Research Project and Seminar

Information and Communication Systems

Performance Evaluation of the Handover Enabled 5G Communication System

by

Azeem Abrar Khan

November 2022

Supervised by

Shashini Thamarasie Wanniarachchi
Institute of Telematics, Hamburg University of Technology

First Examiner | Prof. Dr. Volker Turau
Institute of Telematics
Hamburg University of Technology

Institute of Telematics
Hamburg University of Technology

Table of Contents

TABLE OF CONTENTS

chap/tuhhchap-chapter

Chapter 1

Introduction

The institute of telematics at the Hamburg University of Technology is working on a collaborative project ULTRAS and developing a simulation framework to provide an overall system solution for Urban Air Mobility. Many companies are working on aerial vehicles, which can either be autonomous or pilot controlled, thus creating a need for such a simulation framework. The ULTRAS simulation framework is built on OMNeT++ and uses INET, which provides basic communication protocols, as an external library.

This research project aims to use another external library with the name of "Simu5G" with ULTRAS simulation framework to develop and measure the performance of the 5G new radio (NR) network. A simple network having four base stations, a ground station and multiple user equipment acting as air taxis is modelled first on OMNeT++ then the results are analysed in MATLAB. The user equipment can switch between the base stations as they move throughout the network. The switching between the base stations is known as handover.

Efforts have been made in the past to do the performance evaluation of a 5G network, but they did not consider an aerial vehicle as user equipment, which could fly at high speeds having different altitudes, and did not provide analysis on a broad range of parameters. As an example, [2] only discusses latency. The criteria to evaluate the performance of the above-mentioned network is to measure latency, data delivery ratio, handover success rate and the total amount of data being exchanged between the network nodes when they send GPS coordinates, images or videos, representing different data sizes. The number of air taxis is also varied to observe its effect on the results.

The report is divided into five chapters and is structured as follows. The second chapter describes the working of a 5G network, its architectures, and types of handovers. The simulation setup is described in the third chapter, with a description of every component used in the simulation model. The fourth chapter is based on the performance evaluation, where parameters are compared with each other in different use cases. The fifth chapter concludes the report and provides possible future extensions.

chap/tuhhchap-chapter

Chapter 2

Overview of 5G

A 5G system not only provides high data rates and low latency but also enables cellular networks for innovations such as the internet of things and mission-critical applications. The 5G devices can either be human-controlled or autonomous. The requirements of 5G can be divided into the following three classes.

- The first aim can be to support the internet of things and service densely distributed devices of low complexity and energy.
- The second one can be to use for mission-critical applications, which requires low latency and high availability and mobility.
- To be able to provide high speed internet.

2.1 Main Components

There are two major subsystems of the 5G cellular access network, the Radio Access Network (RAN) and the Mobile Core, as shown in Figure 2.1.

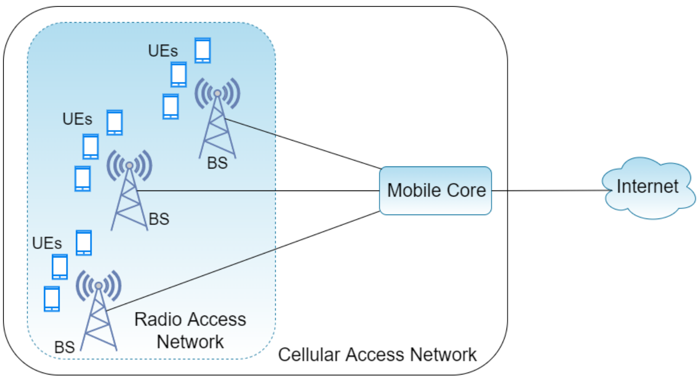

Figure 2.1: Main components of cellular access network

1

2.1.1 Mobile Core

The mobile core is named as next-generation core (NG-Core) specifically in 5G by 3GPP. It is a collection of functionality having multiple purposes such as: providing internet for different user services (voice and data) while ensuring that the overall system fulfils the QoS requirement. It also tracks the real-time movement of user equipment to provide uninterrupted service. It also collects network usage statistics for billing purposes. The core acts as a bridge between RAN and the data network (internet). The core can be divided into separate user and control planes (Core-UP and Core-CP), as shown in Figure 2.2, for better visualization and understanding of the data flow. [1]

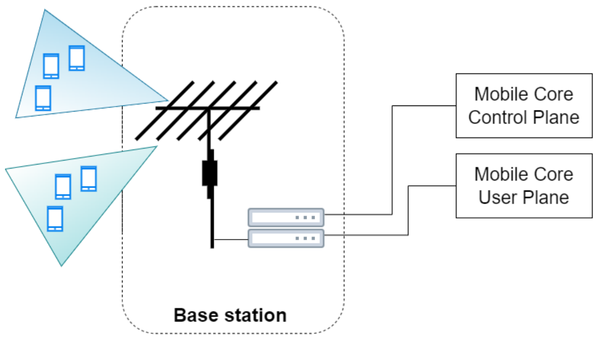

Figure 2.2: Control and user plane of the mobile core

2

3GPP specification standardizes a set of functional blocks for the NG-Core. The functional block running inside the user plane of the NG-Core and is relevant for this research work is known as User Plane Function (UPF). [1]

UPF can be considered as a combination of Packet Gateway (PGW) and Serving Gateway (SGW), which are functional blocks of the 4G Core. PGW is an IP router, responsible for connecting the mobile core to the internet, whereas, SGW connects potential mobile UEs to the mobile core and also involves in the handover procedure. Furthermore, UPF is also responsible for reporting the usage and implementing policies for QoS. [1]

2.1.2 Radio Access Network

The RAN meets the quality of service (QoS) and ensures that the radio spectrum is used in the most efficient way possible. It consists of a collection of base stations, which are called

[1] The inspiration for Figure 2.1 is taken from [1]
[2] The inspiration for Figure 2.2 is taken from [1]

gNBs (g stands for "next Generation") according to the 3GPP standard. A base station has two sub-components, an antenna as an analogue component and a pair of processors acting as a digital component [1]. The illustration can be seen in Figure 2.2.

A base station first establishes a wireless channel to provide a bearer service for every user equipment that is either power-up or comes in contact because of handover. This channel works as a bi-directional link for the user and control data between the user and the base station. When the bearer service is established, the base station connects the user equipment to the corresponding control plane of the mobile core, allowing both entities to exchange control messages. These messages are used by the mobile core to authenticate, register and track the mobility of the user equipment. After that, one or more tunnels are opened by the base station between Core-UP and the user equipment to exchange user data. The base station routes user and control plane packets between these two using GTP/UDP/IP and SCTP/IP protocols, respectively. SCTP stands for Stream Control Transport Protocol and it is a more reliable alternative to TCP to transmit control information. Whereas, GTP, a nested acronym, stands for General Packet Radio Service Tunneling Protocol. It runs over User Datagram Protocol (UDP) protocol and is used to tunnel user data. Base stations also coordinate with each other through direct links, which are implemented as an X2 interface, to process handover whenever user equipment exits the communication range of one base station and enters the coverage area of an adjacent base station. [1]

2.2 Security and Registration

In this section the security architecture and the steps taken by the user equipment to connect to the mobile core are discussed. The security architecture is based on the following two trust assumptions.

- The network used to establish tunnels, SCTP tunnels from base stations to the Core-CP and GTP tunnels to and from base stations to the Core-UP, is secure and private.
- Telecommunication operator provides UE a unique identification number. The provided number can be used to identify the subscriber uniquely, thus establishing the radio parameters required for communication within the network.

The connection sequence of user equipment can be seen in Figure 2.3. When a user's equipment is powered-on or becomes active, it establishes a temporary unauthenticated link with a nearby base station, enumerated as 1. The subscriber's request is then forwarded to the Core-CP over the existing SCTP tunnel to start the authentication protocol represented as 2. After the authentication process, when both entities (Core-CP and UE) are satisfied with the identity of one another, the Core-CP instructs and passes on the parameters, which are required to service the UE, to other components of the network in step 3. The sub-steps of step 3 are: (a) instructing the Core-UP, which in turn sets the QoS class identifier (QCI) parameter and assigns an IP address to the user equipment; (b) create an encrypted link with the UE by sending instructions to the base station; (c) providing the UE with a symmetric key, which can be used to decrypt the encrypted channel. Core-CP uses the UE's public key to encrypt the symmetric key, so it can only be decrypted by the UE with the help of its secret key. The end-to-end channel between the UE and the Core-UP is setup in step 4. [1] [5]

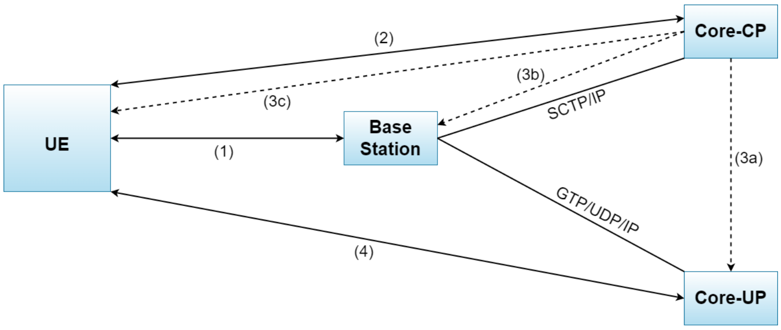

Figure 2.3: Sequence of steps taken by a user equipment to form channels

3

It is to be noted that the secure link established in step 2 remains active throughout the session. It is used to exchange control messages throughout the length of the session. The user plane link resulting in step 4 is known as Default Bearer Service. However, more channels can be formed between the Core-UP and the UE having different QCI values, which might be dependent on the application in use. The core can perform Deep Packet Inspection (DPI) on the ongoing traffic to identify flows requiring better QoS, thus opening new user plane channels between the UE and the Core-UP. [1] [5]

2.3 Handover

As mentioned before, 5G architecture also supports the mobility of user equipment through a handover procedure. Cellular network handovers can be divided into inter-system and intra-system handovers. An inter-system handover involves handing over the user equipment to the network implementing a different standard, such as handing over a device from a 5G to an LTE network. On the other hand, intra-system handover is performed when both the source and target base stations have the same Radio Access Technology (RAT). As the simulation model for this project is purely based on 5G technology, only intra-system handovers are discussed. [3] [5]

[3] The inspiration for Figure 2.3 is taken from [1]

As user equipment and RANs are not part of the 5G core, they do not communicate directly with the core instead, they are connected with secure network interfaces with the core as shown in Figure 2.4. As mentioned earlier, the X2 interface is used to connect two base stations. UE and base stations are connected via N1 and N2 interfaces, respectively. [3] [5]

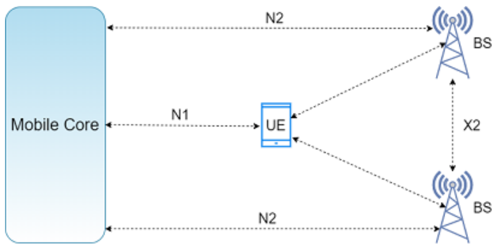

Figure 2.4: Network interfaces of a 5G network

4

In the case of intra-system handovers, the source base station can choose from a set of two handover protocols. The handover can either be performed directly through the X2 interface if it is present or via the N2 interface through the core when there is no direct link between the two involved base stations or in the case of failure through the X2 interface. In the case of X2-based handover, messages are shared directly between the base stations, resulting in a fewer number of messages sent to the core network, which is not true in the case of N2-based handover because of the unavailability of a direct link between the base stations. In the simulation model, all base stations are directly connected, therefore, X2-based handovers are used for this project. [3] [5]

Handover involves one or more steps shown in Figure 2.3. The unauthenticated link represented by 1 enables the UE to identify all base stations in its communication range. UEs report the signal's channel quality index (CQI), a value representing the performance of the channel, to the connected base station. The source network then communicates with the target base station, which has the highest CQI, to initiate the handover procedure. If the target base station is willing to accept the handover request, it sends an acknowledgement message. The request is then passed to the Core-UP, which again executes the steps indicated by 3 in Figure 2.3. Step 3 results in the rebuilding of the user plane channels between the UE and the Core-UP through the new base station. Mobile Core-UP also buffers the packet during the process of handover to avoid dropped packets and retransmissions. [3] [5]

The handover procedure can only provide uninterrupted communication without breaking the session when both the source and target base stations are served by the same mobile core. This means that whenever a user equipment moves between metro zones implemented by different mobile cores, the movement can be distinguishable from powering on the user

[4] The inspiration for Figure 2.4 is taken from [5]

equipment. The new mobile core will perceive it as a new device and assigns a new IP address, resulting in loss of the in-flight data. [3] [5]

2.4 Deployment Options

As the combination of 4G's core known as Evolved Packet Core (EPC) and 4G RAN is already deployed in almost all of the cellular networks, 5G technology must be deployed alongside the existing 4G system during the initial period to make a smooth transition. For that reason, 3GPP has proposed two strategies named non-standalone and standalone deployments as shown in Figure 2.5. [1] [5]

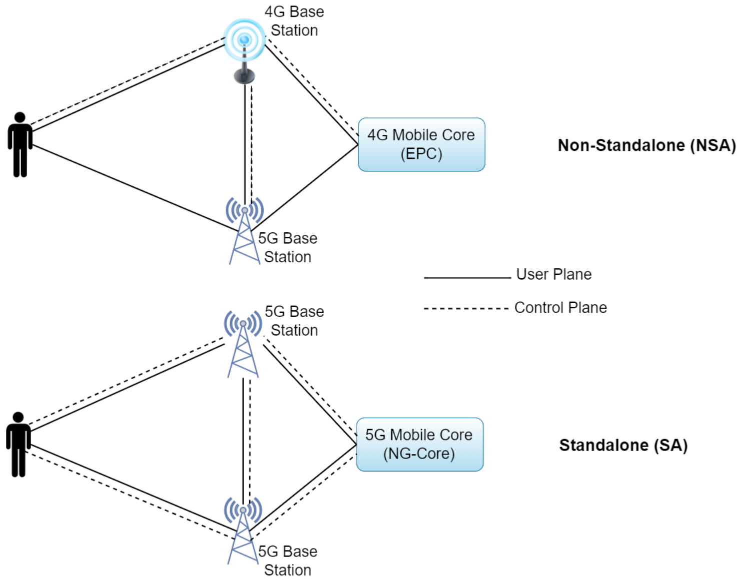

Figure 2.5: Non-standalone and standalone deployments for 5G

5

The non-standalone deployment contains both eNBs (4G base stations), working as master nodes and gNBs, working as secondary nodes. Only eNBs are connected to the mobile core, which is the implementation of EPC in this case. LTE packets pass directly through the eNBs, whereas 5G traffic first goes through the eNBs and then to the gNBs via X2 interfaces between the base stations. [1] [5]

It is expected that the EPC and eNBs will not be required eventually when the 5G system will be fully deployed, including the NG-Core connecting all gNBs. This results in a new deployment scheme known as standalone deployment.

A standalone deployment option is used for the simulation model in this project.

[5] The inspiration for Figure 2.5 is taken from [1]

chap/tuhhchap-chapter

Chapter 3

Modeling and Implementation

3.1 Simulation Model

OMNeT++ v5.6.2 along with INET v4.2.2 and Simu5G v1.1.0 libraries are used with the ULTRAS framework in this project to model and simulate the network.

3.1.1 Network Setup

The network can be seen in Figure 3.1. It contains modules from the two libraries mentioned above and the ULTRAS framework. gNB nodes and UPF are implemented in Simu5g. ULTRAS provides a ground station, agents and the flight schedule manager, whereas, the router is an INET module.

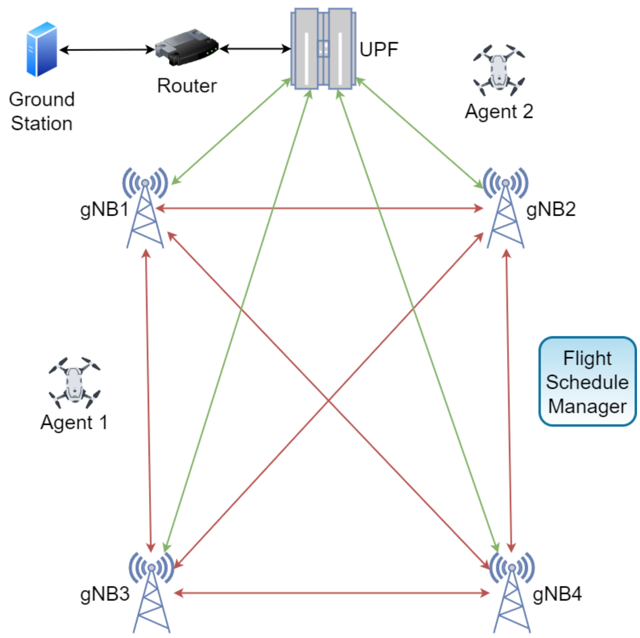

Figure 3.1: Network model

All four gNBs are connected to a UPF node, which acts as the data plane function of the mobile core, with high-capacity bidirectional Ethernet links (represented as green arrows). gNBs are also connected through X2 interfaces (represented as red arrows). UPF is connected to the ground station through a router.

Flight Schedule Manager is one of the most important modules implemented in the ULTRAS framework. It spawns user agents (air taxis), as shown in Figure 3.1, within the specified network area and passes on parameter values during the initialization of agents to manipulate their behaviour. It can either start spawning the user agents as soon as the simulation starts or only in a particular period of the day. The number of agents depends on the 24h clock time. It also provides complete information regarding the path, which needs to be followed by the agent with varying speeds and altitudes. Moreover, it also deletes the user agents on the completion of their path.

An agent is an extension of the Simu5G module named NrUe, which can act as 5g-enabled user equipment. Agents used in this project contain a GPS sensor and a camera module. The camera module can not capture images as this is a simulation framework and can only be used to represent some predefined images.

3.1.2 NR Resource Management

The length of an NR radio frame is 10ms and it consists of 10 sub-frames. One sub-frame is equal to 1 ms. These sub-frames can be divided into many time slots, known as Transmission Time Intervals (TTI). A numerology index specifies the length of TTI. Every gNB performs resource scheduling periodically by allocating resource blocks to connected UEs per TTI, based on the scheduling policy. The number of resource blocks required to transmit the transport block depends on the modulation and coding scheme used for transmission. The base station changes the modulation and coding scheme based on the CQI value. The base station sends the transport block to the scheduled UE using the allocated resource blocks in the downlink (DL), whereas, in the uplink (UL), the base station specifies which resource blocks, coding and modulation scheme should be used by sending transmission grants. DL and UL resources can either be divided in time or frequency, leading to Time Division Duplex (TDD) and Frequency Division Duplex (FDD). The DL and UL alternate with time while sharing a common spectrum, while the two shares the same spectrum in the case of FDD. [5]

More than one carrier component (CCs) can be used at the same time for NR communication. Every CC has a defined number of resource blocks and carrier frequency. Simu5G provides a module named "CarrierAggregation" to support the carrier aggregation functionality of 5G, in which a gNB can have multiple CCs. The module stores the information about CCs used in the network and contains a number of sub-modules named "ComponentCarrier". The configurable parameters of this sub-module are carrier frequency, the number of resource blocks and the numerology index. It also has a flag to either enable TDD or FDD. [5]

Only one CC, operating on FDD, is used in this project having default values of 2GHz and 0 for carrier frequency and numerology index, respectively. The number of resource blocks is set to 25. The zero value of the numerology index defines that there is only one TTI per NR sub-frame with a length of 1 ms.

3.1.3 NR Protocol Stack

NrUe and gNB modules of the Simu5G library implement UE and gNB of the 5G network with NR capabilities. An agent contains IP UDP/TCP protocol layers along with a vector of UDP/TCP applications. The NR protocol stack of UE is provided by its Network Interface Card (NIC), known as NrNicUe and can be seen in Figure 3.2 (a).

A gNB module has protocols up to the IP layer and two network interfaces. The first one implements NR and is known as NrNicGb as shown in Figure 3.2 (a), whereas, the second one is used for point-to-point communication with the mobile core.

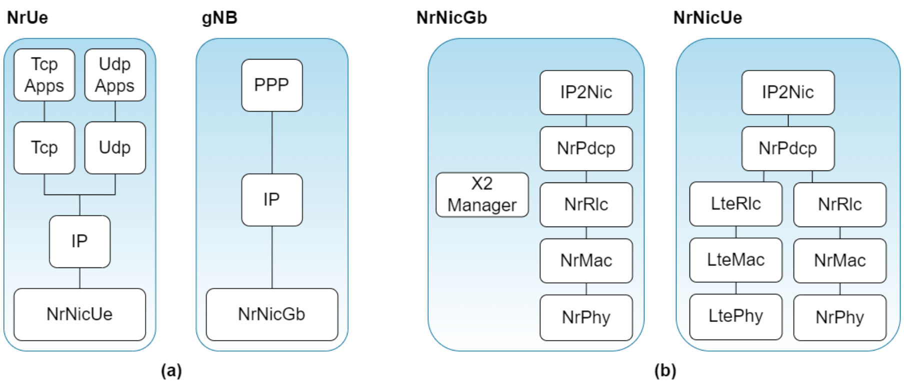

Figure 3.2: NrUe and gNB modules of Simu5G and their NICs

[1]

NR protocol stack has three sub-protocol layers named Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC). NICs in Simu5G are compound modules consisting of one sub-module per protocol of the NR protocol stack.

Simu5G supports both deployment options discussed in Section 2.4. NrNicUe contains two instances of Physical (PHY), MAC and RLC layers prefixed by LTE or NR to support dual connectivity as shown in Figure 3.2 (b). The LTE versions of these layers service eNBs in the network if present. However, the NR versions are used to send or receive data to/from the gNBs. NrNicUe only has one PDCP layer to ensure the in-order reception of the packets. [3]

[1]The inspiration for Figure 3.2 is taken from [3]

On the other hand, NrNicGb contains a single instance of NR protocol stack along with X2 manager as shown in Figure 3.2 (b), which is responsible for handovers. Both NrNicUe and NrNicGb also contain a module named Ip2Nic acting as a bridge between the NR protocol stack and the IP layer. [3]

On the transmission path, the PDCP protocol layer provides encryption to the IP datagrams. It also compresses the header and attaches a connection identifier (CID) to packets. The resulting Protocol Data Units (PDUs) are sent to the lower RLC layer. On the receiving path, it decapsulates the PDUs coming from the RLC layer and sent them to the IP layer. [3]

The RLC layer can be configured in three modes: Acknowledged Mode (AM), Unacknowledged Mode (UM) and Transparent Mode (TM). AM and UM have reception and transmission buffers. RLC PDUs on the transmission path are stored in transmission buffers which are then fetched by the MAC layer when required. On the other hand, the layer uses a reception buffer until RLC PDUs are reassembled into a PDCP PDU, which can then be sent to the PDCP layer. TM mode does not use any buffers and sends the RLC PDUs transparently to the MAC layer. [3]

On every TTI, the MAC layer assigns different numerology indexes to CCs, resulting in different TTI duration. In this way, a gNB has an independent scheduler for every CC. [3]

3.1.4 Additional Network Description

To get a high number of agents, the flight schedule manager is instructed to only spawn agents from 7:00 AM (25,200 seconds from 0 AM) until 9:02 AM (32,500 seconds from 0 AM). Therefore, the total simulation time is set to 33000 seconds with a warm-up period of 25150 seconds to exclude the result values before the time when the first agent is spawned in the network. There are 10 repetitions per simulation use case (discussed later in Section 3.2). An overall view of the network parameters is shown in Table 3.1.

	Parameter value
Simulation time	33000 seconds
Warm-up period	25150 seconds
Loader input file	toolInput.xml (used by flight schedule manager for predefined trajectories)
Agent Module Type	ultras.src.modules.agents.NRAgent (extension of NRUe Simu5G module)
Flight schedule manager - start at zero	false
Flight schedule manager - start time	25200 seconds
Flight schedule manager - stop time	32500 seconds
Channel model - shadowing	true
Channel model - fading	true
Network area	800m x 800m x 800m
gNBs - number of x2 apps	3 (one for every other gNB)
gNBs - server local port	5000 + ancestorIndex(1)
Number of carrier components	1
Carrier frequency	2 GHz
Numerology Index	0 (one TTI of 1ms per sub-frame)
Operation Mode	FDD
Ground station - number of apps	1
Ground station - app type	GSReceiverApp
Ground station - local port	3000
UE - app type	GSSenderApp (Implemented in NRAgent.ned)
UE - destination address	GroundStation (passed by flight schedule manager)
UE - local port	3088 (passed by flight schedule manager)
UE - app start time	uniform(0s, 0.02s) (passed by flight schedule manager)
UE - period	variable, depending on the use case (passed by flight schedule manager)
UE - send images	true or false, depending on the use case (passed by flight schedule manager)
UE - send videos	true or false, depending on the use case (passed by flight schedule manager)
UE - video length	variable, depending on the use case (passed by flight schedule manager)
UE - frames per second	variable, depending on the use case (passed by flight schedule manager)

Table 3.1: Parameter values

3.2 Use Cases

The main objective of the project is to simulate the network for different data types, which are coordinates, images and videos. The data types affect the number of packets needed for the transmission as more packets are needed to be transmitted in the case of a video than in the case of an image or only coordinates. Data can either be sent at high (short period) or low frequency (long period), thus producing more use cases. In the case of video, the number of frames per second (fps) and video length can also be varied one by one to observe their effects.

S.No.	Use case name	Period	Fps	Video Length
1	Coordinates - Slow	uniform(5s,6s)	-	-
2	Coordinates - Fast	uniform(0s,0.04s)	-	-
3	Images - Slow	uniform(5s,6s)	-	-
4	Images - Fast	uniform(1s,2s)	-	-
5	15fps, 5secs Video - Slow	uniform(18s,20s)	15	5s
6	15fps, 5secs Video - Fast	uniform(7s,8s)	15	5s
7	15fps, 10secs Video - Slow	uniform(18s,20s)	15	10s
8	15fps, 10secs Video - Fast	uniform(7s,8s)	15	10s
9	30fps, 5secs Video - Slow	uniform(18s,20s)	30	5s
10	30fps, 5secs Video - Fast	uniform(7s,8s)	30	5s
11	30fps, 10secs Video - Slow	uniform(18s,20s)	30	10s
12	30fps, 10secs Video - Fast	uniform(7s,8s)	30	10s

Table 3.2: Use cases

All the implemented use cases are listed in Table 3.2.

The period always has the unit of seconds and is distributed uniformly between two numeric values. It represents the time interval between two consecutive images or videos. The small period of uniform(0s,0.04s) for use case 2 is efficient for real-time tracking of the UE. Sending images every one to two seconds in use case 4 is sufficient as a period value lower than one second between the two images (frames) is common for a video.

3.3 Application Layer

A gNB requires one x2 app for every connected base station to communicate via the x2 interface. In this project, every base station has three x2 apps. The app is responsible to carry out handover requests to and from the handover manager, which is a sub-module of gNB. The handover manager has also been made capable to record the total and the successful number of handover requests.

An agent transmits its current location through GPS coordinates in use cases 1 and 2. Every agent has a sub-module named "localSituationPicture", which keeps track of the agent's location at any point in time. The location data is very small and can be enclosed in a single packet with a total size of 40 bytes. For the use cases of images, a sub-module is developed for agents with the name "Images". This sub-module contains some predefined drone images encoded in base64 format. The encoding converts data into ASCII text format, which can be stored as a string. The size for every image is between 51,200 bytes and 56,320 bytes. As the maximum size for a UDP datagram can be of size 65,507 bytes, only one packet is needed to be transmitted for every image. In other words, the number of packets sent or received

Use case name	Fps	Video Length	Packets (Fps x Video Length)	Frame's period
15fps, 5secs Video	15	5s	75	66.6 ms
15fps, 10secs Video	15	10s	150	66.6 ms
30fps, 5secs Video	30	5s	150	33.3 ms
30fps, 10secs Video	30	10s	300	33.3 ms

Table 3.3: Number of packets per video and frame's period

throughout the simulation time represents the number of images sent by the agent or received by the ground station. The app running on agents gets an encoded image from the "Images" sub-module at random and sets it as a payload for the new outgoing packet towards the ground station. In the case of sending videos, It is assumed that a single frame of a video is always of size 51,200 bytes and can be enclosed in a packet. Therefore, the total number of frames of a video gives the number of packets needed to represent that particular video. It is also assumed that agents send live videos of their surroundings at uniformly distributed intervals, therefore, a frame (packet) must be sent at a constant interval, which is equal to the time between two consecutive frames and can be calculated by taking the reciprocal of the video's fps. Table 3.3 shows the total number of packets needed for a video and the interval between the frames for every video use case of Table 3.2. It is clear from the table that an increase in video length, while keeping the fps constant, only affects the number of packets, whereas, an increase in fps results in an increased number of packets but a decrease in the frame's period.

The app at the ground station receives packets from agents via gNBs and also records the latency for every packet as a vector. The latency represents the time taken by the packet to reach its destination. The app also calculates the average latency on every reception using the following equation.

$$latency = \frac{latency(numReceived - 1) + currentLatency}{numReceived}$$

where
latency = average latency
currentLatency = latency of the received packet
numReceived = number of received packets

Performance Evaluation

In this section, the use cases are also referenced with their serial numbers mentioned in Table 3.2. As the flight schedule manager only spawns agents from 25,200s to 32,500s, there are no results before 25,200s. Therefore, all vectors in this section have an offset of 25,000s.

4.0.1 Number of Packets

The average numbers of packets sent by agents and received by the ground station are plotted in Figure 4.1. The bar plot for use case 2 can not be visualized together with the small values of use can 1 and 3, therefore, it is plotted separately.

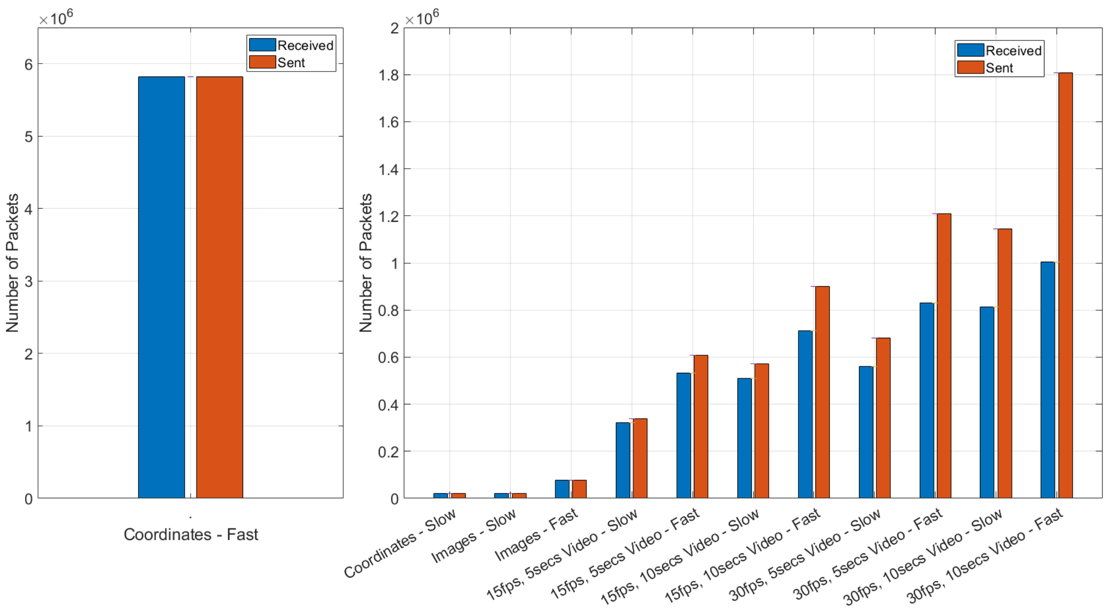

Figure 4.1: Bar plot of the number of packets sent and received

The use cases of sending coordinates and images at a lower rate have the same least number of sent and received packets because both cases use the same period and a coordinate pair or an image only requires one packet to be sent as already mentioned earlier, whereas, sending coordinates at a higher rate yields the maximum number of packets sent and received because of small interval for real-time tracking of the agent. Use cases mentioned with the word 'fast' always have a greater number of packets than 'slow' use cases. In the case of videos, the numbers also increase if either fps or video length increases as more packets are required to represent the data. The numbers of sent and received packets are almost the same in the case of coordinates and images, whereas, the difference between the two increases with the increase of the number of packets in the case of videos.

4.0.2 Number of Bytes

Figure 4.2 shows the number of cumulative bytes sent by the agents and bytes received by the ground station. The graph almost follows the same pattern as in Figure 4.1 with up-scaled values. The up-scaling factor is the packet size in bytes. Although the use case of sending coordinates at a high rate results in the maximum number of packets, it yields the lowest number of bytes as compared to the use cases of images and videos because of the small packet size of only 40 bytes. As the number of bytes sent increases from use case 1 to 12, the difference between the bytes sent and received also increases as the large number of bytes sent causes congestion in the network, which leads to more packets getting dropped. The maximum number of bytes sent and received are 9.26x10^{10} bytes (92.6 GB) and 5.14x10^{10} bytes (51.4 GB), respectively in the last use case 12.

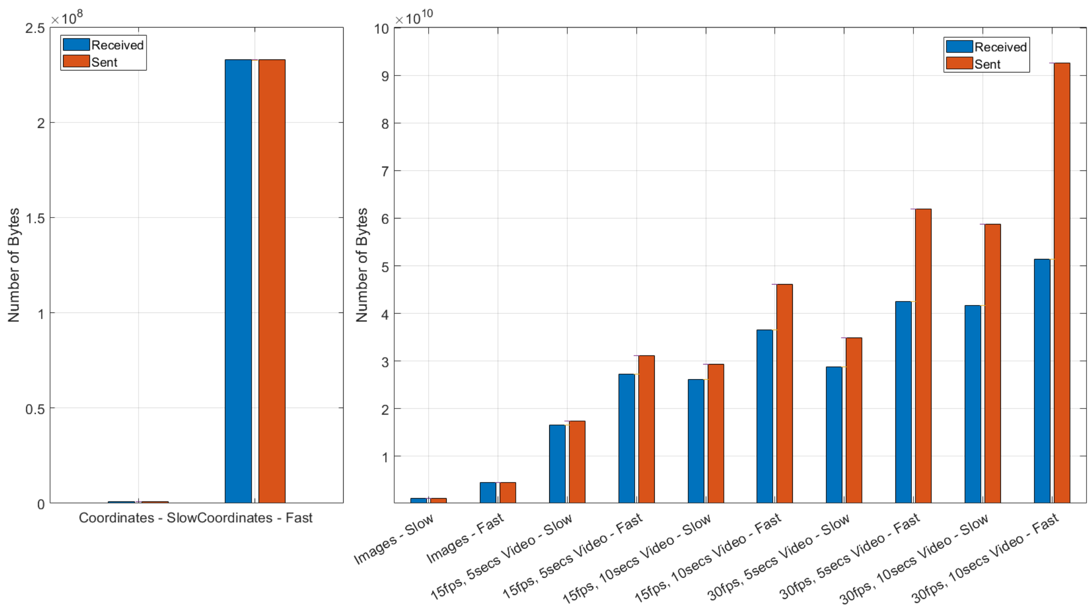

Figure 4.2: Bar plot of the number of bytes sent and received

4.0.3 Packet Delivery Ratio

The packet delivery ratio measures the performance of the network to deliver packets.

$$packetDeliveryRatio = \frac{totalNumberOfPacketsReceived}{totalNumberOfPacketsSent}$$

The packet delivery ratio for all the use cases can be seen in Figure 4.3. The ratio is almost equal to one in use cases associated with coordinates and images because the packet size is small in the case of coordinates and the time interval in the case of images is not that small to congest the network. In the case of videos, if we either increase fps or the video's length in such a way that the total number of packets needed to represent a video remains constant then we get a better packet delivery ratio when we only increase the video's length as compared to the use case in which only fps are increased. It is because increased fps causes more packet drops as more packets are needed to be transmitted at even small intervals, therefore, use case 12 has the worst packet delivery ratio of around 0.55. However, the video may still be useful at the ground station even with packet losses as the loss of a packet only means the loss of the enclosed frame and the video may still be playable at reduced fps.

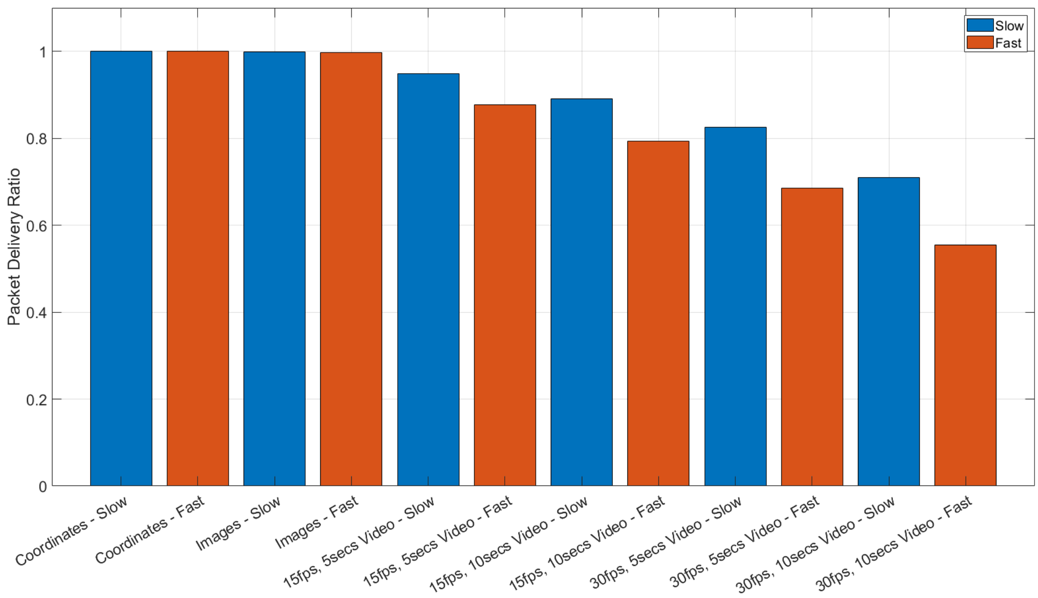

Figure 4.3: Bar plot of packet delivery ratio

4.0.4 Latency

The average latency of the packets received by the ground station in milliseconds can be seen in Figure 4.4. It increases from use case 1 to 12 as the overall size of the data (number of bytes) being transmitted increases. The graph follows the same pattern as Figure 4.2. The latency value for use cases 1 and 2 is around 9 ms, then it reaches a value of approximately 28 ms in the use cases of images. In the end, use case 12 attains latency slightly above 500 ms.

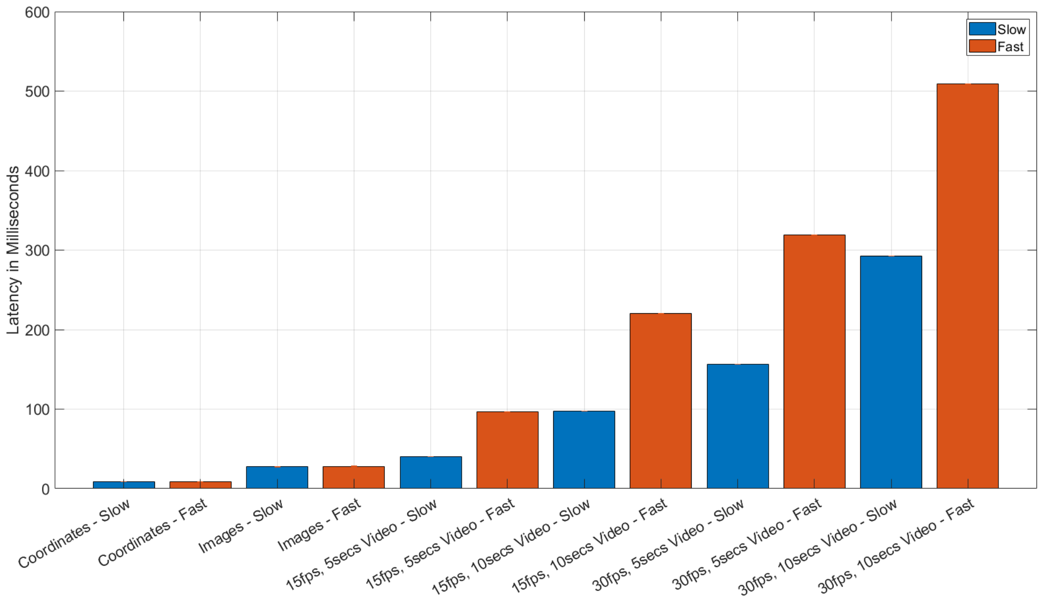

Figure 4.4: Bar plot of average latency

The latency of the incoming packet depends on the number of active agents present in the simulation environment. Therefore, latency vector plots are not understandable without knowing the number of agents communicating at any point in time. Flight schedule manager is used to keep track of the active number of agents and record it as a vector. Figure 4.5 shows the active number of agents with respect to time. The number of agents starts from 0 and reaches a maximum value of 40 multiple times between 4,930 seconds and 5,440 seconds.

The active number of agents and latency vectors are plotted together for every use case in Figure 4.7. For the first four cases, most of the packets have latency values in a specified range except for some outliers. It is because either the packet size is very small (coordinates) or the interval is long enough (images) to provide stable latency. As the interval between the packets is very small in use case 2, agents get in sync with one another to send packets at the same, therefore, creating some peaks. The peaks are not deep because packets only have a size of 40 B, which can be transmitted at a very fast pace and helps to reduce forming queues. In the case of images, although the packet size is big, it is very rare for agents to get in sync because of the long interval between the packets. All use cases having videos as their payload show a similar kind of pattern. Some deep peaks can be seen in every case when the active number of agents is at its maximum level. When a high number of agents are active, it increases their probability to transmit at least some frames in sync with other agents causing peaks in latency at a specific point in time.

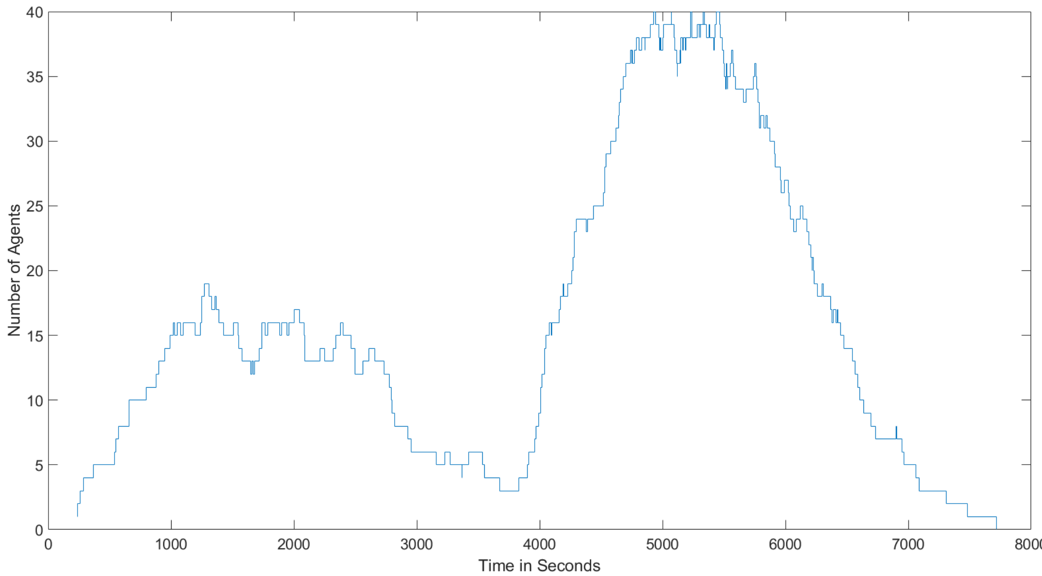

Figure 4.5: Vector plot of active number of agents

4.0.5 Handover Success Percentage

Figure 4.6 represents the total and a successful number of requests to process a handover. A little less than 3000 handover requests are made throughout the simulation time regardless of the use case as handover depends on the movement of an agent, which is the same across all the use cases. Every request becomes fulfilled, yielding a 100% success rate for every use case.

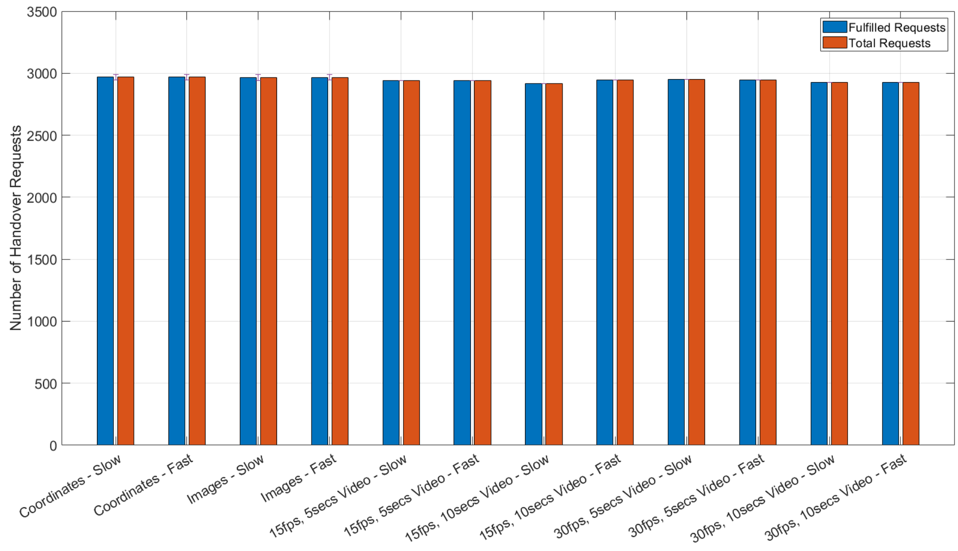

Figure 4.6: Bar plot of handover requests

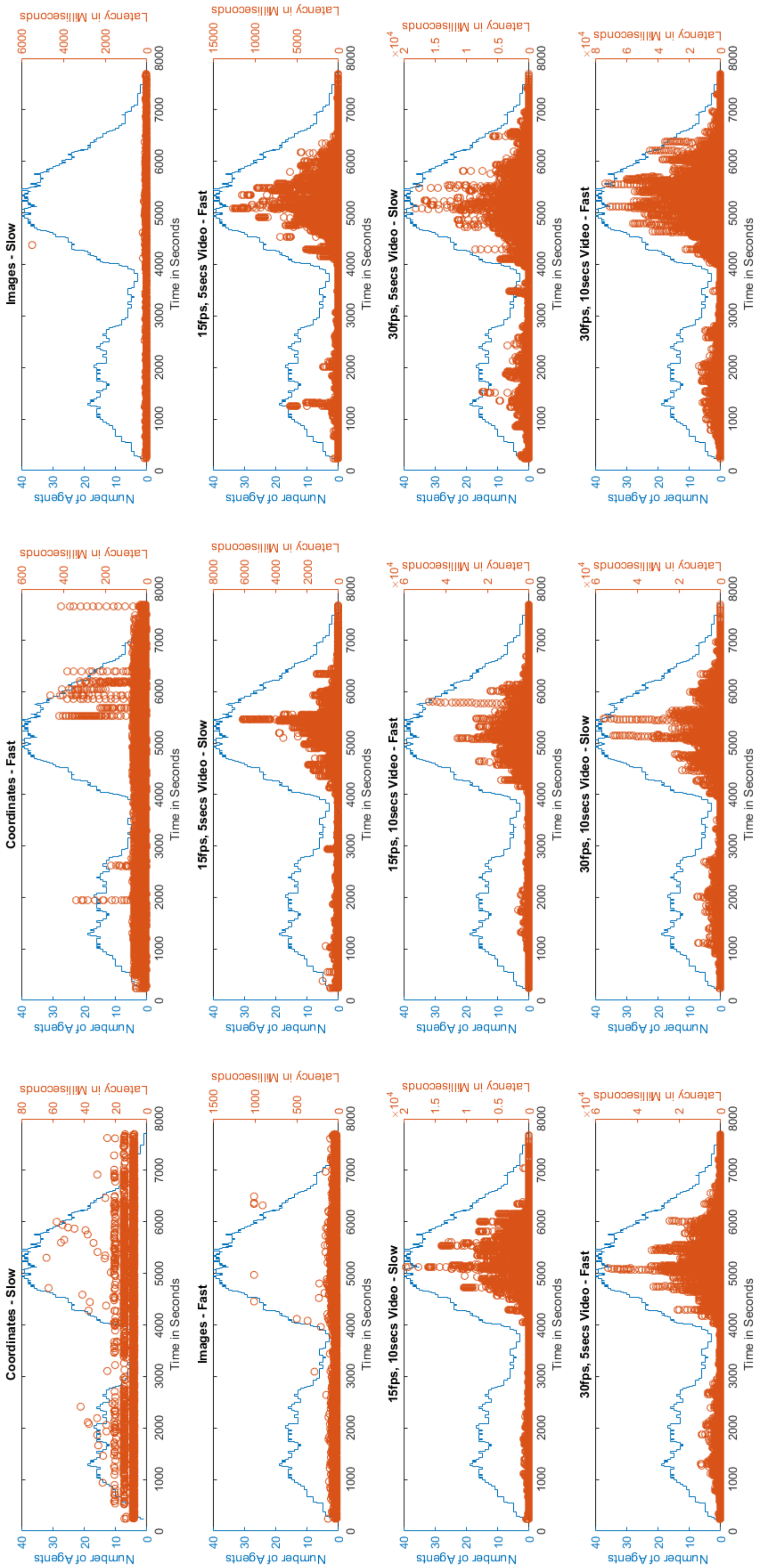

Figure 4.7: Vector plot of latency

chap/tuhhchap-chapter

Chapter 5

Conclusion and Future Extensions

The performance evaluation of a 5G network is performed as the main goal of this project. First, the network was modelled on OMNeT++ with the help of supported libraries then network parameters were selected according to the requirement. UDP app for the NR agents was also implemented to support different types of data including GPS coordinates, images and videos. By analyzing the simulation results, it was found that 5G provides low latency and a convincing delivery ratio even for the high number of packets, which enables 5G technology to be the best choice for mission-critical applications. Moreover, 5G also provides an efficient handover mechanism as proved by the simulation results. The primary objectives of the project have been met and provide a solid foundation for new researchers to extend this work.

As it has been mentioned that default values are used for some NR-related parameters, number of carrier components, their carrier frequencies, numerology index and resource blocks can be varied to produce an endless number of combinations, which can be used to simulate the network for betterment. A larger network with more number of gNBs and agents can be simulated to be closer to the realistic environment. A similar model can be developed for 4G with necessary changes to compare the results between the last generation 4G with the current generation.

List of Figures

List of Tables

Bibliography

[1] *5G Mobile Networks: A Systems Approach*. URL: https://5g.systemsapproach.org/.

[2] Meriem Mhedhbi et al. "Performance evaluation of 5G radio configurations for industry 4.0". In: *2019 International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)* (2019). DOI: 10.1109/wimob.2019.8923609.

[3] Giovanni Nardini et al. "Simu5G-An OMNeT++ Library for End-to-End Performance Evaluation of 5G Networks". In: *IEEE Access* 8 (2020), pp. 181176–181191. DOI: 10.1109/access.2020.3028550.

[4] Giovanni Nardini et al. "SIMU5G: A system-level simulator for 5G networks". In: *Proceedings of the 10th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (2020). DOI: 10.5220/0009826400680080.

[5] Aleksi Peltonen, Ralf Sasse, and David Basin. "A comprehensive formal analysis of 5G handover". In: *Proceedings of the 14th ACM Conference on Security and Privacy in Wireless and Mobile Networks* (2021). DOI: 10.1145/3448300.3467823.

[6] Andras Varga. URL: https://doc.omnetpp.org/omnetpp/manual/.

chap/tuhhchap-chapter

Appendix A

Content of the DVD

The provided DVD contains this report in PDF format along with OMNeT++ scalar and MatLab files in folders named results and MatLab, respectively. The report file can be found in the root location. The MatLab folder includes Matlab's scripts and data sets for all the quantities presented in the performance evaluation section of this report. There is another folder named code, which contains the updated source code of the ULTRAS framework and Simu5G library. There is also a read-me file available, explaining the process of using the source code properly. Figure A.1 shows the file structure of the DVD.

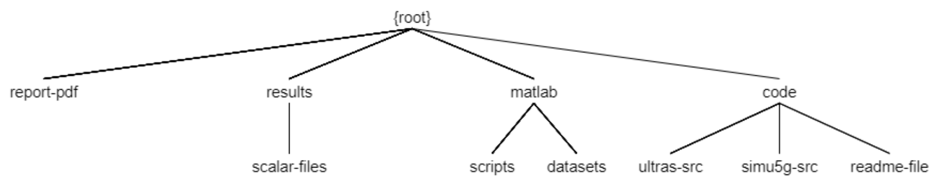

Figure A.1: File structure of DVD