version 11 with two SIM cards, one for Telia's network and the other for NTNU's network. An overview of the networks is provided in Table 4.1.

5G Network	Architecture	Frequency Bands
Telia	NSA	5G: N77; LTE: Various
NTNU (Nokia Digital Automation Cloud)	SA	5G: N78

Table 4.1: Overview of 5G networks used in this experiment

In the pre-project report, it was stated that software from RantCell would be used to conduct the network measurements [8]. After this decision had been made it was discovered that NTNU already had a 5G phone pre-installed with similar network monitoring applications - G-NetTrack Pro, and Speedtest by Ookla. G-NetTrack Pro provides a wide range of network monitoring and logging functionality. The Speedtest by Ookla app provides the ability to determine network throughput and latency with network testing servers located in Trondheim and other places in Norway. The local server connected to NTNU's network could not be tested through the Speedtest by Ookla app which only lists approved and publicly accessible servers. An overview of the servers used to test network performance is provided in Table 4.2.

Server Name	IP Address	Location	Test Method
Telia Norge AS	84.208.29.132	Oslo	Ookla app, Ping via terminal
UNINETT [1]	158.39.1.90	Trondheim	Ookla app, Ping via terminal
NTNU Local Server	Internal IP	Trondheim	Ping (within NTNU's network)

Table 4.2: Servers used to test network performance

Speedtest by Ookla has limitations relating to the reporting of latency measurements. When using the app, the service only reports the average, minimum, and maximum latency values, rather than listing each individual latency measurement. This limits the level of statistical analysis which can be performed on the data and thus it was decided that another tool for measuring latency was required. As a result of Android not having a native terminal app, a third-party terminal emulator app 'Qute' was used. This app emulates a UNIX terminal and supports executing bash scripts and working with root rights [6]. To measure network latency, a bash script was created (see listing 1) which sends 200 ICMP echo request messages to the target server with a 0.5 s interval between each message. The script performs this action for the UNINETT server and the Telia server, and when connected to NTNU's network, the NTNU local server as well. The script records the date and time of each ICMP echo reply message and writes this data to a text file stored in the phone's internal file system.

---

[1] Server name as specified in the Speedtest by Ookla app. The company UNINETT has now become Sikt, however, all references in this thesis will use the UNINETT name.

G-NetTrack Pro	v28.5
Speedtest by Ookla	v4.8.4.182366
Qute: Terminal Emulator	v3.100

Table 4.3: Testing software specifications

Listing 1 Ping bash script

```
#!/bin/sh
ping -i 0.5 -c 200 158.39.1.90 | while read pong; do echo "$(date
↪  +%Y-%m-%d_%H:%M:%S): $pong"; done | tee -a
↪  /storage/emulated/0/Documents/results/uninett.txt
ping -i 0.5 -c 200 84.208.29.132 | while read pong; do echo "$(date
↪  +%Y-%m-%d_%H:%M:%S): $pong"; done | tee -a
↪  /storage/emulated/0/Documents/results/telia.txt
#If testing the NTNU base station, also execute the following line:
ping -i 0.5 -c 200 LOCAL_SERVER_IP | while read pong; do echo "$(date
↪  +%Y-%m-%d_%H:%M:%S): $pong"; done | tee -a
↪  /storage/emulated/0/Documents/results/ntnu.txt
```

4.2 Experiment Details and Preparatory Work

Using the signal strength map from G-NetTrack Pro, three Telia base stations were identified. The location of these base stations was plotted on a map. Five line-of-sight points at 130m (the diameter of an offshore platform [57]) from the base station were plotted on the map. An illustration of this is shown in figure 4.1. The network tests were run at each of these points. As with the Telia base stations, a series of five line-of-sight test points at 130m from NTNU's outdoor base station were plotted onto a map. The network tests were run at each of these points.

G-NetTrack Pro was used to ensure that the phone stayed connected to the correct base station by checking the base station ID before each network test was performed. In Telia's 5G NSA network, the phone was simultaneously connected to a 5G gNB and a 4G eNB. When connected to an NSA network, the G-NetTrack Pro app only reports the eNB identifier of the eNB to which the phone is connected to. Before each network test, this identifier was checked to make sure that it had not changed. When using G-NetTrack Pro on NTNU's 5G SA network, the app reports the gNB ID.

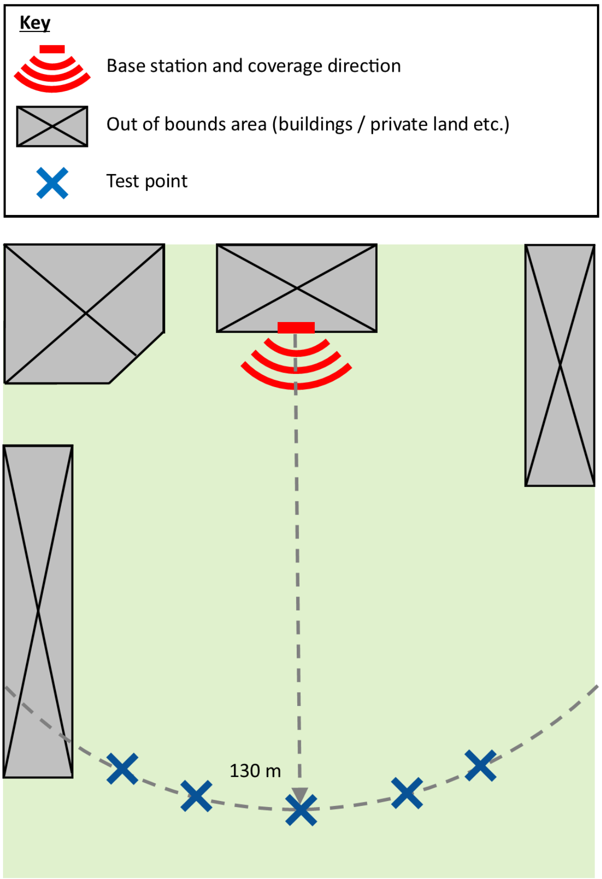

Figure 4.1: Experiment setup per base station

Network traffic is not constant over a 24-hour period [58]. Due to this, it was decided that the experimental procedure described in 4.4 was to be repeated multiple times throughout the course of one day to obtain an average result. Four time periods were defined in which the network tests would be performed:

- 09:00 - 11:00
- 11:00 - 13:00
- 13:00 - 15:00
- 15:00 - 17:00

During preliminary testing, it was found that one round of network testing took 1 hour and 45 minutes to complete. To accommodate for this, time periods spanning two hours were chosen. The four chosen time periods cover most of the working day at NTNU's Gløshaugen campus. It is therefore expected that the number of users on the network will be high during the network tests. In an offshore environment, a 5G network can be used to provide general connectivity for offshore workers, allowing them to use the network for personal use, as well as work-related tasks. Running the network tests during time periods with a high number of connected users will therefore emulate this offshore scenario.

4.3 Latency

End-to-end is defined by 3GPP in TS 22.261 [17] as "the time taken to transfer a given piece of information from a source to a destination, measured at the communication interface, from the moment it is transmitted by the source to the moment it is successfully received at the destination". ITU-R M.2410-0 [32] specifies two types of latency for 5G NR interfaces: control plane latency and user plane latency. Control plane latency refers to the time taken for a UE to transition from an idle state to an active state. For eMBB and URLLC use cases, the requirement is 20 ms (see tables 2.2 and 2.3). User plane latency refers to the time between when a source sends a packet and when the packet is received by the destination. For eMBB and URLLC use cases, the requirements are 4 ms and 1 ms respectively (see tables 2.2 and 2.3).

The aim of the latency measurements in this experiment was to determine whether the latency of the 5G RAN and core is low enough to support the use cases identified in section 3. However, the network tests performed measured total end-to-end latency which includes other sources of latency.

4.3.1 Sources of Latency

Network latency can be divided into two components: user plane latency and control plane latency. User plane latency refers to the time taken for an IP packet to travel from a source to a destination. Control plane latency refers to the time required for a device to transition from an idle state to a connected state. A user's experience of a network service is mostly dependent on the user plane latency, rather than control plane latency [18]. The focus of this experiment is to determine the performance of the network once the user has already established a connection. Therefore, only user plane latency will be considered. In figure 4.2, the sources of user plane latency are numbered, and these are explained below.

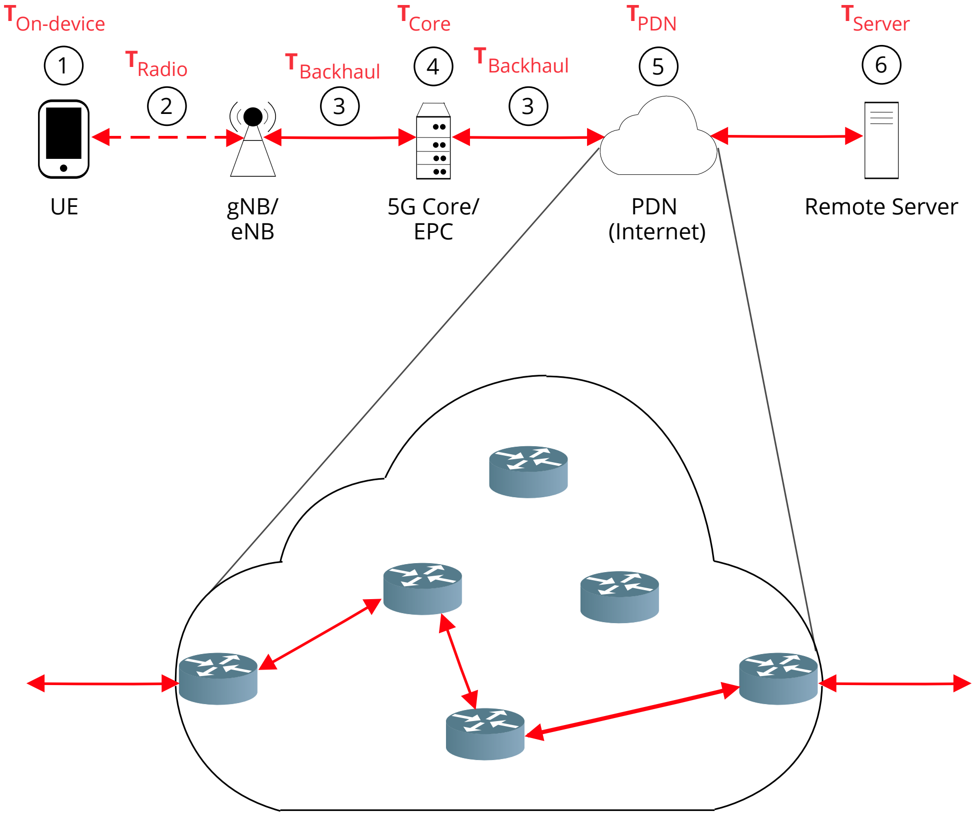

Figure 4.2: Sources of user plane latency.

	Vacuum (∼ air)	**Glass (optical fibre)**
Latency per 1 km	3.33 µs	5 µs

Table 4.4: Latency of transmission mediums. Data from Infinera [29]

1. On-device latency is the latency within the software on the UE. In order to send ICMP echo (ping) requests from the Nokia XR20, a third-party Android application was required. The application possesses an inherent processing delay as it must first process the outgoing request and then the incoming response. The number of processes running on the device also impacts the on-device latency.

2. Radio latency is the time taken from when a packet is transmitted from the UE until it reaches the gNB/eNB. This represents the latency of the air interface. Radio latency is comprised of multiple components:

2.1. Queuing latency is the time in which a packet must wait in a queue for the previous packet to be transmitted. The more processes on the UE requesting packet transmission, the greater the number of packets entering the queue. If the queue is empty, there is zero queuing latency.

2.2. Time-to-transmission latency is the time required to push all bits constituting the packet onto the transmission link.

2.3. Processing latency is the total latency of all physical layer processes as defined in 3GPP technical specifications TS 138.211 [14] and TS 138.212 [13]. These processes include scrambling, layer mapping, encoding/decoding, modulation/demodulation, Cyclic Redundancy Check (CRC) calculation, and channel coding. The degree of latency is determined by the computational power of the UE and gNB/eNB, as well as the degree of optimisation of the physical layer processes themselves.

2.4. Propagation latency is the time taken for the electromagnetic waves to propagate through the transmission medium. In the case of radio latency, the transmission medium is air. The speed of electromagnetic waves, v, in a medium with refractive index, n, is given by:

$$v = \frac{c}{n} \tag{4.1}$$

Where c is the speed of light in a vacuum.

The propagation latency, t for a distance d is given by:

$$t = \frac{d}{v} \tag{4.2}$$

Given that the maximum distance of the UE from the base station in this experiment was under 150m, this results in a propagation delay of $\sim$ 0.5 µs. At such a small distance, propagation latency is an insignificant contributor to overall latency.

2.5. Re-transmission latency is the time taken to re-transmit a lost packet. This form of latency was not applicable in the experiment because ICMP Echo requests do not get re-transmitted when lost. Re-transmission latency contributes to overall latency in applications where it is essential to successfully receive all transmitted packets.

3. Backhaul latency is the latency of the backhaul network which connects the RAN with the core network, and which connects the core to the Packet Data Network (PDN). Latency in the backhaul network arises from two main sources: the propagation latency of the transmission medium and the forwarding latency of transmission devices [18]. 5G backhaul networks can consist of an all-optical network, or use microwave links between sites. The propagation latency of a microwave link is lower than that of a fibre link (see table 4.4).

4. Core network latency is the processing latency inside the core network. The 5GC is built upon a SBA which reduces latency [18] when compared to an NSA 5G network using an LTE EPC such as Telia's.

5. PDN latency is the latency of sending a packet across a route on the internet. In this experiment, PDN latency will not affect traffic to NTNU's local server, which is located within the same network as the 5G core. PDN latency is mostly comprised of the processing latency of routers along the transmission path, as well as the propagation latency of fibre optic links. The hop count of a route indicates the number of devices such as routers which the packets must pass through before reaching their final destination. Each additional hop along a route increases the total processing latency of the route. If routers are under a heavy traffic load, queuing latency will also contribute to total latency. Queuing latency is highly variable due to its dependence on traffic load. Each fixed-route also has a fixed propagation latency. Longer routes will have a greater propagation latency as optical fibre contributes 5 µs latency per kilometre (see table 4.4). There are many operators of fibre networks in Norway, and for the purpose of calculating the fibre distance between Trondheim and Oslo, we will assume that the traffic uses the network operated by Bane NOR. Bane NOR has published the fibre distance between cities connected to their network, with the Trondheim to Oslo link consisting of 543km of fibre [4]. With 5 µs latency per kilometre of optical fibre, it follows that the RTT between Trondheim and Oslo is $\sim$ 5.4 ms.

6. Server latency is the time taken for a server to process a request and respond to it. The server's hardware, software running on it, and the load contribute to server latency.

4.4 Procedure

The following procedure was adhered to for each base station under testing:

1. Enable airplane mode.

2. Position the phone close ($\sim$20 m) to the target base station.

3. Disable airplane mode. This should ensure that the phone connects to the target base station due to a high received signal strength.

4. Using G-NetTrack Pro record the base station ID.

5. Position the phone at the first predetermined test point of the target base station. An illustration of the test points is shown in figure 4.1.

6. Hold the phone parallel to the ground facing the base station.
7. Using G-NetTrack Pro, check to ensure that the base station ID has not changed. Each of the five test points for a base station should record the same base station ID.
8. Using the terminal app, run the bash script in listing 1 and wait for execution to complete.
9. Run a network test on the Speedtest by Ookla app using the Telia Norge AS - Oslo server.
10. Run a network test on the Speedtest by Ookla app using the UNINETT - Trondheim server.
11. Repeat steps 6 to 10 for the remaining four predetermined test points for the base station.

4.5 Constraints and Limitations

As already mentioned, the latency measurements represent the total end-to-end delay from the network testing application on the 5G phone to the application on the remote server which responds to requests. The two servers on the Speedtest by Ookla app chosen for network testing are not edge servers on the 5G network, meaning that traffic must travel across longer links. These factors result in a higher measured latency than the latency of the 5G network itself.

The two networks tested in the experiment used 5G frequencies in FR1. There are currently no commercial licenses for 5G mmWave in Norway [56], and thus it was not possible to test and compare the performance of 5G using frequencies in FR1 with frequencies in FR2.

The experiment can only give an indication of 5G performance at distances of 130m from the base station. Whilst this is useful in determining whether 5G meets the requirements of on-platform use cases, it will not be possible to determine whether 5G can meet the requirements for use cases where the UE is further than 130m from the base station. This is due to the fact that it was difficult to identify test locations at greater distances where a) the UE had a line of sight connection to the base station, and b) the UE remained connected to the intended base station with a line of sight connection, without connecting to another nearby base station.

Chapter 5
Measurements

This chapter presents the measurements and analysis following the experiment conducted in chapter 4.

5.1 Throughput

The throughput measurements are presented in four graphs. Downlink measurements for the Telia and UNINETT servers are first presented, followed by uplink measurements for the same servers. Data in each graph is aggregated by base station and the time period in which the network test was conducted. This method of data visualisation makes it possible to identify whether individual base stations or time periods had an effect on the network throughput.

5.1.1 Downlink

From figure 5.1 and figure 5.2 it can be seen that the downlink throughput has a high variation between base stations in Telia's network, and between NTNU's and Telia's networks. The base stations Telia 1 and Telia 2 both exhibit similar performance, whereas Telia 3 exhibits improved throughput across all four time periods, reaching a peak of 1294 Mbit/s for the UNINETT server. The experiment confirmed that all Telia base stations used the n78 frequency band for transmissions. After further testing, it appeared that the cause of the increased throughput was partly related to environmental factors. Figure 5.3 illustrates the position of the UE at all three Telia base stations. Although the UE maintained a line of sight connection at each respective base station, the height of the ground level with respect to the base station varied for the Telia 1 and Telia 2 base stations (as illustrated in figure 5.3). This results in the loss of ability for the UE to receive reflected signals from the ground. Because the ground level was flat between the Telia 3 base station and the UE, the UE could make use of reflected signals from the ground.

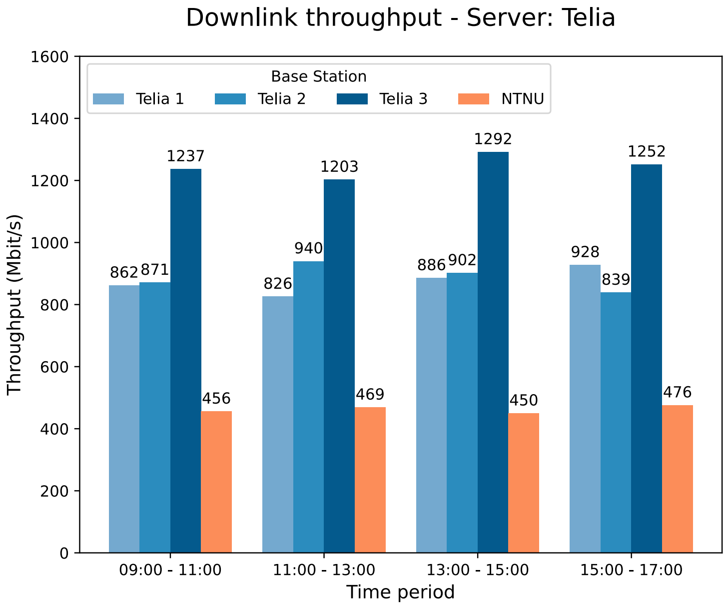

Figure 5.1: Downlink throughput by base station and time period. Test server: Telia in Oslo

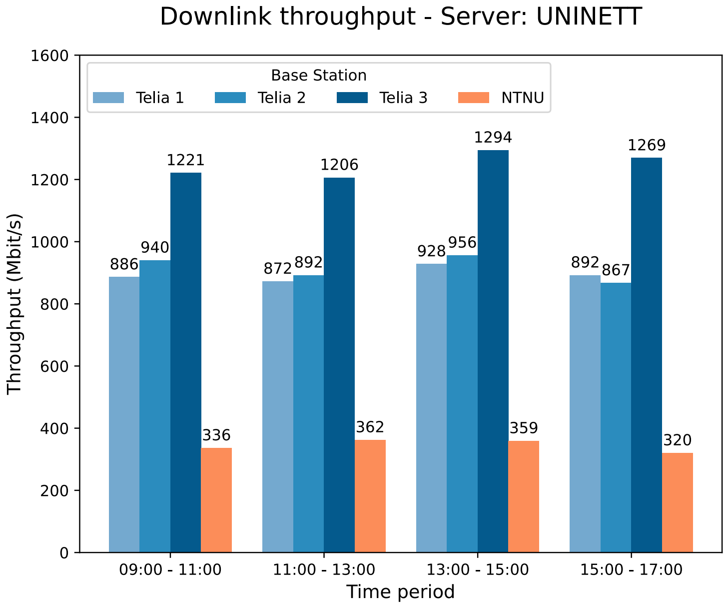

Figure 5.2: Downlink throughput by base station and time period. Test server: UNINETT in Trondheim

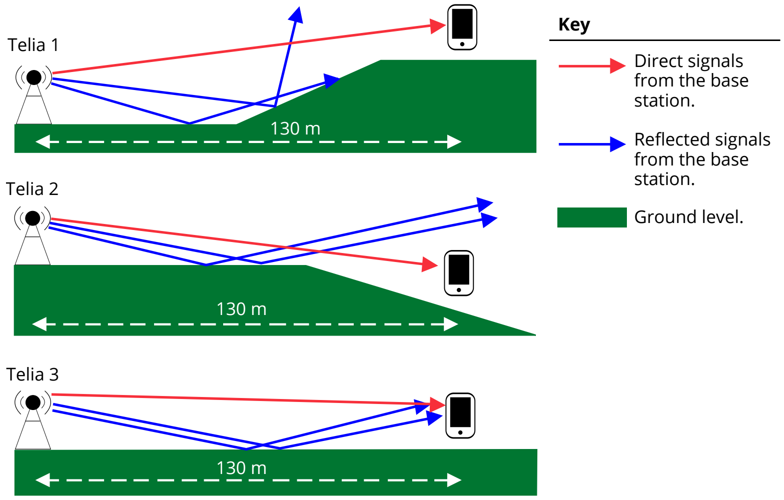

Figure 5.3: Environmental factors for Telia base stations

Additionally, further testing at a range of ∼ 30 m from all three Telia base stations, while ensuring that the ground was flat between the UE and the base station, revealed that the Telia 3 base station constantly recorded higher throughput than the Telia 1 and Telia 2 base stations. While Telia does not publicise the configuration of their base stations, the results could suggest that this base station uses a different modulation scheme, carrier aggregation scheme, or MIMO configuration.

Downlink throughput for NTNU's network was observed to be lower than that of Telia's network. The NTNU base station is connected with a 1 Gbit/s fibre link, meaning the maximum achievable throughput can not exceed 1 Gbit/s. It was therefore not possible to achieve the same throughput as with the Telia 3 base station which recorded above 1.2 Gbit/s in each test for both test servers. The physical size of the Remote Radio Head (RRH) of NTNU's network was smaller than the RRHs used in Telia's network. This suggests that NTNU's RRH uses a different antenna configuration (possibly with fewer antenna elements) than the antenna configuration used in Telia's network. This could result in reduced antenna gain at the UE and lower throughput. Another cause of lower throughput could be due to NTNU's network using a carrier aggregation scheme which provides less aggregated bandwidth than the aggregation scheme(s) used in Telia's network. It was not possible to find publicly available information related to the configuration of Telia's antennas in order to confirm whether this was the case.

Figure 5.1 and figure 5.2 show that for NTNU's network, the server used to measure throughput has a substantial effect on the results. Throughput measurements for the Telia server were ∼100 Mbit/s higher than for the UNINETT server. This consistent difference is not observed in the throughput measurements on Telia's network. Due to the difference in downlink throughput between the two test servers on NTNU's network, it was decided to perform another network test with a third test server - GlobalConnect located in Trondheim. Figure 5.4 shows the test results and the average (median) downlink throughput from both the Telia and UNINETT servers.

From Figure 5.4 it can be seen that downlink throughput for the GlobalConnect server is higher than for the Telia server. This could suggest that there is a large variation in the link bandwidth between NTNU's 5G network and the three test servers.

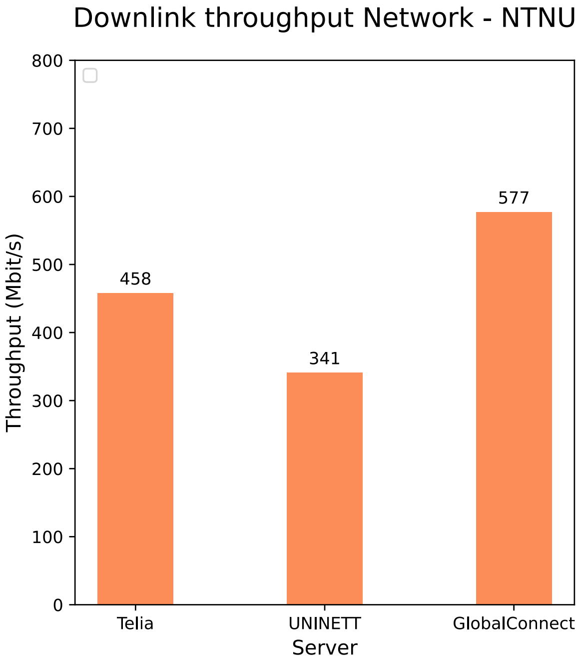

Figure 5.4: Downlink throughput for NTNU's 5G network aggregated by server

5.1.2 Uplink

From figure 5.5 and figure 5.6 it can be seen that the average uplink throughput varied between 140 Mbit/s and 162 Mbit/s for the Telia server, and between 138 Mbit/s and 162 Mbit/s for the UNINETT server. Telia 3 also provided higher average uplink throughput than Telia 1 and Telia 2 in three of the four time periods for both test servers, although the differences are marginal. The fact that the uplink throughput is not significantly higher for Telia 3 than the other Telia base stations (as is the case with downlink throughput) indicates that the network may have reached a bottleneck in the uplink direction.

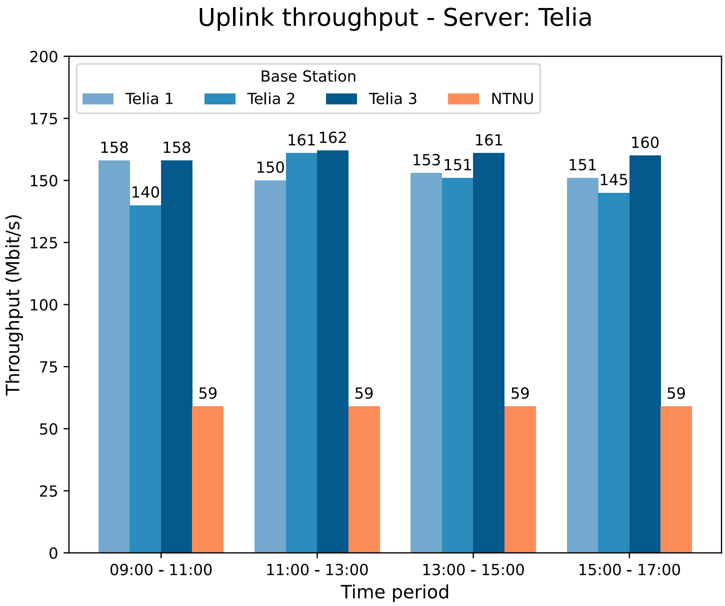

Figure 5.5: Uplink throughput by base station and time period. Test server: Telia in Oslo

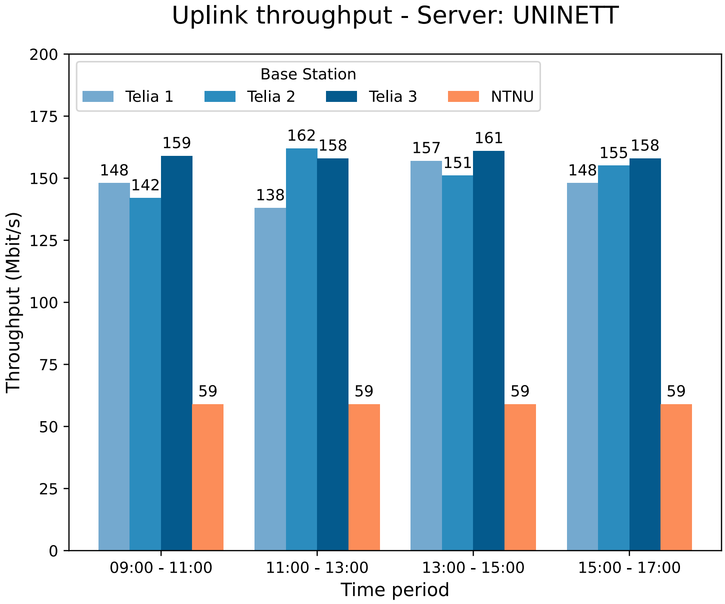

Figure 5.6: Uplink throughput by base station and time period. Test server: UNINETT in Trondheim

Both Telia's and NTNU's 5G networks operate on frequency bands which use the Time Division Duplex (TDD) mode. While the 3GPP 5G NR specification provides a flexible frame structure as described in section 2.2.3, there is a need for mobile operators to follow synchronisation requirements in environments where certain TDD LTE networks are also operating in order to reduce interference. These requirements stipulate that downlink transmissions should happen at the same time across networks and last for the same duration of time. The same applies to uplink transmissions [40]. Mobile network operators must therefore come to an agreement regarding the structure of NR frames in relation to the number of downlink and uplink slots per frame. Figure 5.7 shows one of two possible frame structures when a 5G NR network operates in the same location as an LTE network [21]. The depicted frame structure shows that more downlink slots are configured than uplink slots. This results in a higher downlink throughput than uplink throughput.

A calculation performed by NGMN as part of their white paper titled '5G TDD Uplink' [59] states that under optimum conditions and a frame structure similar to the one depicted in figure 5.7, the peak uplink throughput is 180 Mbit/s. This assumes 100 MHz of spectrum bandwidth and a 2x2 UL MIMO configuration without uplink carrier aggregation. According to the Norwegian Communications Authority (NKOM), Telia has been assigned 100 MHz of spectrum in the 3700 MHz frequency band [40] which is the band used by the three Telia base stations in the experiment. However, we can not confirm the MIMO and carrier aggregation configurations used by Telia or supported by the UE (Nokia XR20). Nevertheless, the calculated figure of 180 Mbit/s aligns with the uplink throughput measurements obtained from this experiment, with a maximum recorded uplink throughput of 162 Mbit/s. This would suggest that NR frame structure is the limiting factor.

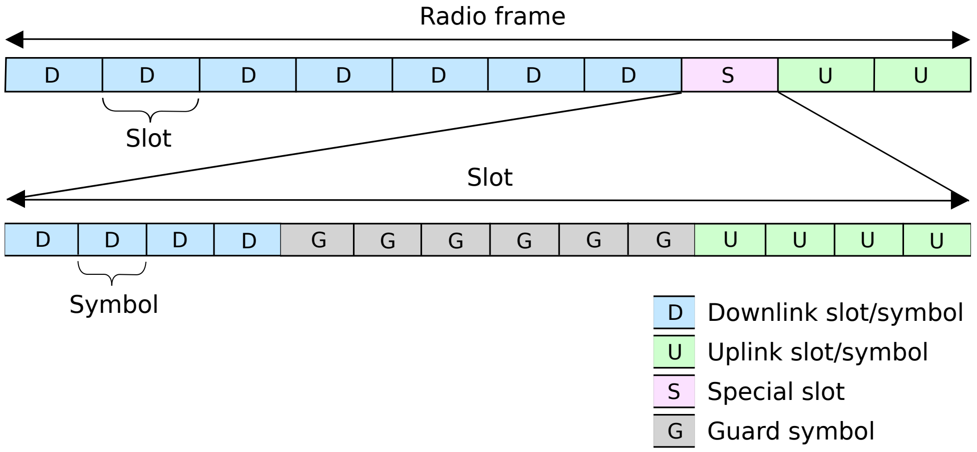

Figure 5.7: Common 5G TDD frame structure

The uplink throughput measured from the NTNU base station was recorded as the same (59 Mbit/s) for both test servers during all four time periods. This suggests that the 5G network was causing a bottleneck and could not provide greater uplink throughput. The recorded throughput of 59 Mbit/s is ∼2.5 times lower than that achieved using Telia's network. The reasons for this could be due to differences in MIMO configurations and carrier aggregation schemes between NTNU's network and Telia's network.

5.2 Latency

5.2.1 How to Interpret the Measurements

The latency measurements are presented as a series of box plots. The elements of a box plot are indicated in figure 5.8 and are described below.

- Mean: The mean of the dataset.
- Median: The median of the dataset. Half of the data points are greater than or equal to this value. The other half are less than this value.
- Lower quartile, $Q1$: 25% of data points fall below this point.
- Upper quartile, $Q3$: 75% of data points fall below this point.
- Interquartile Range (IQR): The middle 50% of data points. $IQR = Q3 - Q1$
- Minimum: The minimum data point excluding outliers. It is the minimum data point in the dataset which falls above $Q1 - 1.5 * IQR$.
- Maximum: The maximum data point excluding outliers. It is the maximum data point in the dataset which falls below $Q3 + 1.5 * IQR$.
- Outliers: Data points less than the minimum or greater than the maximum.

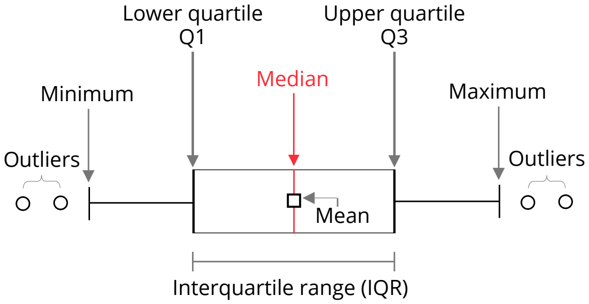

Figure 5.8: Box plot elements

5.2.2 Latency Aggregated by 5G Network and Ping Sever

The graphs in this section present the latency measurements aggregated by 5G network (Telia or NTNU) and ping server (Telia, UNINETT, or NTNU Local).

From figure 5.9 it can be seen that there was a greater variation in the measurements from the Telia network than from the NTNU network. Additionally, the number of outliers is much greater when connected to Telia's 5G network than when connected to NTNU's network. As Telia's network is a public network, it can be assumed that there are many more users simultaneously connected to one of its base stations than for NTNU's private network.

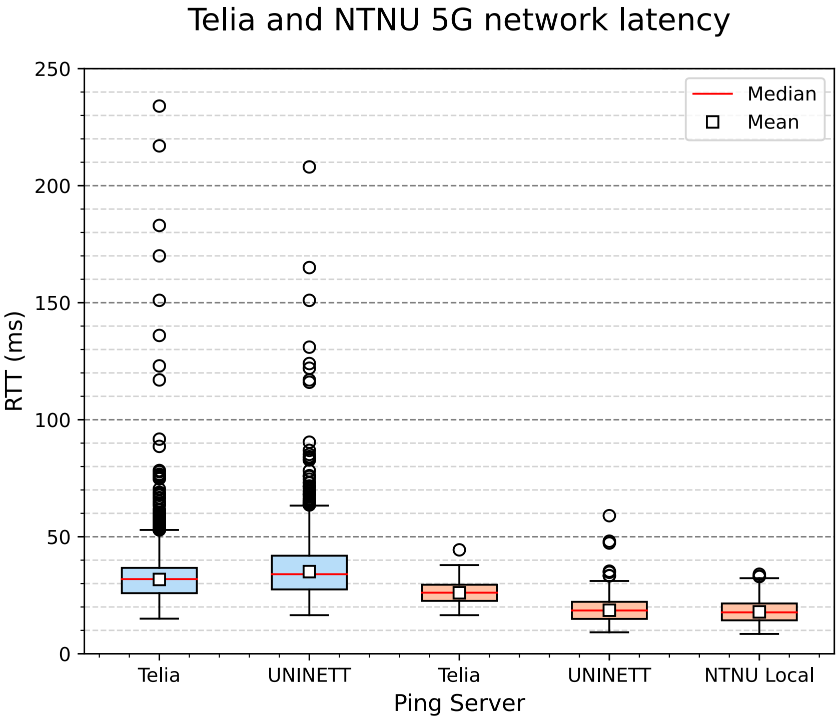

Figure 5.9: Latency measurements for Telia's network (blue box plots) and NTNU's network (orange box plots)

Figure 5.10 presents the same data as in figure 5.9 except that the outliers have been hidden from view and the y-scale has been adjusted accordingly. This provides an enlarged view of the box plots. Key values from figure 5.10 are presented in table 5.1, as well as the number of hops to each server. Additionally, the network test was repeated on a home broadband connection via Ethernet to determine the latency in the fixed network as described, and this data is also presented in table 5.1.

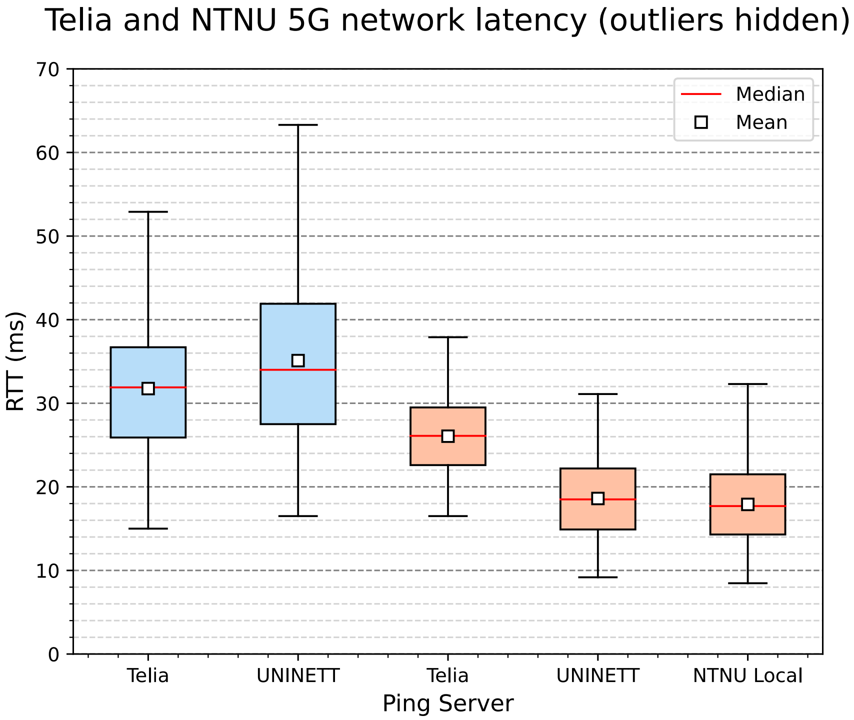

Figure 5.10: Latency measurements for Telia's network (blue box plots) and NTNU's network (orange box plots). Outlier data points hidden from view

Network	**Telia 5G**		**NTNU 5G**			**Telia Home Broadband**	
Ping Server	**Telia**	**UNINETT**	**Telia**	**UNINETT**	**NTNU Local**	**Telia**	**UNINETT**
Median RTT (ms)	31.9	34.0	26.1	18.5	17.7	9.5	2.1
Mean RTT (ms)	31.8	35.1	26.1	18.6	17.9	9.4	2.1
Min RTT (ms) (excluding outliers)	15.0	16.5	16.5	9.2	8.5	9.1	1.0
Max RTT (ms) (excluding outliers)	52.9	63.3	37.9	31.1	32.2	9.8	3.1
Number of hops	N/A	N/A	12	9	2	4	6

Table 5.1: Key latency data

If we compare the measurements from the ping test using Telia's server, we see that NTNU's 5G network provided lower latency than Telia's 5G network when looking at mean and median RTT values. This was expected due to NTNU's network using standalone 5G architecture. The minimum RTT value for Telia's 5G network was 15.0 ms, which is slightly lower than the minimum value of 16.5 ms obtained when connected to NTNU's 5G network.

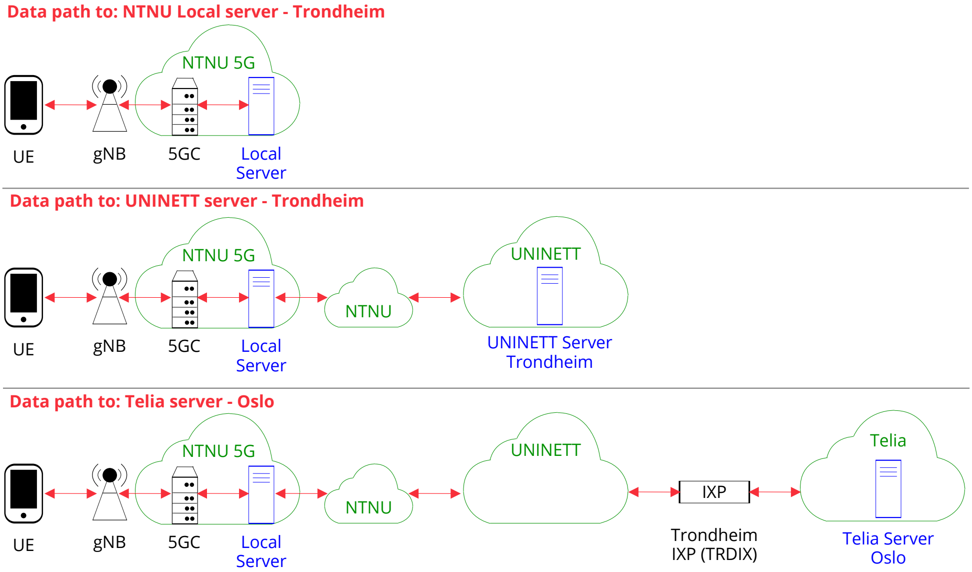

Figure 5.11: Data path to test servers when connected to NTNU's 5G network

Comparing the measurements from UNINETT's server, we see that NTNU's 5G network provided much lower latency than Telia's 5G network when looking at mean and median RTT values. Again, this behaviour is expected partly due to the use of standalone architecture in NTNU's 5G network. Further testing using the traceroute tool revealed that the packets travelled directly from NTNU's 5G network, via NTNU's campus network in Trondheim, to UNINETT's network in Trondheim where the UNINETT server was located. It can therefore be assumed that the propagation delay was minimal.

It can be seen from figure 5.10 that when connected to Telia's 5G network, the average RTT for the UNINETT server located in Trondheim was higher than the average for the Telia server located in Oslo. From table 5.1, the difference in median RTT between the UNINETT and Telia servers is 2.1 ms, and the difference in mean RTT is 3.3 ms. It, therefore, appears that Telia's 5G network was routing traffic destined for UNINETT's server via a longer path than was previously assumed. The Norwegian Internet Exchange (NIX) website states that there is an Internet Exchange Point (IXP) located in Trondheim (TRDIX) and that both UNINETT and Telia are connected to this IXP [44]. With both UNINETT and Telia peering at TRDIX, it would be expected that the average RTT for the UNINETT server should be roughly 5.4 ms less than the RTT for the Telia server, due to the propagation latency between Trondheim and Oslo (as calculated in section 4.3.1). Using the traceroute tool on

Telia's network returned 'request timed out' messages, suggesting that Telia have restricted the use of this tool. It was therefore not possible to determine the data path.

NTNU's local server provided the lowest latency, with a median RTT of 17.7 ms. As the server was located within NTNU's 5G network, it can be assumed that propagation latency was negligible. In addition, with only two hops along the path between the local server and the UE, total router processing latency can be assumed to be less than on the data path to the Telia and UNINETT servers (with 12 and 9 hops respectively).

5.2.3 Telia Network Latency Aggregated by Base Station

Figure 5.12 shows the distribution of RTT values aggregated by base station. All base stations recorded at least one RTT over 100 ms, however, most outlier values were below 100 ms. The minimum number of outlier values recorded by a base station was the Telia 3 base station when testing the UNINETT server which recorded a total of 33 outliers. The maximum number of outlier values recorded by a base station was the Telia 2 base station when testing the Telia server, and the Telia 1 base station when testing the UNINETT server, both of which recorded a total of 41 outliers. The number of outliers per base station per ping server was thus relatively stable, with outliers constituting between 0.83% and 1.03% of total data values.

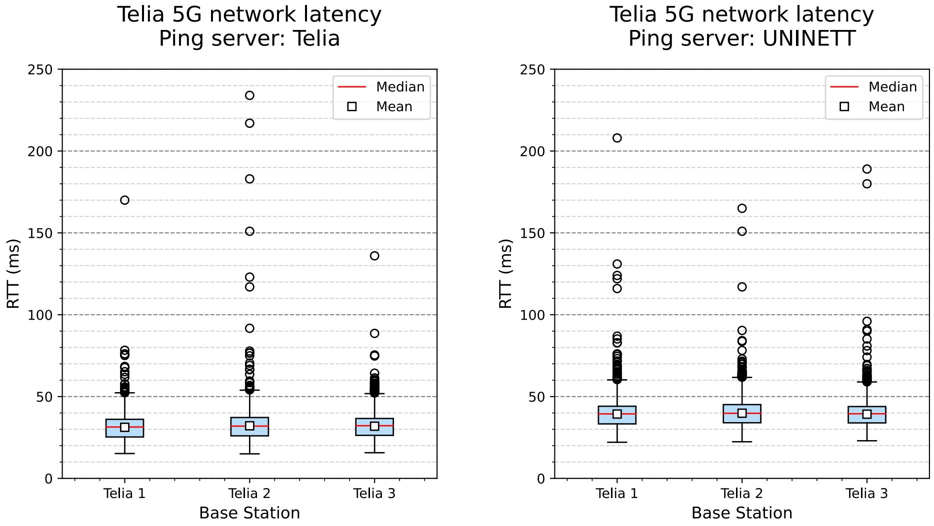

Figure 5.12: Latency measurements for Telia's network separated by base station

Figure 5.13 shows the distribution of RTT values aggregated by base station, except the outlier values which are hidden from view. It can be seen that for both the Telia and UNINETT ping servers, the box plots are similar in size with consistent mean and median values. This indicates that latency was consistent across all Telia base stations.

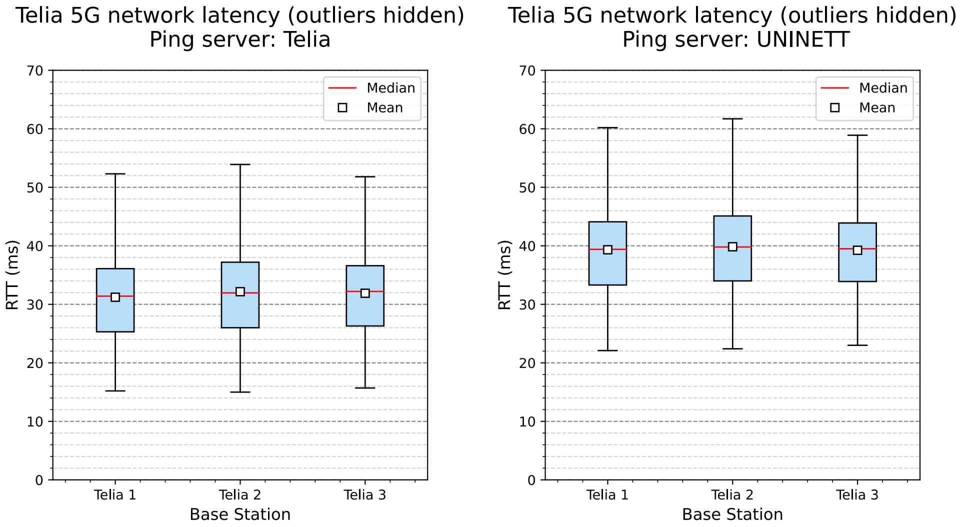

Figure 5.13: Latency measurements for Telia's network separated by base station. Same data as figure 5.12 with outlier data points hidden from view and the y-axis scale adjusted accordingly

5.2.4 Home Broadband Network Test

In addition to the 5G network tests, two further tests were performed from a PC in Trondheim connected to the internet via an Ethernet connection, with Telia as the Internet Service Provider (ISP). The idea of these tests was to determine whether the outliers obtained in the 5G network tests could be attributed to delay within the fixed network or delay caused by the ping servers. The same number of ICMP Echo Request messages as used in the 5G network tests were sent to each server. The result is presented in figure 5.14.

Using the traceroute tool, it was found that traffic destined for the UNINETT server was being routed through the IXP in Trondheim, TRDIX, as was the case for NTNU's 5G network. Figure 5.14 shows that the Telia server records a median RTT of 9.5 ms and the UNINETT server records a median RTT of 2.1 ms. In contrast to the 5G network tests, most outliers were below the minimum point of the box plot rather than above the maximum point. The difference between the minimum and

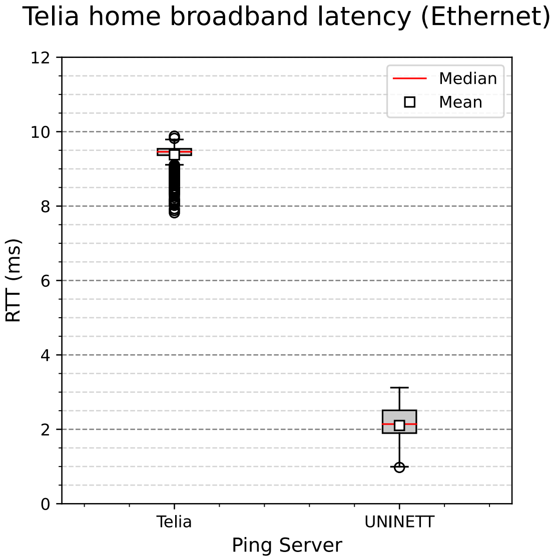

Figure 5.14: Latency measurements for the Telia server in Oslo and the UNINETT server in Trondheim. Measurements obtained from a PC in Trondheim connected to a Telia home broadband service via ethernet

maximum of the box plots in figure 5.14 is 0.7 ms for the Telia server, and 2.1 ms for the UNINETT server. The difference between the minimum and maximum of the box plot when connected to Telia's 5G network was 37.9 ms and 46.8 ms for the Telia server and UNINETT server respectively, and for NTNU's 5G network, the differences were 21.4 ms and 21.9 ms respectively. This data suggests that the delay from the fixed network and ping servers was much smaller and more consistent than the delay from the 5G radio network and that neither the fixed network nor the ping servers were the cause of the outliers seen in figure 5.9.

5.2.5 Speedtest by Ookla Latency Measurements

As previously mentioned, the Speedtest by Ookla app used to record the throughput measurements in the experiment also recorded latency measurements. The only available data the service provided was the average, minimum and maximum latency values. The service did not list individual data points, nor did it state the number of ping messages sent to the target server or the time interval between the messages. For this reason, it was decided to record latency using another method. However, as Ookla latency measurements were obtained along with the throughput measurements, it was decided to compare the two sets of latency data. The Speedtest by Ookla measurements were obtained from the same Telia and UNINETT servers as the measurements from the ping tests. The measurements are presented in figure 5.15.

The box plots represent the data from the ping tests (with outlier values hidden from view), and the Ookla data (mean, maximum and minimum RTT) is overlaid on top in dark blue.

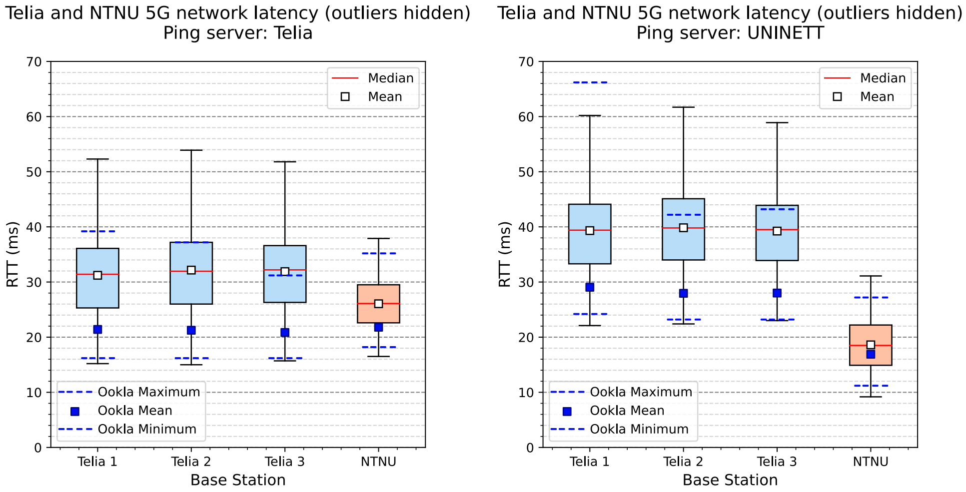

Figure 5.15: Latency data from the Ookla network tests compared to latency data from the ping tests. Outlier data points from the ping tests are hidden from view

For all base stations and both test servers, it can be seen that the mean RTT from Speedtest by Ookla was less than the mean RTT from the ping tests. From figure 5.15 it can be seen that when connected to Telia's 5G network, Ookla returned RTT values of between 10 and 12 ms less than the equivalent values obtained from the ping tests. The minimum RTT values obtained from Ookla were slightly higher than those obtained from the ping tests, however, the maximum values obtained from Ookla were significantly lower in 5 out of 6 of the combinations of Telia base station and ping server. It was not expected that Ookla would report such a large difference in mean RTT compared to the ping tests already performed. It may be the case that Telia allocate Ookla traffic a higher priority in their 5G and fixed network, to provide artificially low latency measurements in comparison to traffic which does not have a high priority, such as ICMP echo request messages. Additionally, the Speedtest by Ookla app is designed for network testing and thus it may be optimised to eliminate as much application latency as possible. There was not any public information available to confirm whether these speculations were true, and at the time of writing, Ookla had not responded to our request for information.

When connected to NTNU's network, the mean RTT values obtained from Ookla were closer to the mean RTT values obtained from the ping tests than when connected to Telia's 5G network. Ookla returned mean RTT values of between 2 and 6 ms less than the equivalent values obtained from the ping tests. This is a decrease from the 10 - 12 ms difference seen on Telia's network and could suggest that Ookla traffic may not be prioritised on NTNU's 5G network and that the difference is only due to a highly optimised app and/or other undisclosed factors.

Chapter 6

Evaluation

In this section, we will evaluate the requirements of the AR/VR for platform maintenance use case presented in chapter 3 with respect to the results from the experimental procedure presented in chapter 5. We consider whether the use case is feasible for today's 5G networks, and we will look into the changes which can be made to enable higher throughput and lower latency in offshore 5G networks.

We first present the key findings from this thesis:

- AR/VR for platform maintenance has varying performance requirements depending upon the required QoE. The highest QoE level requires throughput $\geq$ 1.5 Gbit/s and latency $\leq$ 8 ms.
- Downlink throughput on NTNU's network was much more dependent on the server than it was on Telia's network.
- Base stations within Telia's network exhibit large differences in average downlink throughput.
- Base stations within Telia's network did not exhibit large differences in average uplink throughput. The same applies to the base station in NTNU's network which recorded a constant uplink throughput. This suggests that the NR frame structure was the cause of the bottleneck.
- Average latency was lower on NTNU's SA network than on Telia's NSA network.
- The lowest average latency was achieved when using a local server.
- The range of measured RTT values was much greater on Telia's NSA network than on NTNU's SA network.
- Current 5G networks can support the throughput requirements for the AR/VR use case for a low QoE level. None of the latency requirements were met by either network.

6.1 Augmented and Virtual Reality for Platform Maintenance

Two sets of requirements for this use case were presented in chapter 3. The first set of requirements was defined by GSMA and specifies bandwidth and latency values. The second set was defined by Huawei and specifies bandwidth, latency and packet loss values. The parameters measured in the experiment were only bandwidth and latency. Therefore, packet loss will not be considered in this evaluation. The requirements proposed by Huawei place higher demands on bandwidth and latency than the requirements proposed by GSMA for the equivalent content resolution. For this reason, the evaluation will mostly focus on the requirements proposed by Huawei.

6.1.1 Throughput

The bandwidth requirements proposed by GSMA and Huawei apply to both uplink and downlink directions as explained in section 3.1.4. Due to the throughput from NTNU's 5G SA network being more dependent on the test server than for Telia's 5G network, and the fact that the NTNU base station was only connected with a 1 Gbit/s link, it is not possible to fairly compare the throughput with Telia's 5G NSA network. Therefore, the throughput evaluation will only focus on the results from Telia's 5G network.

Evaluation Against GSMA Requirements

Content resolution (GSMA)	**4K**	**8K**
Bandwidth requirement	50 - 200 Mbit/s	200 - 800 Mbit/s
Downlink supported by NSA?	Yes	Yes
No. tested base stations with average downlink $\geq$ bandwidth requirement	3/3	3/3
Uplink supported by NSA?	Yes	No
No. tested base stations with average uplink $\geq$ bandwidth requirement	3/3	0/3

Table 6.1: Throughput evaluation for AR/VR for platform maintenance. Based on GSMA requirements

Evaluation Against Huawei Requirements

From table 6.2 it can be seen that all Telia base stations met the downlink requirement for the comfortable QoE level. Only one base station met the requirement for the ideal QoE level, with average recorded throughput between **1203 Mbit/s**

QoE level (Huawei)	**Comfortable**	**Ideal**	**Ideal Plus**
Bandwidth requirement	260 Mbit/s	1 Gbit/s	1.5 Gbit/s
Downlink supported by NSA?	Yes	Yes	No
No. tested base stations with average downlink $\geq$ bandwidth requirement	3/3	1/3	0/3
Uplink supported by NSA?	No	No	No
No. tested base stations with average uplink $\geq$ bandwidth requirement	0/3	0/3	0/3

Table 6.2: Throughput evaluation for AR/VR for platform maintenance. Based on Huawei requirements

and **1294 Mbit/s**. The remaining two base stations recorded average downlink throughputs between **826 Mbit/s** and **956 Mbit/s**. None of the tested base stations met the requirement for the ideal plus QoE level.

None of the Telia base stations met the uplink requirement for any of the three QoE levels. The measured average throughput varied between **138 Mbit/s** and **162 Mbit/s**.

6.1.2 Latency

The methodology for evaluation was that for each network (Telia and NTNU) the ping server which produced the lowest median RTT was chosen as the candidate for evaluation. For Telia's NSA 5G network, the lowest median RTT was obtained from the Telia server which was **31.9 ms**. For NTNU's SA 5G network, the lowest median RTT was obtained from the NTNU local server which was **17.7 ms**. Tables 6.3 and 6.4 also present the number of individual ping values measured as less than or equal to the required RTT for each content resolution and QoE level. This data gives an indication of how close the network was to meeting the RTT requirements.

Evaluation Against GSMA Requirements

Content resolution (GSMA)		**4K**	**8K**
RTT requirement		16 ms	10 ms
5G NSA	Supported by 5G NSA? (Based on median RTT from Telia server)	No	No
	Percentage of measured RTT values $\leq$ RTT requirement	1 %	0 %
5G SA	Supported by 5G SA? (Based on median RTT from NTNU server)	No	No
	Percentage of measured RTT values $\leq$ RTT requirement	37 %	1 %

Table 6.3: Latency evaluation for AR/VR for platform maintenance. Based on GSMA requirements

Evaluation Against Huawei Requirements

QoE level (Huawei)		**Comfortable**	**Ideal/ Ideal Plus**
RTT requirement		15 ms	8 ms
5G NSA	Supported by 5G NSA? (Based on median RTT from Telia server)	No	No
	Percentage of measured RTT values $\leq$ RTT requirement	<1 %	0 %
5G SA	Supported by 5G SA? (Based on median RTT from NTNU server)	No	No
	Percentage of measured RTT values $\leq$ RTT requirement	30 %	0 %

Table 6.4: Latency evaluation for AR/VR for platform maintenance. Based on Huawei requirements

From table 6.4 it can be seen that the latency requirements for AR/VR for platform maintenance are not met for any of the three QoE levels by either of the 5G networks tested. The combination of the 5G SA network and the local server returned the lowest latency measurements of the experiment, with a median RTT of **17.7 ms**, falling shy of the 15 ms requirement for the comfortable QoE level of the use case.

In the case that the median RTT did satisfy the latency requirement, it is not certain that this would result in the use case being supported by 5G. This is because it is likely that not all measured RTT values would be less than or equal to the median value. As discussed in section 5.2.2, although the median RTT for NTNU's network with NTNU's local server was 17.7 ms, there was a large variation in measured RTT values from 8.5 ms to 32.2 ms (excluding outliers). If the maximum measured RTT value was 15 ms or less, then it could be concluded that the network supports the latency requirements of AR/VR for platform maintenance.

6.2 Achieving High Throughput Offshore

The experiment was conducted using 5G networks which operate using frequencies in FR1. In section 2.1.1 it was stated that a trial of mmWave 5G (FR2) produced a downlink throughput of 4 Gbit/s in a lab and 2.6 Gbit/s in a 'real-world' implementation. At high mmWave frequencies, the issue of synchronising uplink and downlink transmissions with LTE networks (described in section 5.1.2) would not exist. Mobile network operators should therefore have greater freedom in configuring a more flexible NR frame structure consisting of a more even balance of uplink and downlink slots. It would therefore be expected that mmWave 5G could support the bandwidth requirements for all three QoE levels for both downlink and uplink.

Offshore mobile networks have their own frequency allocation, with five frequency bands currently assigned to offshore use by NKOM [40]. The allocation of the offshore frequency spectrum is independent of the allocation of the onshore frequency spectrum. The frequency bands licensed for use offshore are 700 MHz, 800 MHz, 900 MHz, 1800 MHz and 2100 MHz [40]. These frequencies are lower than the 3700 MHz band used in the Telia and NTNU onshore networks.

As specified in table 2.1, the maximum channel bandwidth for 5G frequencies under 7.125 GHz (FR1) is 100 MHz. For frequencies above 24.25 GHz the maximum channel bandwidth is 400 MHz, and for those above 52.6 GHz, the maximum channel bandwidth is 2 GHz. To achieve the required throughput for AR/VR for platform maintenance, NKOM must first permit and license higher mmWave frequencies to be used offshore. This will mean that larger channel bandwidths can be used which can be expected to result in a higher throughput. The use of high-band frequencies will also allow the 5G network to allocate individual users a greater bandwidth, thanks to more spectrum being available at high-frequency ranges. At the time of writing, NKOM expect licenses for the 26 GHz band to be allocated at the end of 2023 [41]. Additionally, the 42 GHz band is also under consideration for allocation for mobile networks in the coming years [42].

While mobile network operators should consider using mmWave bands to achieve very high throughput at close range, the coverage area of high-band signals is limited in comparison to mid and low-band signals due to higher atmospheric absorption, scattering and fading effects. This is illustrated in figure 6.1. Additionally, high-band signals experience high penetration loss due to their small wavelengths in comparison to the diameter of objects in the environment [5]. It may not be feasible to have a line-of-sight connection to a base station in all areas of an offshore platform due to the presence of buildings and other structures. Therefore, radio signals will be required to penetrate through objects in some cases. Offshore network operators may wish to supplement the network with low or mid-band frequencies, which can penetrate through objects better than high-band frequencies, in order to provide all-platform coverage.

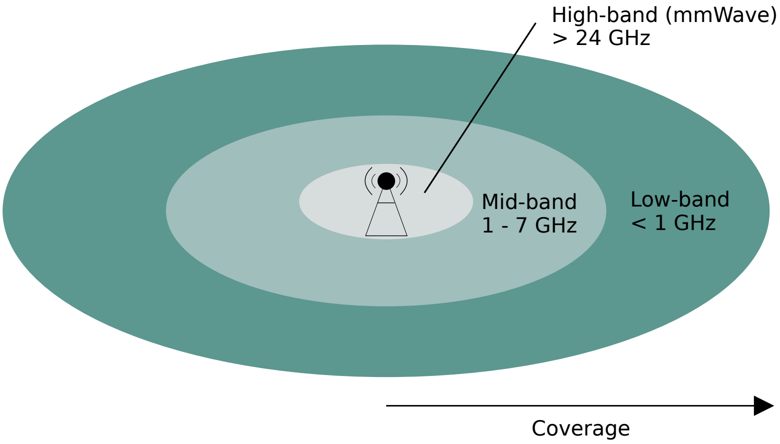

Figure 6.1: 5G frequency band categorisation

A key change which will allow mobile network operators to fully make use of the flexible frame structure in 5G is that NKOM have permitted the use of local mobile networks in the 3.8 - 4.2 GHz band [43]. This will allow industry and companies to deploy their own 5G networks in a specific geographic area. NKOM state that this will enable networks to be configured with a different downlink-uplink relationship than that of current nationwide 5G networks. Thus, companies would be free to configure the NR frame structure to have as many uplink slots as downlink slots, and thus remove the bias towards downlink as was seen in the experimental data and explained in section 5.1.2.

6.3 Achieving Low Latency Offshore

Results from the experimental phase showed that the lowest latency was achieved when using a 5G SA network and a local server. To achieve low latency offshore, edge servers should be located on the offshore platform in order to reduce propagation latency as much as possible. In section 3.1.5, it was calculated that using an onshore server could add 2.1 ms of propagation latency compared to using a server located on the platform itself.

With NKOM permitting localised 5G networks as described in section 6.2, operators should consider optimising the NR frame structure for ultra-low latency communications. For example, the correct selection of transmission numerology for a certain traffic pattern can contribute to reduced latency [46].

Chapter 7

Conclusion

This thesis provided an introduction to the design goals of 5G and the key changes in the specifications which aim to achieve these goals. We have studied three generic usage scenarios for 5G and have identified a key use case with strict requirements on bandwidth and latency - AR/VR for platform maintenance. An in-depth analysis of this use case was undertaken which resulted in a series of performance requirements. There was not a single set of performance requirements which once met, would enable the use case. Instead, varying QoE levels were identified each with its own set of requirements.

We conducted an experiment using two different 5G networks to determine the performance metrics of current and future 5G networks. Furthermore, we evaluated the results of the experiment with respect to the requirements of the AR/VR use case to determine whether 5G could support this use case.

Results from the experiment showed that Telia's NSA 5G network provided higher uplink and downlink throughput than NTNU's SA 5G network. This result does not reflect a comparison between SA and NSA 5G networks due to the difference in link capacity connecting the respective base stations, with NTNU's base station using only a 1 Gbit/s link. We have shown that end-to-end latency was lower on a standalone 5G network than on a non-standalone network. We have also seen that the lowest latency recorded in the experiment occurred when an edge server was the target of the ICMP echo requests.

In conclusion, the results from the experiment show that 5G can meet the bandwidth requirements for one of the lower QoE levels of AR/VR for platform maintenance, but that it falls short of meeting the requirements for the highest QoE level. Additionally, the results show that neither the standalone nor non-standalone 5G network could meet the latency requirements for any of the QoE levels for the AR/VR for platform maintenance use case.

7.1 Future Work

There are multiple avenues for future work related to this thesis. The first would be to perform an in-depth analysis of more use cases considering that AR/VR for platform maintenance is a use case with the strictest performance requirements. It may be of interest to explore use cases related to industries other than oil and gas, for example, offshore energy, shipping or fisheries which may have different performance requirements. To support this work, experiments could be performed to measure the performance of 5G at distances greater than 130m.

The experiment performed in this thesis is limited in that it represents the performance of onshore 5G networks as of today. With NKOM expecting to allocate licenses for the 26 GHz 5G band by the end of the year, there will be a possibility to repeat the experiment once 5G networks and UEs support these higher frequencies. mmWave was one of the key changes in the 5G specifications, acting as an enabler for eMBB use cases. It would therefore be of great interest to determine the performance of mmWave 5G with respect to the AR/VR use case.

One key performance metric not measured in the experiment was packet loss. The packet loss requirement for the highest QoE level of the AR/VR use case was 1e-6. To reliably test whether 5G meets this requirement would have required sending millions of packets in one long uninterrupted data stream. The fact that it was only possible to maintain a 130m distance to outdoor base stations meant that it was not possible for the UE to remain continuously connected whilst keeping safe from the weather and holding enough power to remain switched on for a long duration of time. A specialist setup could achieve this and would thus be able to test the packet loss performance metric.

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