Analysis of backhaul networks for developing countries to support next generation communication systems

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By

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Abstract

In its most basic form, the target of fifth generation (5G) is to provide reliable and continued connectivity for the user despite obstacles and challenges. These obstacles and challenges vary depending on the scenario, whether it's an urban or rural area in developed or developing countries.

This thesis focuses on the 5G backhaul for standalone (SA) network and the impacts of backhaul technologies on the Quality of Service (QoS) and user experiences, in particular, end to end delay (E2E) and capacity planning requirements. In particular, the aim is to facilitate the work of providers, developers, and investors when planning to introduce 5G technology to developing countries. This work looks into employing simulation-based approach to consider bandwidth aspects when designing/ upgrading current/ future cellular systems in developing countries. It presents a scheme to maximize the use of bandwidth considering both capacity and delay aspects and helps to identify major parameters that influence system design for different 5G use cases and scenarios.

The result proves that the method to determine the required link capacity is by observing the traffic delay and users access statistics as well as by increasing the capacity incrementally by changing the factor for each link in the network, until optimal capacity is achieved. It also indicates that within the "broadband in the crowd" scenario for 5G services and applications, the necessary bandwidth for last-mile network connections can vary depending on the service type. Specifically, bandwidth requirements can be lessened for ultra-low latency services and applications, with even greater reductions possible for those that do not require such low latency. These adjustments are observed when the backbone link is operating at its full capacity.

The finding shows that for developing countries, and by considering the cost of the bit per second, user down link/ uplink, and convenience of user terminals as more critical considerations for the adoption of one of the technologies for backhauling 5G traffic, a satellite and hybrid topology based on the existing networks, financial considerations will play an important role in determining the backhaul network topology with optimizing for the specific requirements.

Keywords: 5G, Backhaul, QoS, Developing countries, Delay, Bandwidth, NTN, Satellite

All praises and thanks
are due to Allah (God), the Almighty, the Most Gracious, and the Most Merciful, for His countless blessings. Prayers and peace be upon Muhammad, His servant and messenger. I could have never finished this thesis without the faith I have in Almighty Allah and His prophet Muhammad (PBUH).

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List of abbreviations

5G	Fifth generation
3G	Third generation
4G	Fourth generation
HTS	High throughput satellite
IAB	Integrated Access and Backhaul
eMMB	Enhanced Mobile Broadband
CC	Critical Communications
URLLC	Ultra Reliable and Low Latency Communications
E2E	End to End
QoS	Quality of Services
LEO	Low Earth Orbit satellite
vLEO	very Low Earth Orbit satellite
mIoT	Massive Internet of Things
IoT	Internet of Things
LTE-A	Long Term Evolution-Advanced
ITU-D	International Telecommunication Union - Development Sector
CAPMAS	Central Agency for Public Mobilization and Statistics
AI	Artificial Intelligence
6G	Sixth generation
3GPP	Third Generation Partnership Project
IMT	International Mobile Telecommunications
EU	Europe
METIS	Markets and Energy Technologies Integrated Software
RAN	Radio Access Network
EPC	Engineering, Procurement, and Construction
MN	Master Node
SA	Standalone
NG-RAN	Next Generation-Radio Access Network
NSA	Non-Standalone
5GC	Fifth Generation Core Network
Xn-C	Fifth Generation Interface
ITU-T	International Telecommunication Union-Telecommunication Sector
ITU-R	International Telecommunications Union-Radiocommunications
CU	Central Unit
DU	Distributed Unit
RU	Radio Unit

NEC	National Electric Code
TDM	Time Division Multiplexing
ATM	Asynchronous Transfer Mode
IP	Internet Protocol
NGOF	Next Generation Optical Network Forum
BBU	Baseband Unit
RRU	Remote Radio Unit
L2	Network OSI Layer 2
L3	Network OSI Layer 3
RRC	Radio Resource Control
SDAP	Service Data Adaptation Protocol
PDCP	Packet Data Convergence Protocol
RLC	Radio Link Control
MAC	Media Access Control
PHY	OSI Physical Layer
AAU	Active Antenna Unit
IXP	Internet Exchange Point
HFC	Hybrid Fibre- Coax
PON	Passive Optical Network
QoS	Quality of Service
V2N	Vehicle to network
V2N2V	Vehicle to network to vehicle
V2X	Vehicle to everything
TEA	Techno-economic analysis
CLOS	Clear Line of Sight.
LOS	Line Of Sight
e3nb	Engineering-Economic Evaluation of Diffractive NLOS Backhaul
mm Wave	millimetre wave
MIMO	Multiple-Input and Multiple-Output
MILP	Mixed Integer Linear Programming
UAV	Unmanned Aerial Vehicle
FSS	Fixed Satellite Services
MSS	mOBILE Satellite Services
BSS	Broadcast Satellite Services
EMEA	Europe, Middle East, and Africa
GEO	Geostationary satellite
NGEO	Non GEO Satellite
GSMA	Global System for Mobile Communications Association
MOC	Ministry of communications
CMC	Media commission

HAP	High altitude platform.
UC	Use Case
NGMN	Next Generation Mobile Networks
E2E	End to End time delay
MLA	Microwave Link Aggregation
CN	Core Network
gNB	5G base station
UE	User
DSL	Digital Synchronous Line
TT	Transmission time
TTI	Transmission time interval
UBR	User Bit Rate
BWF	Bandwidth Factor
MUES	Maximum number of users to be served
ALB	Actual link bandwidth
GUB $U\phi$	Aggregated maximum number of user bandwidth.
H	Number of hops.
DSRC	Dedicated Short-Range Communications
WAVE	Wireless Access in Vehicular Environments
CALM	communications Access for Land Mobile
ITS	Intelligent Transport System
DL	Down-link.
DWDM	Dense Wavelength Division Multiplexing.
NTN	Non terrestrial network.
UMTS	Universal Mobile Telecommunications System.
WRC	World Radiocommunication Conference.
ISL	Inter satellite Link.
RN	Relay Node.
QoE	Quality-of-Experience
HDTN	NASA's High Rate Delay Tolerant Networking project.
UAS	Unmanned Aircraft Systems.
GSO	Geostationary Orbits.
NGSO	Non Geostationary Orbits.
HAPS	High Altitude Platform Systems.

Chapter 1

Introduction

1.1 Background

The fifth-generation (5G) technology is seen to be a solution for developing countries to improve their quality of services in terms of transportation, education, health, agriculture, and other fields, thereby holding the promises of economic transformation by improving productivity and quality of life. However, their legacy infrastructure is considered one of the main obstacles that providers, investors, and operators may face when planning to introduce any new technology to those countries. Most of them have yet to achieve near-complete population coverage of the third generation (3G) cellular infrastructure. It was challenging to deliver significant infrastructure upgrades with the fourth generation (4G) deployment [1]. However, with 5G technology is now being rolled out, and the use cases that have been offered different services and applications with different requirements, a new technology required to overcome the infrastructure issue and to cope with 5G requirements [2]. The new generation of wire and wireless backhaul technologies such as mm Wave, high throughput satellite HTS, integrated access and backhaul IAB, and others that are planned to be used for backhauling 5G traffic will be an effective solution to overcome infrastructure issues in developing countries.

However, to merge their existing legacy infrastructure with the new technologies a new design is required that will help to study the behaviour of the network in terms of each technology as this will help to choose the proper technology for each 5G use case [3].

1.2 Significance of the research and motivation

With the joint efforts of the institutions and community to help developing countries benefit from the latest technologies in the field of telecommunications, Mobile technology is increasingly seen as a cornerstone for sustainable development, therefor adopting a new model to approve the performance of different backhaul technologies will assist to deliver significant infrastructure upgrades that will help the developing countries cope with the rest of the world in terms of new technologies [4]. However, since the costs of introducing a new technology are considering as a bottleneck for developing countries due to the lack of financial resources compared with the developed countries, reducing the percentage value of the bandwidth will have a good impact on facilitating the introduction of 5G to these countries, and thus by observing the network behaviour in different scenarios and case. Moreover, 5G technology and beyond will provide a variety of services and applications under the use cases like eMBB, CC and URLLC and mIoT that required reliability and low latency, design a model that grantee the QoS for the services and application is an important factor [5][6].

1.3 Research scope

This research mainly aims to facilitate the work of investors, deployers, and developers who are planning to deploy 5G technology in developing countries, and thus by studying the backhaul network behaviour for different technologies as a replacement of their legacy infrastructure, the primary aims of this study will realised by performing the following objectives:

- Conducting a literature study that reviewing of technologies for implementing of 5G network for developing countries, and emphasize the crucial role of backhaul infrastructure in delivering high data rates, low latency, and seamless connectivity. The review explores challenges specific to developing countries such as limited availability of suitable backhaul options and strategies to overcome these challenges to ensure the effective implementation of 5G networks.
- Developing a MATLAB design model of 5G network with different backhaul technology to analyze the network behavior. The model will form based on the data rate requirements of individual scenarios and it will compute user access statistics and delay for each scenario to help maximize bandwidth utilization in communication link for future mobile communication technology in the countries facing infrastructure and cost challenges.
- Investigating the behaviour of the network for different backhaul technologies to provide an insight into the trade-offs between bandwidth allocation, user access, and delay, offering guidance for designing efficient communications networks.
- Disseminating the findings and conclusion of the present study to provide the research community with the solid basis for future experimental and/or numerical studies on the relevant topics. Also, to highlight the economic im-

plications of latency reduction strategies and consider the regulation bodies to ensure that latency requirements align with policy objectives.

1.4 The relevance of the methodology

The initial phase of my research focused on literature review, relevant research articles, books, research papers which includes conference proceedings and journal papers, IEEE standards, progress and proposals of IEEE task groups, and different white papers on developing countries infrastructures and the issues that they were facing to cope with rest of the world in terms of mobile technology. In addition, this phase discussed the backhaul technologies that proposed for 5G networks, basic definitions, types and classifications of transport and backhaul network were examined and issues related to each technology and its recent extinctions, delay, bandwidth, and cost were identified.

Literature review was followed by mathematical study of different types of end to end delay (E2E) delay, link capacity, and the percentage number of users without access that may affects network performance and the quality of services that delivered to each individual user. The data for each scenario is forwarded in the downlink direction from the core towards the end user. Multiple parameters and scenarios for each case was carried out using different variables and strategies according to each scenario. In addition to the performance of each proposed solution that will be testing, it will help developing a different perspective such as, looking at the economic implications of latency reduction, and population density in a certain geographic area.

In the final stage, development of MATLAB simulation model of 5G network has been implemented and different backhaul technologies have been adopted in order to compare them with the solutions introduced through this research. The research will focus on examining physical layer performance parameters of modelling different scenarios for different type of users to identify user requirements and to compare between the major backhaul technologies that may use to secure the requirements of 5G technology for developing countries. Although, employing MATLAB to model backhaul networks is a challenge due to its limited tools in term of 5G technology, it provides easy, interactive environment and fast numerical algorithms. It allows matrix manipulation, plotting of functions and data, Implementation of algorithms, creation of user interfaces and interfacing with programs in other languages.

1.5 Contributions to knowledge

This study contributes to the knowledge by modelling a design of 5G network based on one of the major mobile providers in one of the developing countries with multiple wire and wireless backhaul technologies, aiming at selecting a proper solution to introduce 5G technology for the countries with a legacy infrastructure. Furthermore, the thesis presents a novel mechanism for bandwidth utilization in communication links associated with future cell-based communication systems that can be useful for developing countries where system upgrades present significant cost challenges.

The key contributions are summarized as follow:

- Development of a system model to analyze different technologies by deploying a mechanism to estimate the percentage number of users that can access the network and the E2E delay for each backhaul technology, considering all type of delays, processing, queuing and transmission, and propagation delay, in a specific coverage area and user density when modeling the network of each backhaul technology.

- Comparison of different terrestrial backhaul technologies to aid 5G deployment in developing countries A wire and wireless network for backhauling 5G traffic modeled, which aiming at selecting a proper solution to introduce 5G for developing countries. This is by comparing the performance of the network with each technology in terms of delay, the number of users that can access the network, and the maximum bandwidth utilization of each technology.

- Investigation of satellite based backhaul technologies to aid 5G deployment in developing countries a MATLAB design is focusing on the satellites for backhauling 5G traffic from core network to the end user. It mainly adopts the most promising satellite's orbits, vLEO, LEO and MEO to that cope with 5G services and applications requirements. The design considers 5G standalone network, it deployed to deliver the services from Core to each gNB that connected to the network through satellite network. E2E delay statistics and capacity planning based on users access statistics are both considered and by observing link utilization for which the delay requirements are met the 3GPP standards is an efficient method to propose the most efficient backhaul technology to deploy 5G network in developing countries.

1.6 Research structures and outlines

This thesis contains six chapters arranged according in the following sequence:

Chapter 1 : Introduction

This chapter introduces the problems of introducing 5G technology from quality of services background in the world to developing countries background, and related research background of 5G technology. In addition, it explains the significance of the research, discusses the research aims and objectives, describe the research methodology, introduces the research contributions of the knowledge, presents the research structures and outlines, and finally depicts the publications that contributes to the work of the research.

Chapter 2 : Literature review

This chapter reviews the literature which concerned with four aspects as follow:

- To highlighted the obstacles and challenges that may face those who plan to invest, deploy or develop 5G technology in developing countries.
- To present the standardisation that have been adopted of the 5G transport and backhaul networks which will play a major role in 5G network development.
- To understand the new technologies that proposed by several studies which can be used for the backhaul network and will facilitate the deployment of 5G in developing countries.
- To illustrate the existing infrastructure in developing countries and their steps towards obtaining 5G technology.

Chapter 3 : Modeling and Simulation Framework for 5G Backhaul Network Design

This chapter focuses on the primary research. It shows research process; provides 5G backhaul network for different technologies, and presents the methods and methodologies which are used to approach this study. The main contents include discussing the QoS in terms of capacity and E2E delay, modelling and simulation which discuss the model that been adopted in this study, and the evaluation cases and scenarios of backhaul design model of 5G network that have been examine in this study.

Chapter 4 : Simulation study for exploring network behavior for various backhaul technologies

This chapter mainly discuss the network behavior for various backhaul technologies that have been simulated in this study. the chapter included the simulation design of each technology, simulation parameter of each 5G scenario that will examine, and the results of each scenario in terms of percentage number of users without access, E2E delay, and capacity. In addition to the compartive analysis of each scenario across technologies and bandwidth factor of each link in the network.

Chapter 5 : Satellite backhaul and analysis for Non Terrestrial Network (NTN)

This chapter presents a simulation model to evaluate the capability of satellite network in multiple orbits to support the broadband in the crowd services and applications. Several combinations of BWFs and maximum number of users are tested for different satellite orbits MEO, LEO/vLEO with varying link capacities. The research highlights how the use of different orbits, will influence latency, reliabil ity, and users statistics.

Chapter 6 : Summary and future works

In this chapter a summary of the research is presented, and a brief explanation of each chapter is explored. In addition a proposed future works are introduced in this chapter to inspire other authors and researchers to continue the work.

1.7 Publications

Portions of the work detailed in this thesis have been presented in national and international scholarly publications, as follows:

Journal papers

- I. Sawad, R. Nilavalan, H. Al-Raweshidy, “Backhaul in 5G systems for developing countries: A literature review”, IET Communications, January 2023, pp. 659 -773.
- I. Al-Zubaidi, R. Nilavalan, H. Al-Raweshidy, “Performance Parameters Consideration for Cellular System Upgrades in Developing Countries”, IEEE ACCESS, February 2025, pp. 41309 - 41323.

Conferences papers

- I. Al-Zubaidi, R. Nilavalan, H. Al-Raweshidy, “Service requirements of 5G network for developing countries”, Conference: 27th Annual Technological Advances in Science, Medicine and Engineering Conference 2023, May 2023, Canada.
- I. Al-Zubaidi, R. Nilavalan, H. Al-Raweshidy, “Bandwidth Consideration for Cellular System Upgrade in Developing Countries”, Conference: ICCMS 2023: 2023 The 15th International Conference on Computer Modelling and Simulation, June 2023, China.
- I. Al-Zubaidi, R. Nilavalan, H. Al-Raweshidy, “Performance parameters consideration for 5G backhaul network”, 2023 IEEE International Workshop on Technologies for Defense and Security (TechDefense), November 2023, Italy.

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Chapter 2

Literature review

2.1 Introduction

Throughout all the different generations of mobile technology, there have been major differences in network performance between countries. This is because the more developed countries have been able to use the latest releases of mobile network technology and have advanced, up-to-date infrastructures, while the less developed countries have struggled to adopt the new technology, in particular, in terms of upgrading and/or expanding their infrastructures. Indoria [1], in a published study, listed the main challenges that developing countries could face with the implementation of 5G technologies. The study particularly focused on the lack of infrastructure, which includes poor fiber construction, no proper mechanism for the rapid increase in the number of users, low rates of data speed, high costs as well as political and security issues, thus hindering the development of the telecommunications sector. The study also discussed the need for 5G and its applications given its advantages over 4G and the future prospects for its implementation. While Tom [2], in an article discussed the implication of 5G technology for enterprises in developing countries and its effect on Internet of Things (IoT), the advantage and difficulties of integrating 5G technology into the IoT landscape and how it might change the industry field in developing world. The article highlighted the challenges of deploying 5G in these countries such as the requirements of legal framework, security precautions, and talent development. This study mainly aimed to help improve awareness of the potential effects of 5G technology on the IoT landscape and offering guidance for investors, operators, and policymakers. It is also important to look into the economic developments/costs associated with implementing 5G networks, for instance, Oughtona [3] in a published article, also studied the growth of data traffic of 5G infrastructure strategies for the period between 2016 and 2030. The study found that there will be a 90 percentage of data growth due to technology change from 4G to 5G. They also highlighted the techno-economic problem of deploying 5G due to the cost. In this regard, they pointed to the large number of new components required to operate enhanced network infrastructure, including base station units and backhaul transmission, as well as the associated costs of site installation and operation, network optimization and maintenance. While Shin [4] focused on analyzing the 5G users and data traffic demand and how that demand would change based on several attributes, including the content amount, additional monthly fees and additional cost of devices. The study revealed a crucial foundation for mobile service providers' investment and marketing strategies that aim to maximize profits. In addition, Forge and Vu [5], in a published study, discussed the network performance variation between developed and developing countries. Their aim was to provide policymakers in developing countries with a clear understanding of 5G deployment in terms of demand levels, infrastructure costs, challenges of a dense deployment infrastructure, technical complexity and the need to create effective future strategies for deploying the new generation. The authors cited an example based on a survey carried out in 2019 comparing the average download speeds rate for the existing 4G called Long Term Evaluation-Advance (LTE- A) networks. The survey showed that the download speeds were 52 Mb/s for the Republic of Korea and 33.0 Mb/s for Japan, as an example for lead or developed countries, while this fell to 1.6 Mb/s for Iraq, as an example of a developing country. Muluk [6], the ITU-D representative, stated in his presentation at the ITU Regional Forum on New Technologies the importance of 5G for developing countries for eliminating the number of transport accidents, which, according to the CAPMAS-Central Agency for Public Mobilization and Statistics are high in those countries. He stated that 5G will have a good impact to improve the transport system in terms of quality and availability. Also, 5G will lead to reduction in latency to (1ms), thus enabling remote health assistance in terms of performing surgery. The specialists could join a surgeon remotely for diagnosis and follow-up. In terms of education, 5G will offer new ways of learning in the classrooms, with students being exposed to a more visual and interactive learning experience (Augmented Reality, Virtual Reality, and Virtual Presence). Moreover, teachers will be able to deliver their classes to students not necessarily in the same room. 5G technology will assist developing countries in optimizing growth and minimizing the use of water and fertilizers through more targeted application in water and agriculture systems, as well as other fields. From another point view, Farooq [7] in a study explores the impact of 5G and 6G, alongside artificial intelligence (AI) on freedom of expression in developing countries. He highlighted how 5G and 6G networks, complemented by AI are reshaping freedom of expression in developing countries, the importance of providing democratic digital environments in these countries. The smart network communications environments of 5G are increasing the demand for high-speed data, and introducing new requirements of network and infrastructure, especially the transport network.

The chapter aims to review the studies and researches on 5G backhaul network and the proposed solutions offered to deploy 5G technology in developing countries.

It is organized as follows. In Section 2, a detailed review of 5G transport networks is described. In Section 3, the backhaul network is discussed. Whilst in Section 4, the latest backhaul technologies are derived. In Section 5, the developing countries and their progress toward 5G technology discussed. In Section 6, the role that cost plays to deploy 5G technology in developing countries is considered. Finally a summary of the whole chapter presents in section 7.

2.2 Transport network

Recent ongoing research efforts and standardisations are concerned about the crucial role of the transport network in 5G technology. For instance, the Third Generation Partnership Project (3GPP) studied the evaluations and the enhancements of the existing 4G network and how to upgrade to the new era of 5G in its standards Release (15) and then, Releases (16), (17), (18). Jaber [8] stated in a published study that the main role of the transport network is to provide connectivity between the radio base station and the core functional modules. She also discussed the determination of the preferable deployment topologies with the considerations of the cost, region type, and 5G applications that may be provided. Ericsson [9], in a published booklet, discussed the transport network infrastructures needed to handle the demands of tomorrow in terms of traffic growth, machine-centric communications, high-quality wireless video streaming, social networking, and unforeseen applications, that are including in the International Mobile Telecommunications IMT-2020 standard. The Europe EU project METIS [10] introduced five 5G scenarios based on five fundamental challenges relevant to set the foundation of 5G mobile and wireless networks beyond 2020 that may have a major impact on the transport network. For instance, providing very high data rates, and great service in a crowd scenario will require a transport network that needs to support huge traffic volumes and provide very high capacity on-demand to the specific geographical area, as Table 2.1.

Table 2.1: The METIS scenarios and their challenges[10]

Scenario	Challenges
Amazingly fast	Very high data rate
Great services in a crowd	Very dense crowds of users
Ubiquitous things communicating	Very low energy, low cost, and a massive number of devices
Best experience follows you	Mobility
Super real-time and reliable connections	Very low latency

With the 4G RAN/EPC network currently in the field along with the 5G New Generation-Radio Access Network NG-RAN Core recently deployed, the migration from 4G to 5G will be a challenge. The 3GPP TR 21.915 (Release 15) standardization [11] discussed several architectural options for migration to 5G. Not all of these options are currently fully supported, but more are expected to be available in different releases of the 5G specifications, which will provide flexibility to service providers. The two most popular options discussed are as follows.

- Non Standalone NSA This option will be available without the need for network replacement of 4G. The 5G Radio Access Network NG RAN over 4G's Evolved Packet Core EPC or over 5G's New Generation Core (NG-Core) is proposed for dual connectivity, with the 4G Evolved Packet Core EPC. The master node (MN) is the eNB, whereas the secondary node (en-gNB) is the en-gNB (SN), as in Figure 2.1 [11].

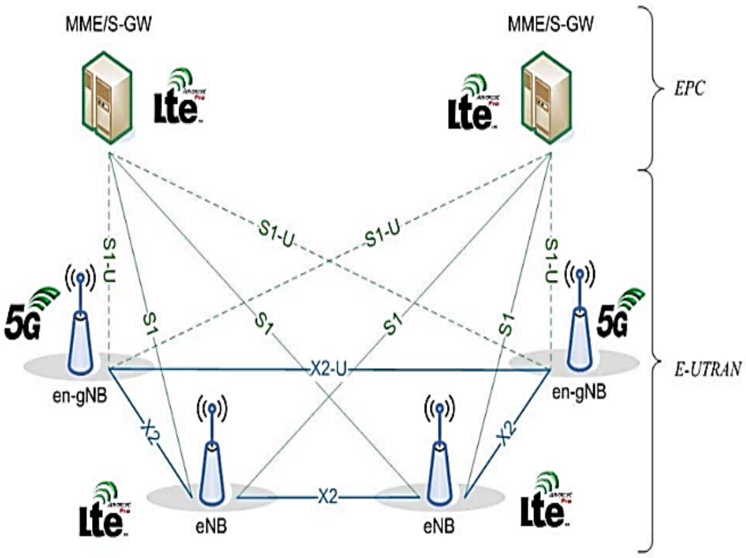

Figure 2.1: Non-Standalone NSA 5G network [11]

While the second option is

- Standalone SA

  In this option the architecture represents full 5G deployment. The 5GC core is connected to the NG-RAN network, as in Figure 2.2. No 4G components are presented [9].

The selection between the two architecture options is depending on the feasibility of deployment, infrastructure availability, and profitable for cellular operators, as well as the assessment of the sensitivity parameters of the techno-economic factors

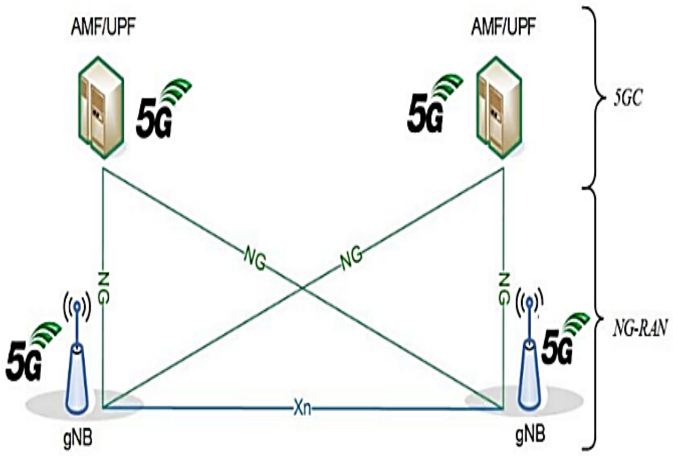

Figure 2.2: Standalone SA 5G network [11]

such as cost structure, financial viability parameters that significantly affect the deployment.

According to the 3GPP 5G standalone architecture specified in TS38.401 (Release 15) [12], the overall architecture of the NG-RAN network introduces new interfaces and functional modules. It describes that NG-RAN consists of the new 5G base station gNB connected to the new 5G core 5GC via new interfaces NG and connected to each other via an Xn-C interface. NG-RAN can be implemented and deployed in different ways based on the operator's requirements, as in Figure 2.3

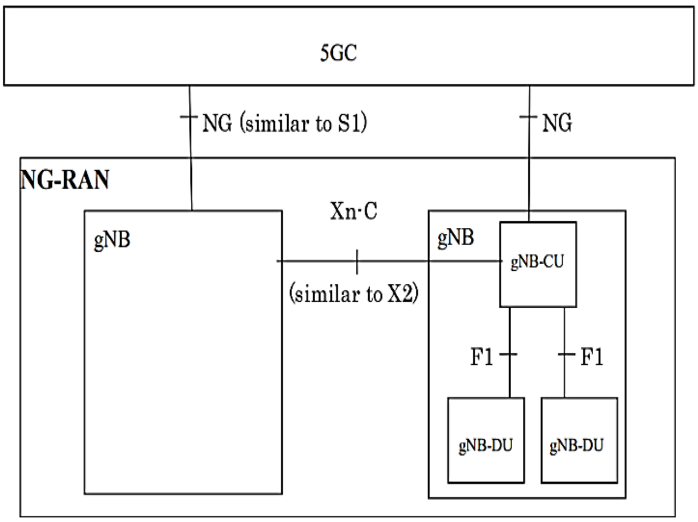

Figure 2.3: Overall architecture [12]

In addition, the 3GPP is leveraging the upcoming of 5G- Advanced, it is announced in its standard Release 18 that 5G-Advance is set to enable a next-generation of extended reality, high-accuracy positioning, low-power IoT applications, and other emerging use cases to provide better network performance, resiliency, and efficiency [13]. 5G-Advanced is considered as a the second phase of 5G evolution, where networks are adopting a 5G Stand-Alone (SA) core, moving towards more open, virtualized, and centralized architectures alongside network slicing and analytics-driven automation, Figure 2.4 [14].

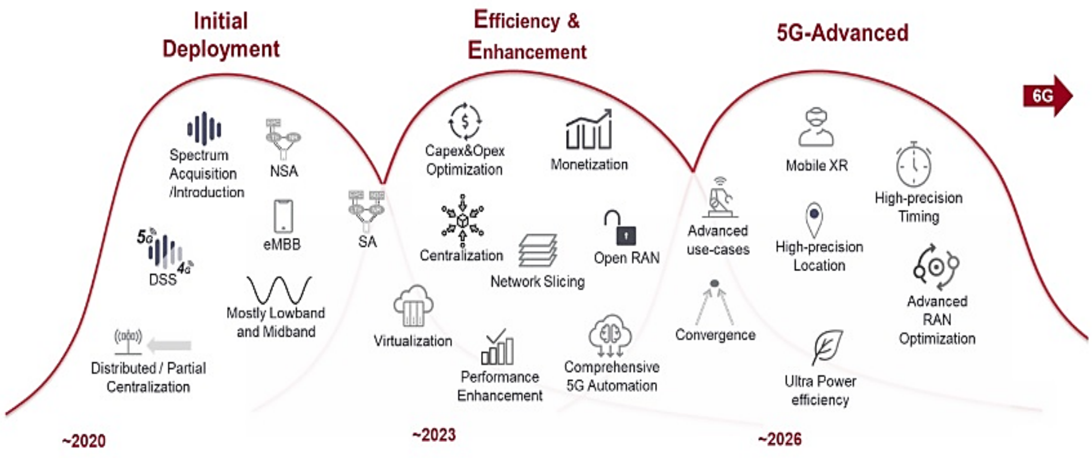

Figure 2.4: 5G-Advanced [14]

As a continuation of 5G Advanced, Release 19 will primarily focus on improving performance and addressing critical needs in 5G commercial deployments. We see that 5G Advanced will continue to evolve within 3GPP during this decade and, in parallel, 6G standardization is expected to ramp up in Releases 20 and 21 starting from 2025 [13], Figure 2.5.

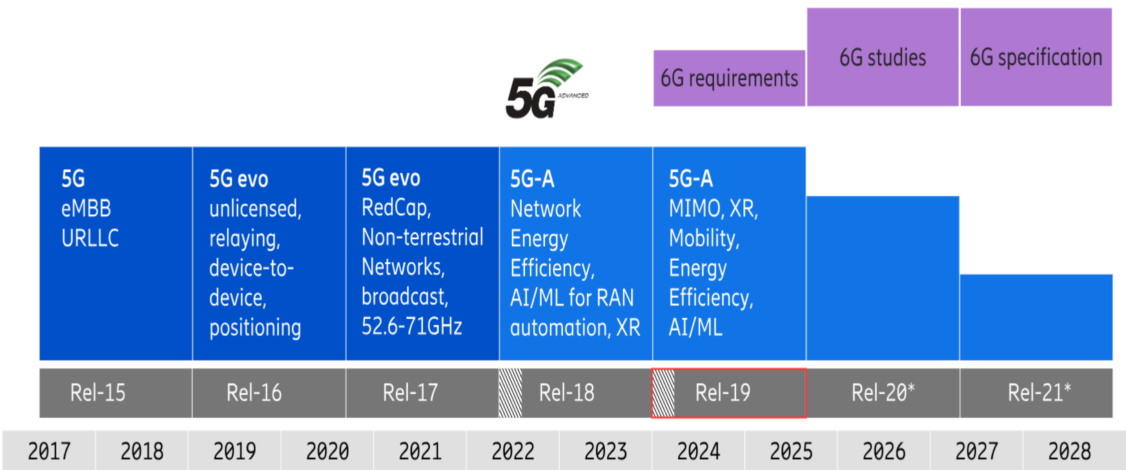

Figure 2.5: Ericsson's view of the 5G Advanced and 6G timeline of 3GPP (dates beyond 2025 are indicative) [13]

Eventually, operators are expected to complete the 5G migration by deploying a New Generation (NG) Core to work as standalone network. Based on Fujitsu's white paper [15], the NG-RAN architecture consists of three main functional modules that are mapped in the 5G base station (gNB). These are the central unit, distributed unit, and radio unit, which can be deployed in multiple topologies to provide flexibility for the 5G network. Furthermore, the International Telecommunication Union (ITU) in its Telecommunication sector (ITU-T) [16] introduced those topologies in a technical study released in February 2018. According to the study, the transport network design is made up of three logical elements: The Central Unit (CU), the Distributed Unit (DU), and the Radio Unit (RU). Those logical elements can be combined in different topologies to produce the actual physical network parts of the 5G transport network. According to these topologies, the transport network layout design will consist of fronthaul, that pointed to the connection between the DU and RU, midhaul, that pointed to the connection between the CU and DU, and backhaul that represent the connection between 5GC and DU. That mainly depending on the network requirements, and operator requirements. A 5G Americas white paper [17], has identified four Radio Access Network (RAN) deployment scenarios for designing a 5G transport network as follows.

- **1st Scenario:**

  The layout of the transport network will consist of fronthaul, midhaul, and backhaul networks. The RU, DU, and CU are co-allocated in different sites. The CU connects to the 5GC to form the backhaul network, whilst the connection of the CU to the DU and the DU to the RU will form the midhaul and fronthaul networks, respectively, as in Figure 2.6.

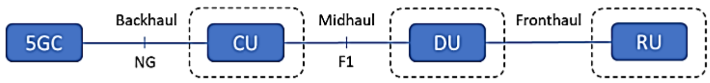

Figure 2.6: 1st Scenario of transport network layout [17]

- **2nd Scenario:**

  The layout will consist of only a fronthaul and backhaul network. The CU and DU in this scenario are co-located at the same site, while the RU is in different site. The CU and DU connect to the 5GC to form the backhaul network and connect to the RU to form the fronthaul, as in Figure 2.7.

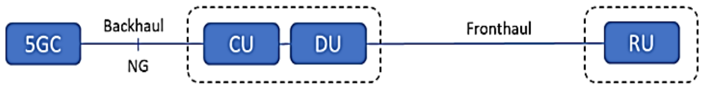

Figure 2.7: 2nd Scenario of transport network layout [17]

- **3rd Scenario:**

  This layout consists of a midhaul and backhaul network. The DU and RU are co-located at the same site, while the CU is located in different site. The CU is connected to 5GC to form the backhaul network and connected to the DU and RU to form the midhaul network, as in Figure 2.8.

Figure 2.8: 3rd Scenario of transport network layout [17]

- **4th Scenario:**

  The layout consists of just a backhaul network, with the RU, DU, and CU being co-located together. They are connected to 5GC to form a backhaul network only, as in Figure 2.9.

Figure 2.9: 3rd Scenario of transport network layout [17]

The fourth scenario allows for the adaptation of various network architectures, applications, and transport network needs. The appropriate technology depends on the individual applications, deployment scenarios, market environment, existing infrastructure, etc.

2.3 Backhaul network

Over the last 20 years, backhaul networks have developed with each generation of mobile networks. McClelland [18], Ericsson's expert, discussed the backhaul networks evaluation from 1G to 5G. He stated that the transport networks implemented and designed for the previous mobile generation will be insufficient for the new era of 5G. NEC [19] and Raza [20] stated that the migration from 1st generation (1G) and 2nd generation (2G) mobile networks used Time Division Multiplexed (TDM) and Asynchronous Transfer Mode (ATM) technology that supported voice traffic only, to the 3rd generation (3G) mobile network that required a new transport network with Internet Protocol (IP) technology that supported the new data applications, as shown in Figure 2.10, the evolution from phase 1 to phase 3.

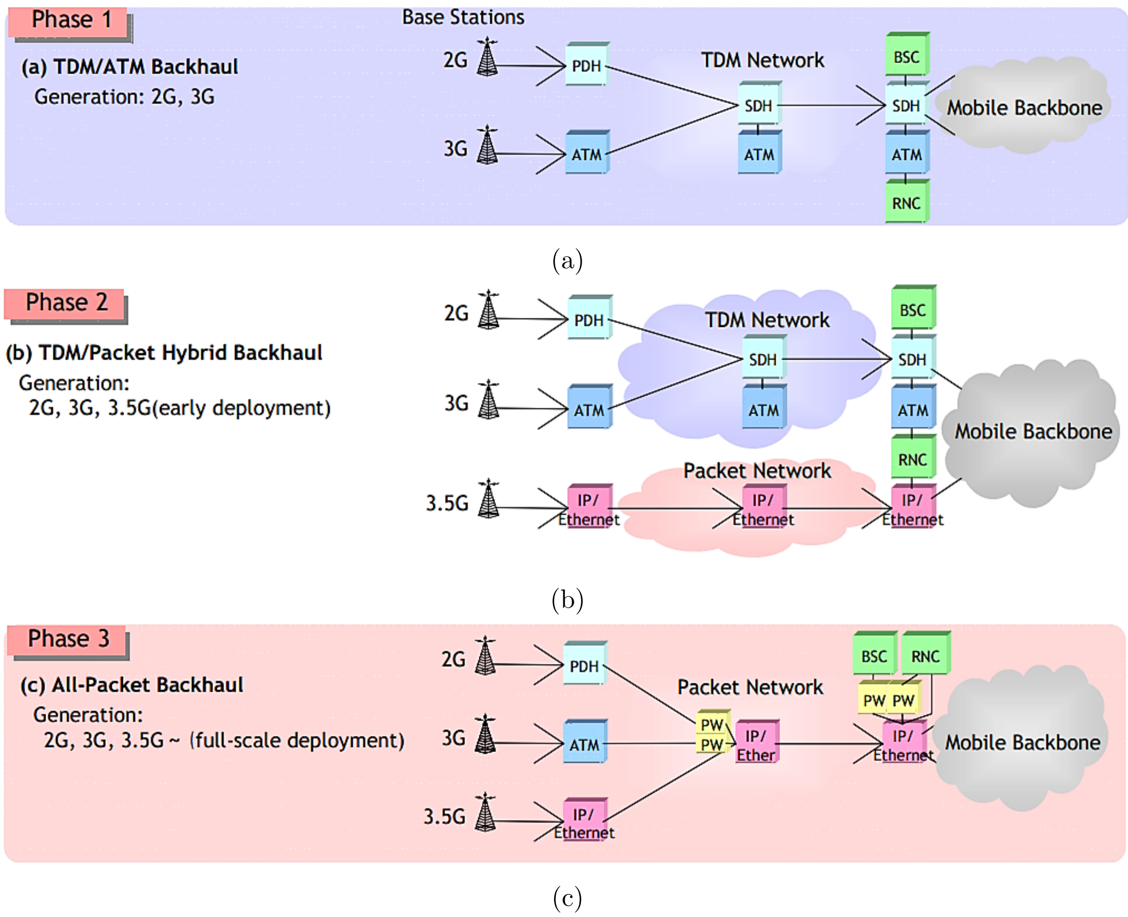

Figure 2.10: 2G, 3G, and 3.5G backhaul network evolution [19]

However, based on NGOF (Next Generation Optical Network Forum) white paper [21], to migrate from 4G to 5G networks, the two-level structure of 4G that comprises of a Baseband Unit (BBU) and a Remote Radio Unit (RRU) will be upgraded to a more complicated 5G transport network that comprises of three-level structures. The BBU splits to a new structure called the CU, which processes L2 and L3 non-real-time protocols and services, that mainly includes RRC, SDAP, and PDCP protocol and DU, which mainly responsible for layer 1 and L2 real time protocols and services, that mainly runs the RLC, MAC, and parts of the PHY layer. While the original functions and some physical layer processing are moved to the Active Antenna Unit (AAU) or RU. Furthermore, a 5G Americas white paper [17] pointed out that a transport network that connects the BBU in 4G or the CU in 5G networks and beyond to the core network represents the backhaul link, as in Figure 2.11

It has also been contended that when it comes to 5G backhaul the best technology depends on the applications, deployment circumstances, market situation, existing infrastructure, and so on. Another important factor that need to be considered is the networks that supports/connects to the 5G networks. Appropriate Internet Exchange Point (IXP) infrastructure is essential to provide sufficient QoS

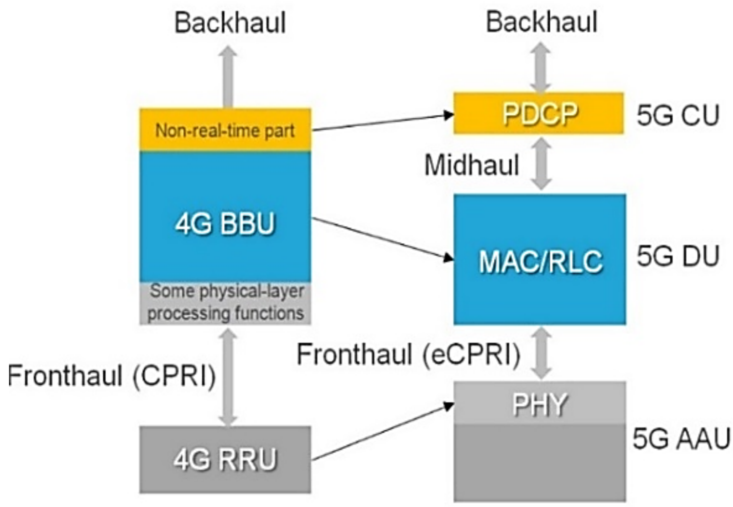

Figure 2.11: The evolution from 4 to 5G backhaul [21]

and experience. The communication networking requirements for this core internet infrastructure also need to be carefully considered when implementing 5G networks in developing countries. Studies on global internet interdomain data traffic are limited and beyond the scope of this review paper. Some studies have looked into these requirements and Hoeschele [22] studied the impact of 5G networks on the internet exchange point (IXP). This work looked into a method to identify the 5G use cases that will affect the traffic levels at the core Internet, in particular at interdomain infrastructures. They concluded that three use case groups, namely video in 5G, Health, and VR & AR, will likely have the strongest impact on the Internet traffic growth at interdomain infrastructures until the year 2025. In regions where the respective infrastructures exist, new shared technology, like Hybrid Fibre-Coax (HFC) and Passive Optical Network (PON) technologies, are suitable for cost-effective and speedy 5G network deployment [17]. Several technical solutions adopted by mobile operators for backhaul vary between wireline and wireless solutions. The GSMA [23], in its published study, stated that backhaul technology mainly relies on three physical medias: copper, optical fibre, and microwave radio links. Recently, satellite links have been used to overcome coverage drawbacks present in the other mediums. Optical fibres are usually installed in densely populated urban and suburban regions with heavy traffic. On the other hand, microwave radio and satellite connections are used in places where cable backhauls are difficult to establish. Leased T1/E1 copper lines dominate backhaul systems, because they accommodate voice traffic well, with predictable Quality of Service (QoS), low latency, and low delay variation [24].

Researches and studies introduced E2E latency model for different services and application. In [25], presents a novel E2E latency model for 5G vehicle to network/vehicle to network to vehicle V2N/V2N2V communications. In [26] the author proposes a hierarchical network model using superimposed independent homogeneous Poisson point processes and thus to solve the backhaul issue in heterogeneous cellular networks, then in [27] the authors collaborate by a backhaul model for four promising backhaul technologies as a means to investigate the effect of different backhaul technologies on the network performance. They also propose a backhaul aware BS association policy for two-tier cellular network, aiming to minimize the mean network packet delay. In [28], the study utilizes a sensitivity option with a techno-economic analysis (TEA) simulation model to evaluate business options influencing successful 5G NSA deployment in the emerging countries' market.

2.4 New backhaul technology

Regarding the new challenges brought by 5G, particularly for developing countries, most ongoing research efforts on 5G mobile networks has been concentrated on different aspects to cope with the new requirements and to serve the high demand of the new applications. Fiorani and Monti [29] have argued that, with ongoing cell densification and the growing number of the various types of services needing to be provided, the challenges of the transport network, in particular, backhaul, will be the main focus of present and future investigations. According to Jaber's study [8], most of the current backhaul networks are built with microwave and fibre/copper-based links. Fibre optics backhaul is considered to be the best performing technology amongst them. However, it is economically challenging for operators to deploy compared with the other technologies, as much more civil work is required. In addition, it is not available worldwide. A compilation of available and potential backhaul technologies is presented in this study that may allow 5G networks to cope with the demands for bandwidth, ultra-low latency applications, and other future applications. A new alternative backhaul solutions are proposed for standalone 5G networks. This study selected the most effective technology that may be considered as a proper solution for backhauling 5G traffic in developing countries.

2.4.1 Combining CLOS and NLOS Microwave Backhaul for rural areas

Nowadays, microwave backhaul is implemented using Clear Line of Sight (CLOS) technology. Because of the nature of remote rural areas, it is a challenge to guarantee Line of Sight (LOS) between settlements without using a repeater or reflector, which means extra cost. To address this, according to the Facebook study by Kusuma [30], the physics phenomenon of "diffraction" can be used. Diffraction is well-known in radio propagation modelling, it being a phenomenon that conveys signal energy into the shadow NLOS phase as in Figure 2.12.

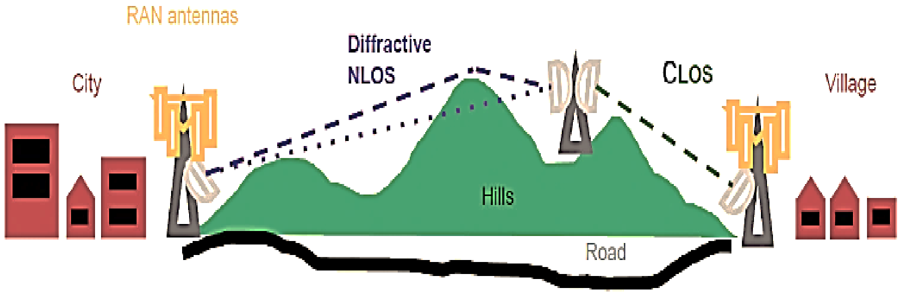

Figure 2.12: CLOS and NLOS microwave backhaul [21]

The main drawback is the limited spectrum resources. As GSMA [31] discussed in their published article, microwave backhaul requires a licensed frequency, which is considered to be a key challenge for this technology in terms of availability and cost. However, the V-band is unlicensed, and the E-band is only licensed with a light touch. To help solve the rural and deep-rural connectivity issues and thus, prepare their infrastructure for coping with 5G demand, several recent studies have focused on using a hybrid combination of CLOS and NLOS approaches as a practical and cost-effective networking solution. For instance, there is the study "Combining CLOS and NLOS Microwave Backhaul to Help Solve the Rural Connectivity Challenge" by Boch, Kusuma, and Park, which was published in 2021 [32], and "Diffractive NLOS Microwave Backhaul for Rural Connectivity Network as a Service Solution Group" by Telecom Infra Project, which was published in 2021[33]. In addition, Oughton and Boch studied the evaluation of the engineering-economic implications of the diffraction NLOS backhaul in their paper "Engineering-Economic Evaluation of Diffractive NLOS Backhaul (e3nb): A Techno-economic Model for 3D Wireless Backhaul Assessment", published in 2022 [34].

Based on the Telecom Infra Project [33], the use of this new technology will allow for the designing and building of new wireless networks in challenging environments, eliminate the need to use repeaters and make the network design more flexible and efficient. It may also provide better coverage, with some RAN sites being better positioned or redeployed using shorter towers.

2.4.2 mmWave backhaul

The millimetre-wave (mmWave) backhaul network has recently been identified as a viable technical innovation for the upcoming 5G technology that will use a higher frequency (over 6GHz), which will significantly improve network performance. According to a study by Liang and Li [35], this new technology will overcome the obstacles of the earlier generations of 2G, 3G, and 4G, which work on a lower frequency (6GHz and lower), with limited bandwidth and relatively low spectral efficiency. That is, this new configuration will be able to satisfy the ultra-large traffic demand and the supermassive connection required for the new generation, as in Figure 2.13.

A study by Zhao and Li [36] discussed the challenges that this innovation may face. These include its vulnerability to shadowing, which can become catastrophic in many scenarios, like a street to street or street to roof; however, advances in massive MIMO may be able to address this deficiency. In addition to its propagation limitation, it has a sensitivity to weather and, the legacy frequency spectrum limitation. The work on mmWave backhaul is ongoing, with there being several pieces of research in progress. For example, "Optimizing mmWave Wireless Backhaul Scheduling" by Arribas and Anta, published in 2020, discusses the challenges of mmWave backhaul scheduling and derives a Mixed Integer Linear Programming (MILP) formulation for it as well as setting upper and lower bounds [37]. Further, in the research paper "Stochastic Geometry Analysis of Hybrid Aerial Terrestrial Networks with mmWave Backhauling" by Kouzayha and ElSawy [38], published in 2020, the results of the quality of the unmanned aerial vehicle (UAVs) backhaul link, which has a major role in improving the UE experience, were provided. The findings also revealed the impact of different UAV height regimes on the coverage probability. Moreover, Tang and Wen [39], discussed the use of mmWave in their published paper in 2022 "Physical layer authentication for 5G/6G millimeter wave communications by using channel sparsity", the study shows the mmWave channel perturbations that will degrade the detection performance. According to a 5G Americas white paper [17], the mmWave is immune to other cell interference, allows for frequency reuse and maximisation of spectrum efficiency as well offering very high bandwidth. Moreover, the deployment of MIMO technology or a multi-beam system planned for use in a 5G network. R& D project by Shinbo [40] was conducting to develop management technologies for high-reliability communications in the advanced 5G network. The approach mainly consider mm Wave band which can cover an area with an approximately 50-m radius (nano area). All this will present the opportunity for a new backhaul solution that known as IAB, which is considered as being one of the cost-effective technologies for handling 5G traffic.

2.4.3 Integrated access and backhaul (IAB)

It is defined by 3GPP TS 38.175 (Release 16) [42]. It states that the same infrastructure and spectral resources are utilised for both access and backhaul, as in Figure 2.14. Simsek and Narasimha [43] reported from their study that IAB nodes can operate as relay nodes or access points. With the introduction of high mmWave

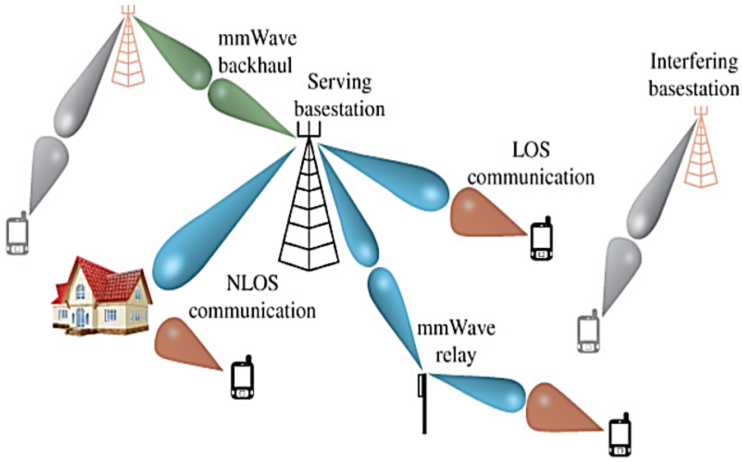

Figure 2.13: mmWave backhaul [41]

bandwidths, the attention to this technology has increased as a solution for meeting 5G requirements. Teyeb and Muhammad [44] pointed out in their study that 3GPP has been working on IAB since 2017, and it was standardised for Release (16), which was completed in mid-2020. Ronkainen and Edstam [45] stated that, in IAB, multi-hop backhauling can be provided by employing the same or different frequency bands for access and backhaul. The proposed architecture involving the integration of backhaul and fronthaul transport network for the first time was published in a study by Antonio De La Oliva [46]. Its goal was to develop the next generation of 5G integrated backhaul and fronthaul networks that allow for flexible, software-defined reconfiguration of all networking parts in a multi-tenant and service-oriented unified management environment, thereby addressing the aforementioned challenges with 5G technology. Key challenges that need to be addressed are the formation of an efficient IAB topology, providing topology updates, dealing with link failure or congestion, and establishing efficient topologies, in particular, the identification of the links that need to be activated to maximise the lower bound of the network capacity [43]. Several studies, such as "Millimeter-Wave Integrated Access and Backhaul in 5G: Performance Analysis and Design Insights", by Saha and Dhillon [47], investigated the use of this technology in a 5G network. It has been argued that, this new technology is crucial for facilitating better traffic flow, reducing congestion, and increasing resilience to backhaul connection failure. In addition, Sadovaya and Moltchanov [48] reviewed and characterised the system-level impact of multi-hop, multi-connectivity, and multi-beam operations on IAB performance in their study "Integrated Access and Backhaul in Millimeter-Wave Cellular: Benefits and Challenges", which published in 2022. Furthermore, directed communication using beamforming can minimise cross-link interference between backhaul and the access lines, thus allowing for higher densification.

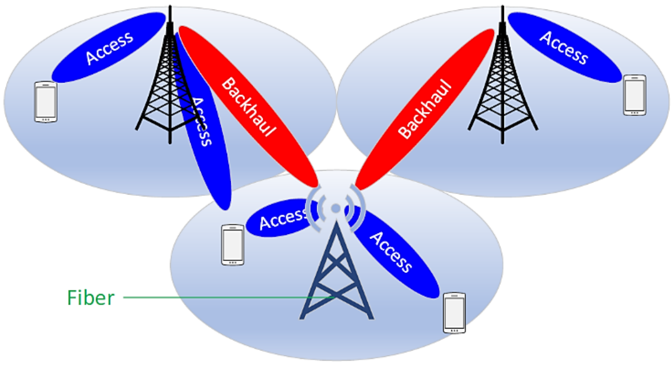

Figure 2.14: IAB layout [17]

2.4.4 High throughput satellites (HTS)

Satellite communications technology has progressed through different generations, resulting in substantial improvements in data transfer capacity and throughput. Ippolito, in his book [49], discussed how broadband satellite has become popular in the new generations of satellites. He stated that broadband satellites are those satellites that operate in the Ka-band Fixed Satellite Services FSS. More recently, the focus has been on those broadband satellites that can provide a significant increase in capacity. The 3GPP [42] studied and demonstrated the importance of satellites for mobile networks for the first time in Release (14), followed by TR38.811 (Release 15), TR22.822 (Release 16), and then, led by TS22.261 (Release 18) that 5G with satellite access and its requirements being outlined. All have highlighted the value that satellites will bring, particularly for industrial applications that require specific coverage and have introduced non-terrestrial networks as a new backhaul for 5G networks. The EMEA Satellite Operators Association [50] stated that Ka-band (and higher) for HTS will be a key for mobile cellular networks by the year 2025. It is anticipated that there will be over 100 HTSs in the orbits, geostationary GEOs and non-geostationary (NGEO) satellites delivering terabits of global connectivity traffic.

The ITU-R Resolution 174 (WCR-19) [51] was developing the road map for 5G networks through the International Mobile Telecommunications (IMT-2020). The document includes convergence of service delivery via multiple fixed networks FSS, mobile-satellite service (MSS), and broadcast-satellite service (BSS) satellites operating in new and expanded frequency bands. Studies like "Load balancing for 5G integrated satellite-terrestrial networks" by Shahid, Seyoum, and Won published on 17 July 2020 [52], and the "Uplink zone-based scheduling for LEO satellite based Non-Terrestrial Networks", by Mandawaria and Sharma [53], published in 2022, investigated the challenge of integrating satellites with terrestrial 5G networks. All classes of High Throughput Satellite (HTS) systems are expected to dramatically increase total throughput, achieve low latency, and allow for further significant reductions in bandwidth costs [54]. Figure 2.15 depicts the differences between traditional satellites and HTSs.

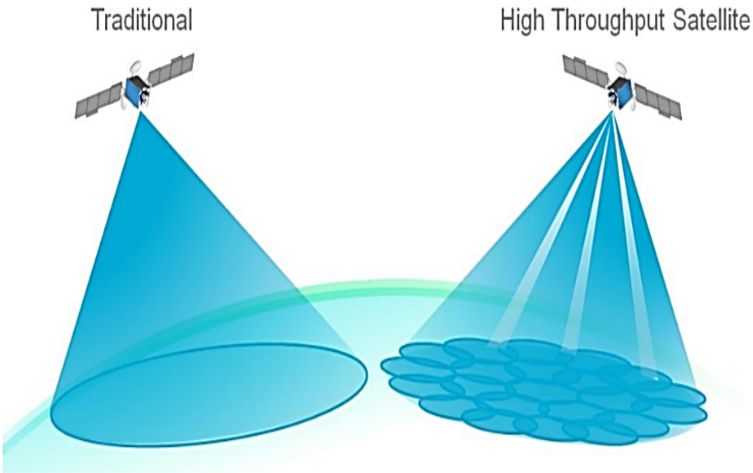

Figure 2.15: High throughput satellite (HTS) vs traditional satellite in terms of coverage [55]

A comparison is made between some key performance parameters of the new backhaul technologies, as shown in Table 2.2, in terms of cost, coverage, latency, and capacity. From the table, it can be seen that the mm Wave is a much more cost-effective approach to backhaul the 5G traffic than the legacy cellular architectures, which connect the micro base station to the core network through fibre. In addition, the mm Wave allows the micro base stations to cooperate with each other by acting as relay nodes. It is not only a more cost-effective approach compared with fibre but also, with the other new proposed backhaul technologies, as CLOS/NLOS, and HTS due the frequency reuse. The mm Wave also provides ultra-high-speed radio access and is ideally suited for efficient and flexible wireless backhauling for dense deployments, where a mm Wave macro base station can serve a large number of mm Wave micro base stations [37]. However, the development of the IAB approach, allows for rapid and affordable mm Wave installations through self-backhauling, which uses the same wireless channel for coverage and backhaul communication to base stations. This results in better performance, efficient use of spectrum resources and lowers latency due to the simultaneous receive and transmit [56]. It is considered as being the most cost-effective approach among all the four proposed new backhaul technologies due to the frequency reuse and resources sharing, but still lacks a regulatory framework for spectrum rules. In comparison with mm Wave and IAB, the table shows that the usage of CLOS combined with diffractive NLOS leads to higher cost owing to the frequency licences, installation and equipment costs. Whilst it does provide wider coverage than the mm Wave and IAB, it is still limited in terms of capacity [34]. When it comes to the HTS, this is considered as being the best approach for backhauling 5G traffic in terms of capacity and coverage, but remains challenging regarding manufacturing cost and latency. Whilst latency and cost remain an active area of research in relation to meeting 5G requirements, several studies consider the cost of the bit per second, user downlink/ uplink, and convenience of user terminals as more critical considerations for the adoption of HTS for 5G networks [57][58].

Table 2.2: Comparison between the four proposed new technologies [57, 59]

Backhaul types	**Cost**	**Coverage (km)**	**Latency**	**Capacity (Gbps)**
mmWave	Low compared with CLOS/NLOS, HTS	< 1	10 µs	< 100
IAB (mmWave)	More cost-effective than mmWave	< 1 (donor coverage)	< 10 µs	> 25
CLOS/NLOS	High	7–150	50 µs	1–5
HTS (Ka band)	Highest	50 LEO 400 GEO	< 30 ms	> 140

2.5 Cost Challenges and Financial Constraints in 5G backhaul Network Implementation

In the 5G era, estimating the cost for providing the services is becoming increasingly important. Cost estimation has become a common challenge for deploying telecommunication infrastructures across national territories. For any digital infrastructure, the expense of supply can exceed the price users are able to pay, especially in developing countries, where the annual income for the citizens is limited and governments struggle to secure financial resources for basic life infrastructure. These considerations become even more salient, with the new era of 5G technology, which is expected to require an advanced transport network, with a large number of cellular sites to provide greater capacity and coverage [60][61]. According to global system for mobile communications association (GSMA's) published research report [62], in 4G technology and 5G technology, the main reason as to why the cost has doubled is choosing fibre optics for backhauling the traffic, although this can meet the higher levels of user capacity demand. It has also been pointed out that, despite microwave having been considered as being more attractive for operators for over two decades compared to the high cost fibre optics, spectrum limitation remains a key challenge for delivering communication services. Hence, the innovations in the satellite field and producing a range of cost-effective new Low Earth Orbit (LEO) satellite constellations deployed to expand the coverage to rural and remote areas will play a vital role in backhauling 5G traffic. For some scenarios, the 5G campus network discussed in Section 2 will be beneficial when considering cost. It may be a promising solution and a first step to introduce 5G technology in developing countries [63]. 5G campus network can provide a localised network with 5G capabilities without the requirement for a costly backhaul networks. Though limited to a local area, this network can be useful in addressing specific localised needs and aid future developments and full-scale deployment.

2.6 Developing countries moving towards 5G Mobile networks

According to several studies, many developing countries lack or have a very limited 3G or 4G network. Masselos [64], discussed in his presentation that the operators prefer to concentrate only on making investments in infrastructure that is future-proof. Thus, outdated legacy infrastructures and equipment results in lack of access and backhauling infrastructure in most rural and urban areas in those countries. To illustrate the existing infrastructure in developing countries and their steps towards obtaining 5G technology, three examples are discussed below In Africa, for example, fixed wireline is practically non-existent in many regions, based on an Intelsat and Analysys Mason published article [65]. The article stated that in most circumstances, microwave connections are utilised as the equipment is widely accessible and spectrum licences are simple to obtain. Many African villages with huge populations are isolated, far away from their nearest neighbours. In these conditions, mobile operators are planning to deploy satellite as a backhaul and they have two alternatives for such connectivity, linking each base station to a single aggregation node or adopting a hybrid strategy that combines microwave and satellite technologies to expand for 5G. For instance, Gabon started testing the technology through Gabon Telecom in November 2019, but it has yet to become commercial and Geostationary satellite (GEO) based services are considered for 2023 [66]. In India, backhaul is also based on microwave connectivity and this will continue to be a crucial component until fibre connectivity is made generally available across the country, as Vatts from Bharti Airtel Limited stated in his published article [67]. Moreover, he stated that big investment has been made in the microwave to play a vital role as backhaul for mobile networks through all the generations. The major advantages of long-term backhaul implementation are better QoS and lower latency. According to the Indian Prime Minister, one of the most important criteria for delivering ubiquitous broadband access, is a reliable fibre backhaul network that ensures high capacity and speeds. The difficulties facing fibre penetration in India are delays due to the bureaucratic process of obtaining permission from the government authorities and cost. As a result, it remains a highly under fiberised country providing connectivity to less than 30% of the mobile towers and 7% of homes. On November 2021, Bharti Airtel telecommunication provider reported that the Airtel India had conducted a 5G trial for the first-time using SA mode, with coverage of 400 km between two sites. They did test the spectrum in multiple bands for the validation of 5G use cases [68]. In Iraq, according to the latest published report on the Iraqi telecoms industry [69], the destruction and degradation of telecommunications as a result of the Gulf War in 1991 were significant and so too were the economic sanctions that followed, resulting in a drop in the infrastructure of fixed telephones density to 3.3% of that in 2002. Moreover, Iraq has struggled to cope with the technological challenges owing to lack of copper and very limited optical fibre fixed-line infrastructure. The mobile services were delivered to the Iraqi citizens for the first time after 2002. It was a rapid start from zero before 2002 to 50% penetration rate in mid-2008. Thus, because of series developments which designated by the government of Iraq through the Ministry of Communications (MOC), and the Media Commission (CMC) in a planned development strategy for 2007-2010, to upgrade the telecommunications infrastructures [70]. In 2020, the three major operators, Zain Iraq, Asiacell, and Korek Telecom, owned 90% of the mobile infrastructure. The majority of this was based on GSM, 3G, and 4G in most regions of the country. To summarise, there is no one solution to 5G backhaul, i.e. no unique technology to meet 5G backhaul requirements. The main point is that to build future backhaul, current transport networks must be optimised, incumbent solutions, such as HTS must be developed and new technologies, such as mmWave, sub-6GHz, IAB, and others, must be investigated. For developing countries, there are different scenarios to be considered involving a number of factors, including the existing 3G or 4G network infrastructures, the available financial resources for deploying a 5G network and the population density in a certain geographic area. Given most developing countries are still struggling to launch 4G technology along with the obstacles to 5G implementation discussed in this paper, it is proposed that the preferred solution should be to align with recent research that puts a strong focus on the 4th scenario in Section 2 as a cost-effective transport network layout where the backhaul represent the entire transport network, and satellite backhaul, in particular, HTS. That is, this backhaul solution is recommended in the near future for 5G deployment for developing countries, for the following reasons.

- It will enable mobile operators to provide coverage in all rural and remote areas as well as overcoming the terrestrial infrastructure obstacles, such as civil wars, which can hinder any upgrade or expansion, and some random street civil work that may damage the underground and/or overground cables or any other telecommunications infrastructures.

- It would reduce the cost of mobile coverage as many companies are planning to produce low-cost nanosatellites, high throughput LEO satellites, and also, using laser technology can be used to connect satellites and high-altitude platforms (HAPs).
- Although, considered as the highest cost approach for backhauling 5G traffic, some studies have concentrated on satellite-based quantum communications [68] when adopting HTS for 5G networks.

2.7 Summary

This work has highlighted the obstacles and challenges those providers and operators who plan to invest, deploy or develop 5G technology in developing countries may face. The 3GPP and non-3GPP standardizations have been discussed in terms of the 5G transport and backhaul networks as vital parts that will play a major role in 5G network development. Introducing the new technology proposed by several studies that can be used for the backhaul network will facilitate the deployment of 5G for developing countries. Examples of existing infrastructures in developing countries in Africa, India and Iraq have been presented, with proposed solutions for the deployment of new 5G technology being provided.

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Chapter 3

Modeling and Simulation Framework for 5G Backhaul Network Design

3.1 Introduction

5G networks provide higher quality of services and improve the performance compared to previous cellular technologies. This has raised the expectation of the possibility of supporting advanced networks and providing unprecedented levels of flexibility and adaptability that are necessary for implementing diverse sets of services and applications [1]. 5G technology has been marketed as an "all-in-one" communications solution for a variety of application scenarios that have strict requirements for the dependable real-time transmission of data packets and reliable low-latency communication, such as industrial automation, Internet of Things (IoT), E-health, and self-driving vehicles[2]. Research on this new generation of technology and beyond has been increasingly undertaken in recent years. Notably, a number of EU-funded initiatives have endeavoured to develop cutting-edge scenarios for determining the needs of 5G. Similar to this, other efforts, like Next Generation Mobile Networks (NGMN) and standardization bodies, like the 3rd 3GPP and the International Telecommunications Union-Radio communications (ITU-R), have worked to identify the fundamental requirements to guide ongoing research into how to fulfil future demands. These efforts have resulted in a number of scenarios focusing on diverse requirements[3][4] as follows.

- Enhanced Mobile Broadband (eMBB).
- Critical Communications (CC) and Ultra Reliable and Low Latency Communications (URLLC).
- Massive Internet of Things (mIoT).

The characterization was based on the performance attributes of each UC's requirements, with respect to usage, for instance, the eMBB requires higher data rates and capacities whereas high reliable communication is required for URLLC and mMTC because they are considered as a latency sensitive UC [5][6][7]. As Table 3.1

Table 3.1: 5G use-case (UC) characteristics [7]

Use case (UC)	Characteristics	5G network layout	Application / services example
eMBB	Coverage, capacity, and super data layer	5G NSA	Broadband in the crowd
mMTC	Coverage and capacity layer	5G SA	Medical monitoring
uRLLC	Super data layer	5G SA	Roadside backhaul transport

It is also important to look into the economic developments/costs associated with implementing 5G networks, for instance, Oughtona [8] in their published study indicated there will be a 90 percentage of data growth due to technology change from 4G to 5G. They also highlighted the techno-economic problem of deploying 5G. In this regard, they pointed to the large number of new components required to operate enhanced network infrastructure, including base station units and backhaul transmission, as well as the associated costs of site installation and operation, network optimization and maintenance. While Shin [9] focused on analysing the 5G users and data traffic demand and how that demand would change based on several attributes, including the content amount, additional monthly fees and additional cost of devices. The study revealed a crucial foundation for mobile service providers' investment and marketing strategies that aim to maximize profits. Maximizing the use of bandwidth is an important consideration for developing countries because of lack of existing infrastructure and the lack of ability to upgrade them to support future communication schemes to offer the benefits of 5G and beyond systems. It is essential to provide the benefits to all so that developing countries do not lag behind other countries in this new digital age.

This chapter focuses on presenting the research modelling approaches, scenarios and technologies, and simulation platform that has been adopted in this study.

3.2 Modeling Framework for 5G Backhaul Network Evaluation

Although The IMT-2020 proposal [10] defines the minimum latency support for user plane latency need to be 4ms for eMMB and 1ms for URLLC, no specific study or research paper concentrate mainly on calculating the end to end (E2E) delay in details. Several studies considered the processing delay as a neglected value compared with other types of delay, other studies consider the transport network delay as a neglectable value compared with other parts of network. With 5G and the critical services and applications offered, it's important to consider all the delays may occur in each node from sender to receiver. For instance, in [11] the authors, present latency parameters for V2X packets which has shown some minor differences from the 3GPP report. The one-way delays are varied between 10-20 ms. However, the use of deterministic values to model the latency does not consider the impact of 5G network deployments and configurations, as well as varying network traffic loads, on the latency. while, in [12], the total delay when a packet is routed between consecutive virtual nodes consist of packet processing delay, packet queuing delay, and packet transmission delay, and is determined using network traffic measuring tools instead of analytical modelling. The E2E delay for packets going through each source - destination node pair in an embedded virtual network is then calculated to achieve QoS aware multi-cast virtual network embedding. However, in [13], the authors discussed the applications, the UCs as well as the massive Multiple-Input-Multiple-Output technologies, for example antenna beam-forming and network densification to enhance the system capacity and mobility of 5G cellular networks. In [14], the authors discussed the predicting communication bandwidth using signal strength parameters and other physical factors that can affect the exactness of achievable prediction using machine learning methods. In [15] the authors, presents an experiment on 5G backhaul Small-Cell, includes an advanced Microwave Link Aggregation (MLA) technique to provide enough backhaul capacities for 5G network. The advantage of this study is employing simulation-based approach to consider total E2E delay from core to the end users, and users access percentage to evaluate the optimal bandwidth factor for each link in the network while designing/ upgrading current/ future cellular systems in developing countries.

In 5G, the transport network considers as one of the key aspects for guaranteeing QoS needs to be flexible and future proof. It is the network that needs to provide optimal connectivity between the radio access network (RAN) and the core network (CN), whilst ensuring an appropriate level of flexibility in terms of delay and capacity due to their impact on the network's performance [16].

The design is focused on a 5G standalone network (SN). The communication infrastructure in most developing countries is set up using a Core – L3 switches – base station equipment. This equipment is linked using communication links with specific characteristics to support the intended network performance. By observing the output traffic delays, the required link capacity is determined from various random scenarios. Observing link utilization for which the delay requirements are met the 3GPP standards is an efficient method to propose the most efficient backhaul technology to deploy 5G network in developing countries.

3.3 MATLAB model details

E2E QoS is an essential performance requirement for 5G services and applications, which must be ensured across different deployment areas. It needs to be achieved in a cost-effective manner that does not require the over provisioning of network resources.

5G backhaul network expected to reflect several benefits and advancements in terms of data speed, latency, capacity, energy, cost, coverage, and network reliability, Table 3.2.

Table 3.2: 5G matrices [17][18]

Metric	Results	Percentage
Data speed	10 Gbps	100 %
Latency	1 ms	90%
Network capacity	100X	10000%
Energy efficiency	50%	50%
Deployment cost	30%	30%
Network coverage	95%	95%
Network reliability	99.999% uptime	99.999%

MATLAB simulation was carried out based on the network layout in Fig. 3.1 [19]. The assumed actual link delay and bandwidth were computed for the communication links between Core and L3 switches, L3 switch interconnects in a ring layout and L3 switch and gNB. Random distribution of users distributed with an expected maximum of number of users of i, where i depends on the case that will be simulated. A simulation model was formed based on the data rate requirements of individual cases and the model was employed to compute user access statistics and delay for each case based on available bandwidth in the links. Simulations were repeated a fixed number of times (1000) and the results were averaged to have confidence in the results.

3.3.1 E2E Delay statistics

From 3GPP Release 8 ("Rel-8") to Release 13 ("Rel-13"), the industry has been moving forward along a "faster" trajectory. Subsequently, 3GPP found that it was not enough to just emphasize speed, for attention also needed to be paid to the time delay. Moreover, it became apparent that delay was not only affecting the network speed, but also, bringing challenges to guaranteeing the QoS and user experience [2]. E2E delay is one of the significant performance parameters under ultra-density circumstances. It is defined as a latency perceived by the user that pertains to the

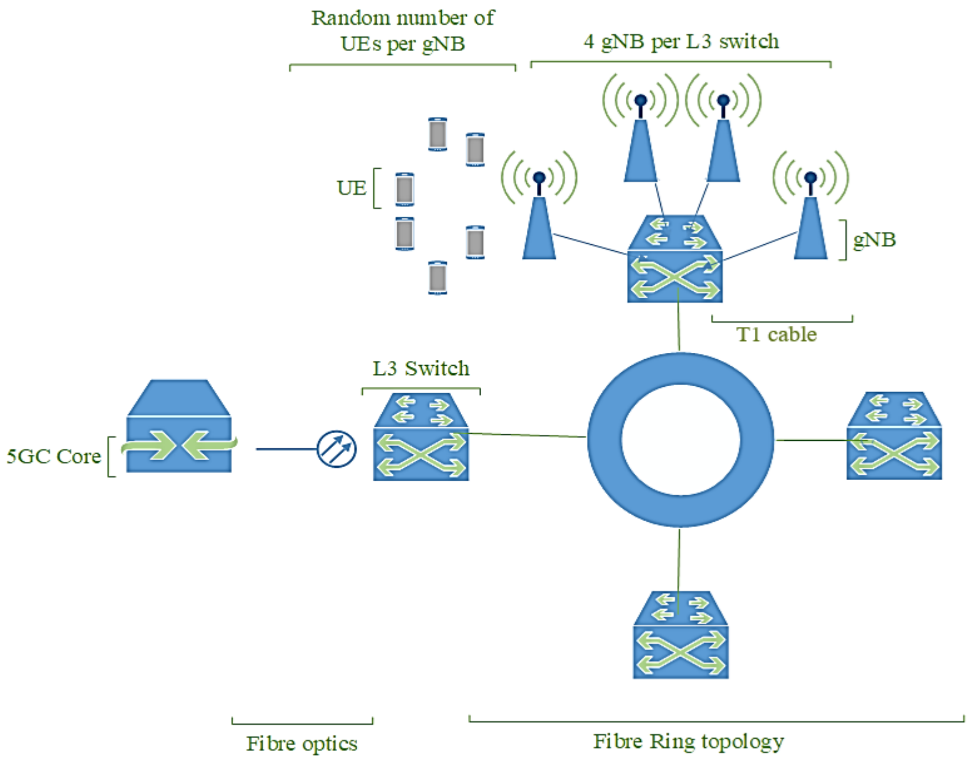

Figure 3.1: Simulation network layout-Fibre optics

round-trip time from the application layer of the source node to the destination node at the same layer. When the lower layers (physical and mac layers) are taken into consideration, the E2E delay of a flow is evaluated according to the propagation delay in links, the transmission time in sending packets to media, the queuing delay that is the waiting time in forwarding devices and the processing delay, that is, the time passed for forwarding decisions [20]. Delay considerations will strongly influence the network's performance and the user's experiences as it will have an impact on the current and foreseen applications and services of the 5G networks and beyond. In this study, it is considered that the total E2E (DL) delay ($\mathfrak{D}$) can be expressed as the sum of the delays experienced by all the network's entities, mainly the transport network delay $T_{\text{transport}}$, core delay T_{core}, L3 switch delay $T_{\text{L3 switch}}$, gNBs delay T_{gNB}, and end user delay T_{user} [21, 22], as follows Equation 3.1 (3.1a -3.1i):

$$\mathfrak{D} = T_{\text{transport}} + T_{\text{core}} + T_{\text{L3 switch}} + T_{\text{gNB}} + T_{\text{user}} \tag{3.1a}$$

The transport network delay (DL) in this study is defined as the sum of the backhaul network and fronthaul delay, Equation 3.1b [21, 23].

$$T_{\text{transport}} = T_{\text{backhaul}} + T_{\text{fronthaul}} \tag{3.1b}$$

However, the 5G transport network adopted for this study is represented by the backhaul network only [24], Figure 2.9 in Chapter 2, Section 2.2.

Based on Equation 3.1b, the transport network delay $T_{\text{transport}}$ is equal to the backhaul network delay T_{backhaul} , as in Equation 3.1c.

$$T_{\text{transport}} = T_{\text{backhaul}} \tag{3.1c}$$

The backhaul delay comprises the propagation time T_{g} of the packet that travels through the links, the processing time T_{p} of the packet in each node, and the transit time delay, which includes the queuing time T_{q} of the packets in each network node, and the transmission time T_{t} over the backhaul network from the core towards the gNB and then to each user. In this study, packet retransmission is not considered. The transport network delay is expressed as Equation 3.1d:

$$T_{\text{backhaul}} = T_{\text{transit}} + T_{\text{g}} + T_{\text{p}} \tag{3.1d}$$

a. Transit delay

Represents the time that packets spend in the transport network node (s), it includes:

- Queuing delays between the time a packet is assigned to a queue for transmission and the time it starts being transmitted,
- Transmission time delays,

The estimation of the transit time delay is represented by (T_{g} + T_{t}). Each element in the network is modelled as an M/M/1 queue, and considers a Poisson process for each packet that arrives with an average arrival rate (λ), and receives the packets at an average service rate (μ)[25], Equation 3.1e.

$$T_{\text{transit}} = T_{\text{q}} + T_{\text{t}} \tag{3.1e}$$

Using λ and μ, the average transit time delay when the packets pass through n network elements towards the end user is expressed following Jackson's theorem [25] as Equation 3.1f:

$$T_{\text{transit}} = \sum_{i=1}^{n} \frac{1}{\mu_i - \lambda_i} \tag{3.1f}$$

Where, the μi and λi are the traffic service and arrival rate delivered in the downlink channel through the transport network elements i, i = 1. . . , n. By using the properties of the Poisson process, the average arrival rate of the traffic that the element i has to dispatch through each of the m links for the downlink is determined as Equation 3.1g [25]:

$$\lambda_i = N_i \cdot \frac{B}{\mathcal{P}} \tag{3.1g}$$

Where, Ni is the number of users attached to the element i in the network, B is the experienced data rate in bps, and packet size ($\mathcal{P}$) is the message size, in bits, that arrives for each 5G service or application. All the packets arriving at the network element i have to be dispatched to their destination through m links, with the service rate of a transport network element i and the next element i+1 in the downlink being computed as Equation 3.1h:

$$\mu_i = \frac{\alpha \cdot C_i}{\mathcal{P}} \tag{3.1h}$$

The service fraction α is the fraction of the link capacity that is allocated for the downlink. C_i is the link capacity that connects the i transport network's elements in bps, and packet size is the message size, in bits, that arrives for each 5G service or application. Equation 3.1g and Equation 3.1h are both used to calculate the transit time delay by Equation 3.1f.

b. propagation time delay

The time it takes a packet to travel through the links that interconnect the nodes of the transport network. The propagation time delay computed as Equation 3.1i:

$$T_{\mathrm{g}} = \frac{\mathrm{D}}{\mathrm{S}} \tag{3.1i}$$

where, D is the total distance that the traffic travels from sender to receiver in the backhaul network, and S is the speed of the link that it will pass through.

c. Processing delay

The time it takes to handle the packet on the network system. For mobile networks, the processing delay in the UE includes packets processing and decoding in each node, while on the UL, includes packets processing and decoding in each node. In gNB processing delay mainly caused by scheduling process [26]. Although, the processing delay has been considered as a negligible time delay in the previous mobile networks however, that this is not the case anymore as packet processing on mobile nodes becomes more complex. The packet processing can take considerable time when ultra-low latency applications are involved. Encryption of a single packet, for example, can take in the order of milliseconds, which contributes as much, as Table 3.3 of the overall packet delay [27].

As in the table, processing times will decrease in 5G simply because of the shorter transmission time TT. 5G supports the shortest transmission time interval TTI of 0.125ms, while LTE Release 8 has 1ms TTI and HSPA has 2ms TTI [33].

Table 3.3: Two ways processing delay

Delay component	**Processing Time**
Core Processing (ms)	0.05 [28]
UE processing (ms)	0.2 [29]
gNB processing (ms)	0.2 [29]
Transport and core (ms)	0.1 [29]
Repeater (ns)	0.5 [30]
Re-generator (ns)	20 [30]
L3 Switch (ms)	0.0001 [28]
mm Wave (ms)	0.02 [31]
DSL (ms)	0.02 [31]
MW (ms)	0.02 [31]
Fibre (ns)	50 [32]

3.3.2 Capacity planning based on users access statistics

Capacity is the fundamental difference between 5G and previous generations, which will allow for increased access to connectivity for new applications and services. It is primarily required for end user and network delivery of the eMBB UCs, while it has less impact on the services and applications classified under the UCs the mMTC and URLLC [13]. Planning optimized capacity for 5G networks and beyond is a challenging task due to its major impact on the QoS and users' experiences. Specifically, 5G networks are designed to provide new services, such as video surveillance, industrial control sensors, cloud VR, in addition to intelligent building services and work with the robotics. In order to keep up with the booming and diversified 5G services, a flexible capacity planning needs to be adopted to cope with the future needs in terms of changing volume requirements of services, areas variety and the rapid increase in traffic [34].

To calculate the link capacity C, need to consider the user bit rate (UBR), the maximum number of users to be served (MUES) and to define bandwidth factor (BWF) of the expected maximum number of users in a cell, for achieving system requirements in terms of delay and sufficient link capacity, Equation 3.2 (3.2a - 3.2b) is considered. Where ALB is the actual link bandwidth and GUB is the aggregated maximum number of user bandwidth. [35][15]:

$$\mathcal{BF} = \frac{\text{ALB}}{\text{GUB}} \tag{3.2a}$$

$$C = \mathcal{BF} * \text{UBR} * \text{MUES} \tag{3.2b}$$

While, the percentages rate of user without access Uϕ of different BWFs for all the links is defined as Equation 3.3, where UEϕ is the number of users without access.

$$\text{U}\phi = \frac{\text{UE}\phi}{\text{Total UEs}}\% \tag{3.3}$$

The number of users without UE ϕ access is determined by considering the maximum capacity of the communication links for each technology to the required capacity to service the actual number of users of the network and the total traffic demand generated by the users that are allocated to each gNB.

In addition, two types of relay hops are considered; repeaters, and re-generator. The selection between them mainly depend on the network deployment and design, and whether its ultra low latency or not due to the high processing delay in the re-generator. The number of hops for each technology is determined based on Equation 3.4. The number of hops (H) mainly depends of the required coverage distance D_Total over the maximum technology distance D_Tech.

$$\mathcal{H} = \frac{D\_Total}{D\_Tech} \tag{3.4}$$

The velocity factor is also considered in this simulation to ensure accuracy and bring the results closer to real-world design. For different backhaul technology, different velocity factor has been adopted. The velocity Factor is the ratio of the speed at which a signal travels through a transmission medium to the speed of light in a vacuum, and its calculated based on the technology used for backhauling the traffic, as Equation 3.5 (3.5a - 3.5c):

$$\text{VF} = \frac{V}{C} \tag{3.5a}$$

where V is the signal speed in the medium and C is the speed of light in vacuum.

$$V = \frac{C}{n} \tag{3.5b}$$

Combining (3.5a) and (3.5b) gives

$$\text{VF} = \frac{1}{n} \tag{3.5c}$$

Example (fibre optics, target VF = 0.8). Choose $n = 1.25$:

$$C \approx 3 \times 10^8 \text{ m/s},$$
$$V = \frac{3 \times 10^8}{1.25} = 2.4 \times 10^8 \text{ m/s},$$
$$\text{VF} = \frac{1}{1.25} = 0.8.$$

The below table shows the velocity factor calculated for each technology has been adopted in this research:

Table 3.4: The velocity factor

Fibre optics	0.8
MW	1
mmWave	1
DSL	0.65

3.3.3 Evolution cases and scenarios

The scenarios presented in this study are utilized to evaluate the performance of 5G which supports different services and applications with different requirements. Following the 3GPP standard [6], each case is modeled based on the parameters shown in Tables 3.5, 3.6 and 3.7 respectively. The data for each case forwarded in the downlink direction from the core through a fiber optic or microwave ring topology of L3 switches towards the end user. The backhaul network is implemented based on the reference network model defined by one of the major cellular mobile networks in Iraq (ASIACELL) [19][36].

Case 1: Broadband access in a crowd (eMMB)

The case for stationary users, pedestrian users, and users in vehicles, for example, in offices, city centers, shopping centers, residential areas, rural areas and in high speed trains. The passengers in vehicles can be connected either directly or via an onboard base station to the network. One major example of this case is the stadium, which is considered a challenging core case for operators in providing their services and building their brand and reputation by delivering a reliable high capacity and low latency service [6][34]. This case is simulated based on the values in Table 3.5.

Case 2: Wireless roadside infrastructure backhauls (URLLC)

Traffic light controllers, roadside units, traffic monitoring in urban areas these are wirelessly connected to traffic control centers for management and control purposes

Table 3.5: KPI Parameters for Broadband in the crowd applications [37]

Max. delay	Data rate	Packet size	UE Density	Service area
5 ms	25 Mbps	1500 Bytes	3000	7000 km^2

via wireless technologies like Dedicated Short-Range communications (DSRC), IEEE 802.11p for high-speed vehicles and roadside infrastructure known as Wireless Access in Vehicular Environments (WAVE), Bluetooth, and Communications Access for Land Mobile (CALM). The use of intelligent transport system (ITS) can aid in handling the issue of traffic congestion. Several innovations have been put into practice, including those related to mobility, self-driving cars, real-time location, road safety, intelligent traffic lights, connectivity, smart logistics, and innovative trains[38]. This case was simulated based on the values in Table 3.6.

Table 3.6: KPI Parameters for Wireless roadside infrastructure backhauls [38]

Max. delay	Data rate	Packet size	UE Density	Service area
15 ms	10 Mbps	1500 Bytes	4000	5 km^2

Case 3: Medical monitoring (mMTC)

To support thousands of medical devices simultaneously, from sensors to mobiles, medical equipment, and video cameras. Supplemented by a 4k or even 8k ultra-high-definition television, or monitor system, this could offer sharper, clearer streaming video with more detail content resolved information beyond the retina. High-bandwidth 5G enables the sharing of 3D 4K pathological images of patients, and low latency can allow for the realization of real-time multi-screen interaction, where doctors can discuss and annotate in real time and deliver medical solutions in a timely manner. Hence, the network planning and design must coordinate delay and capacity planning for different functional areas, as well as provide dynamic network adjustment and optimization for these areas [16][39]. This case was simulated based on the values in Table 3.7.

Table 3.7: KPI Parameters for Medical monitoring [6]

Max. delay	Data rate	Packet size	UE Density	Service area
50 ms	1 Mbps	1000 Bytes	12000	12000 km^2

The simulation was set up with a random number of users per cell (gNB), while fixing the expected maximum number of users in each, with the same maximum number of users assumed per cell for simplicity. Four cells were assumed to be served by a L3 switch as L3 switch locations centered around served cells, with these arranged in a ring topology with one-way traffic. case 1 in Table 3.5 is the case that was adopted to simulate and analyze in this study, and further future work will consider cases 2 and 3. To simulate E2E one-way delay (DL), the transit delay is calculated based on Equation 3.1e and Equation 3.1f for the links from the core to the L3 Switch, L3 switch to the next L3 switch, and L3 switch to gNB. The total propagation delay for all the links from the core to each user was calculated based on Equation 3.1i. A fixed high transit delay was assumed when there is a high arrival rate compared to the service rate at a node (20 ms). In addition, the approximate processing delay for the backhaul network was estimated based on the study [29][40], as shown in Table 3.8.

Table 3.8: Estimated values for processing delay [29]

Node	Core	L3 Switch	gNB	UE
Processing delay	0.05 ms	0.001 ms	0.1 ms	0.1 ms

The estimated link capacities for core to L3 switch, L3 switch to L3 switch, and L3 switch to gNB were estimated based on Equation 3.2a and Equation 3.2b. While, the percentage rate of user access for the users who cannot be granted access of different BWFs, was simulated based on Equation 3.3.

3.4 Case Study: Simulating Backhaul Performance Under Variable Bandwidth

MATLAB based simulations were carried out based on the parameters in Table 3.9. Fibre links were assumed in the backhaul with one way communication in the ring for simplicity.

Table 3.9: Simulation parameters

Number of runs for averaging	10000
User bit rate	10 Mbps
Packet size	800 bits
Velocity factor for fiber	0.8
Number of cells (gNBs)	16
Number of cells per L3 switch	4

Random distribution of users in a specific run is shown in Fig. 3.2 These are distributed with an expected maximum of number of users of 40 in each cell. The same 40 maximum users were assumed for all cells in the network.

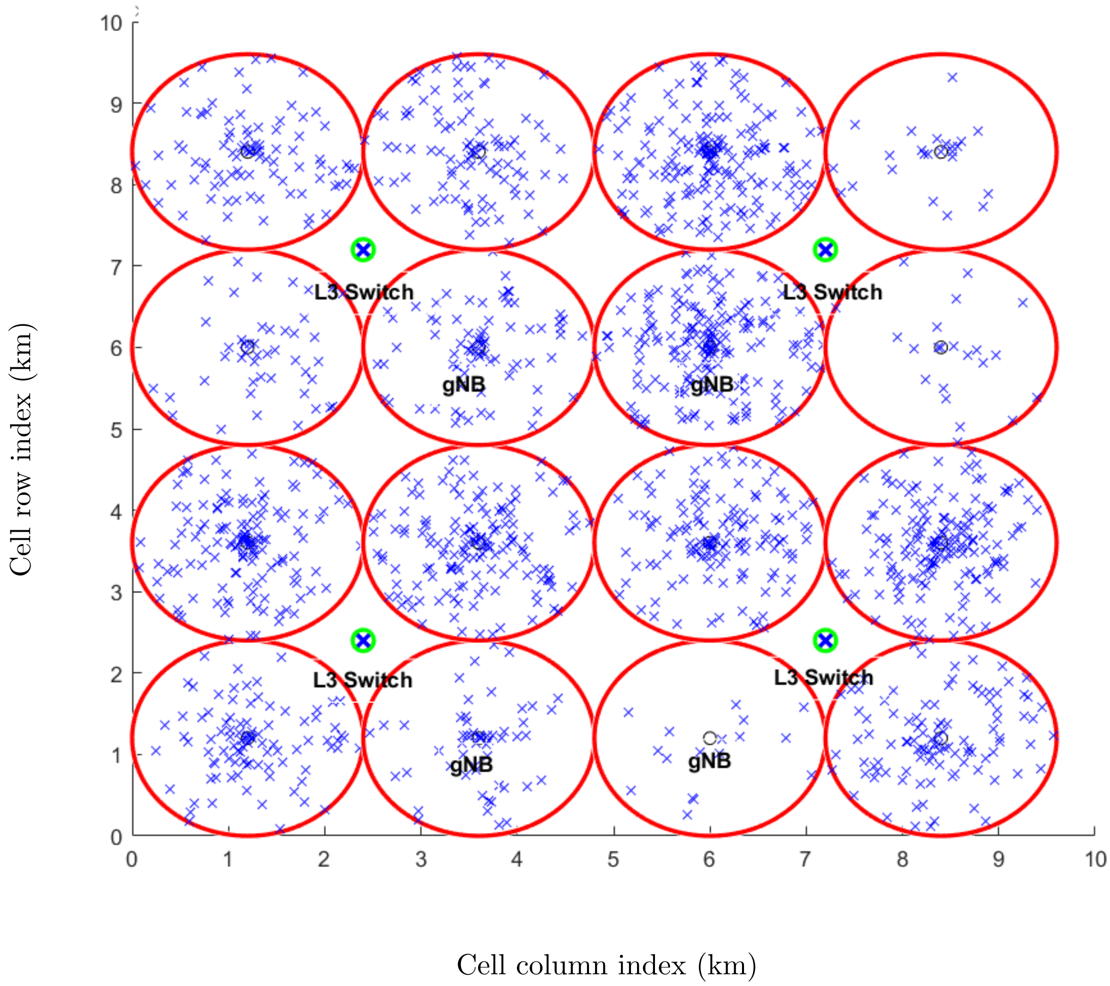

Figure 3.2: User distribution across a 4 × 4 cell grid (16 cells) with a gNB at each cell center.

The fractional bandwidth factor between the L3 switches were varied while keeping the fractional bandwidth between L3 switches and the gNB at 1 and the Core – L3 fractional bandwidth factor equal to the varied factor between L3 switches. Fig.3.3 shows the average user access statistics based on available bandwidth and Fig.3.4 shows the computed average downlink delay between Core and the user. These statistics were initially averaged by the number of users and then by the number of runs.

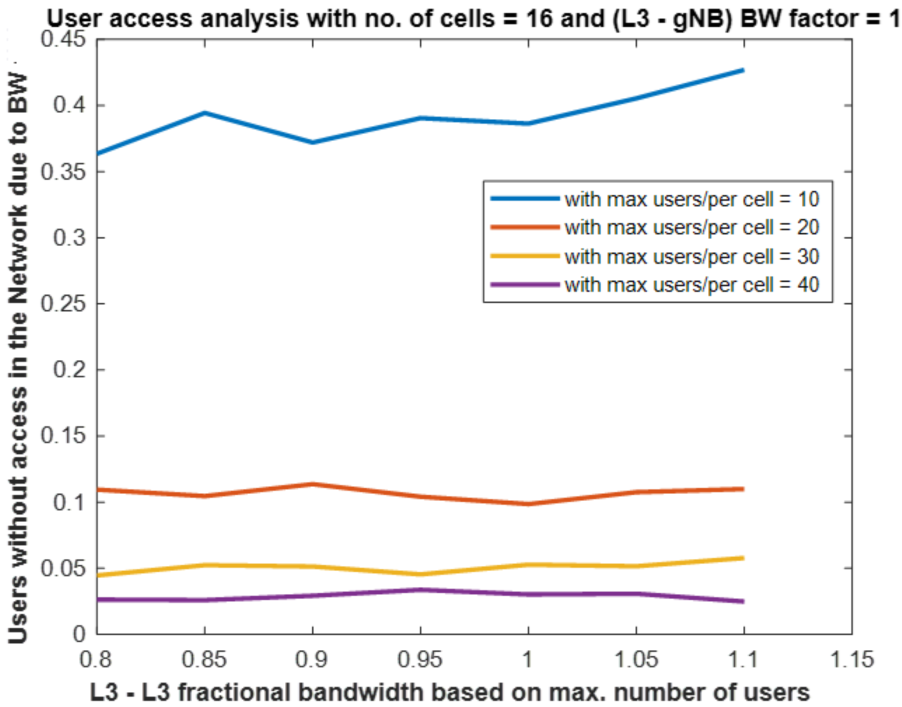

Figure 3.3: User access statistic in the network with varying fractional bandwidth between L3 switches.

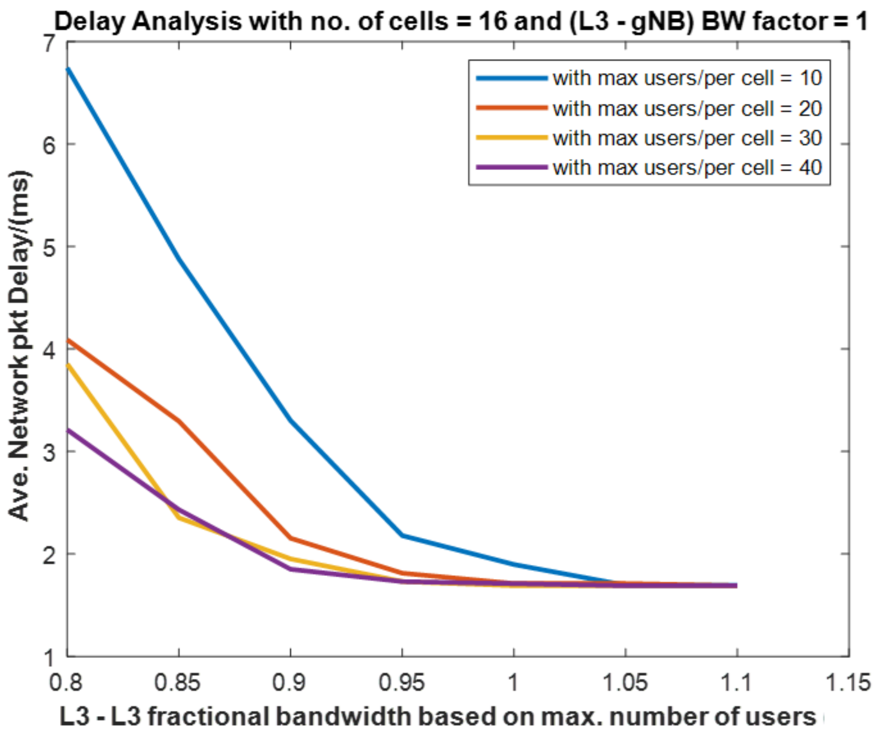

Figure 3.4: Computed average downlink delay between Core and the user with varying fractional bandwidth between L3 switches.

These results clearly show the importance of bandwidth with respect to user access and delay. Although lower fractional bandwidths can help to provide reasonably good user access, delay requirements might prevent using lower fractional bandwidths. For systems where delay is not an important requirement, system designs can focus on maximizing the use of bandwidths in these links. Dynamically varying the bandwidth allocation is also a possibility in these scenarios depending on the type of users in the system. Further analyses were also carried out to investigate transit delay and propagation delays and shown in Fig 3.5. This figure shows how increasing the L3 fractional bandwidth reduces average queuing delay significantly while causing only minor variations in average propagation delay for different maximum users per cell.

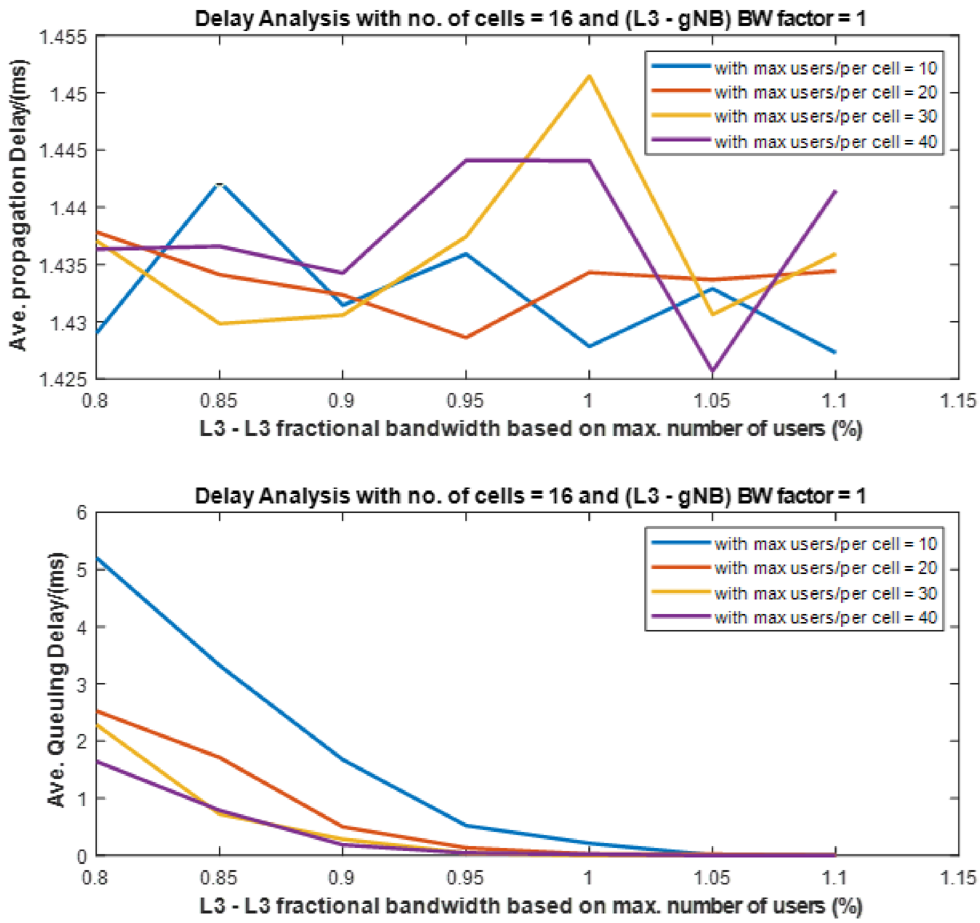

Figure 3.5: Computed average downlink transit and propagation delay between Core and the user with varying fractional bandwidth between L3 switches

3.5 Summary

This chapter builds the model used for the rest of the thesis and applies it to a realistic eMBB case. The bandwidth factor (BWF) is treated as a ratio on each backhaul link and tied to real capacity (e.g., on a 10 Gbps link, BWF = 0.4/0.8/1.0 corresponds to 4/8/10 Gbps). Increasing this ratio consistently admits a larger share of users and lowers average end-to-end delay. The largest gains occur when moving from low to mid BWF; near full allocation, returns diminish.

The delay breakdown clarifies the pattern: at low BWF, queues dominate, so modest capacity increases have a strong effect; at higher BWF, the residual is mostly propagation delay, yielding smaller improvements. If the core–satellite trunk operates at a lower BWF than the Sat–gNB segment, it becomes the choke point—raising only the access side yields limited benefit because the core trunk caps throughput. Higher user density pushes the system into saturation earlier, degrading both access and delay unless links are provisioned accordingly.

Practical implication: for the modeled eMBB traffic, setting the tighter backhaul link around BWF 0.8 (8 Gbps on a 10 Gbps link) generally meets the delay target; below 0.6, drop rates and queueing delay rise noticeably. These patterns guide the technology choices and sizing decisions in subsequent chapters.

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Chapter 4

Simulation study for exploring network behavior for various terrestrial backhaul technologies

4.1 Introduction

Chapter 3 has introduced the methods and methodologies which were used in this research. This chapter will present the simulation results for different backhaul technologies in order to study the behavior of each one in terms of different users.

4.2 Modelling different backhaul technologies

The possibility of 5G supporting different applications and scenarios depends on its capacity to satisfy their latency requirements. The main method to determine the required link capacity is by observing the traffic delay and increasing the capacity incrementally by changing the factor for each link in the network, if needed, to achieve the optimal capacity. BWF of each link should adher to standard average E2E delay values, and optimized to ensure a minimum percentage user access rate.

3GPP establishes strict reliability and latency requirements defined in Chapter 3, Table 3.5, 3.6, and 3.7. To ensure 5G quality of services for broadband in a crowd application as an example, the one-way delay strictly needs to be below 5 ms and the percentage users access rate between 0.05 and 2.5 [1]. Hence, modeling and comparing the performance of various backhaul technologies will offer valuable insights for designing systems to deploy 5G networks with strict delay requirements.

Four scenarios are adopted in this research for backhauling the traffic in 5G network, Fiber optic and DSL backhaul technologies as a wire backhaul and Microwave and mmWave technologies as a wireless backhaul. The selected parameters of the maximum bandwidth is given in Table 4.1, and the maximum distance and the number of hop of each technology are given in Table 4.2, where the hop length is the maximum unrepeated span of a link the longest distance between two active endpoints without any repeater, amplifier, or regenerator in between [2]. Various users density and cell size are considered in each scenario of the fourth scenarios.

Table 4.1: Parameters setting for both Fiber optics, mmWave, MW, and DSL scenarios in terms of distance in terms of bandwidth [3][4]

Backhaul technology	Bandwidth
Fiber optics (DWDM)	600 Gbps
Fiber optics	10 Gbps [5]
DSL	100 Mbps [6]
Microwave	1-10 Gbps [7] [4]
mmWave	10-100 Gbps [8]

Table 4.2: Parameters setting for both Fiber optics, mmWave, MW, and DSL scenarios in terms of distance and number of hops

Backhaul technology	Max. distance	No. of hops
Fiber optics (ring)	60 km	No hops [5]
DSL	150 km	hop length [6]
Microwave	2 - 4 km	hop length [4]
mmWave	1-3 km	Hops lenght [4]

4.2.1 Fiber optic backhaul scenario

In wire scenario, the simulation set up with fiber optics backhaul from 5G core network to each gNB, as Figure 4.1. In this type of backhaul, the maximum distance can cover till 60 km without need to a repeater, Table 4.2 [9]. The maximum bandwidth adopted in this scenario for the ring Dense Wavelength Division Multiplexing (DWDM) based on the exist network parameters that used in one of the developing countries. The velocity factor adopted to this scenario is 0.8.

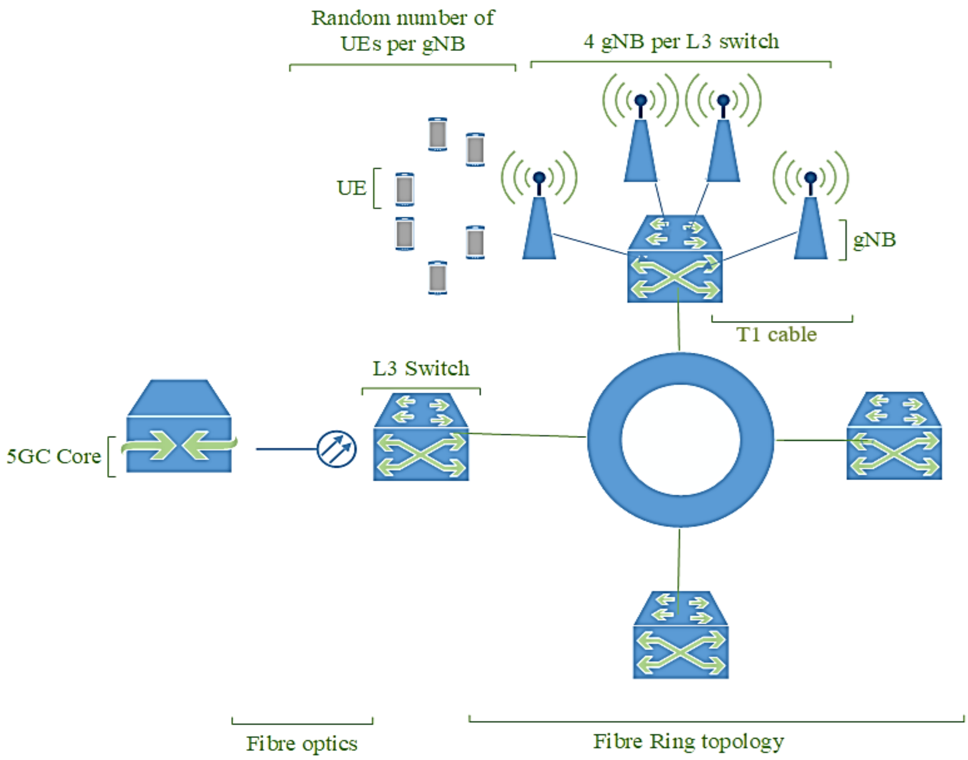

Figure 4.1: Fiber optics simulation network layout

4.2.2 xDSL backhaul scenario

Another wire backhaul scenario, the Digital subscriber line DSL backhaul is considered as a multi hop link and it fits for links with modest length Fig 4.2. The simulation set up with a copper cable T1/E1 to provide a connection from L3 Switch to each gNB in the network. For this scenario the maximum coverage distance without rely hop is 150 km, as Table 4.2, after this distance repeater required. The velocity factor adopted to this scenario is 0.65.

4.2.3 Microwave backhaul scenario

Microwave technology used worldwide for backhauling mobile traffic due to its low deployment time and cost. In this wireless scenario, the simulation set up with microwave link from L3 Switch to each gNB, Fig.4.3. The maximum coverage distance for this technology is 4 Km hop length. The velocity factor adopted to this scenario is 1.

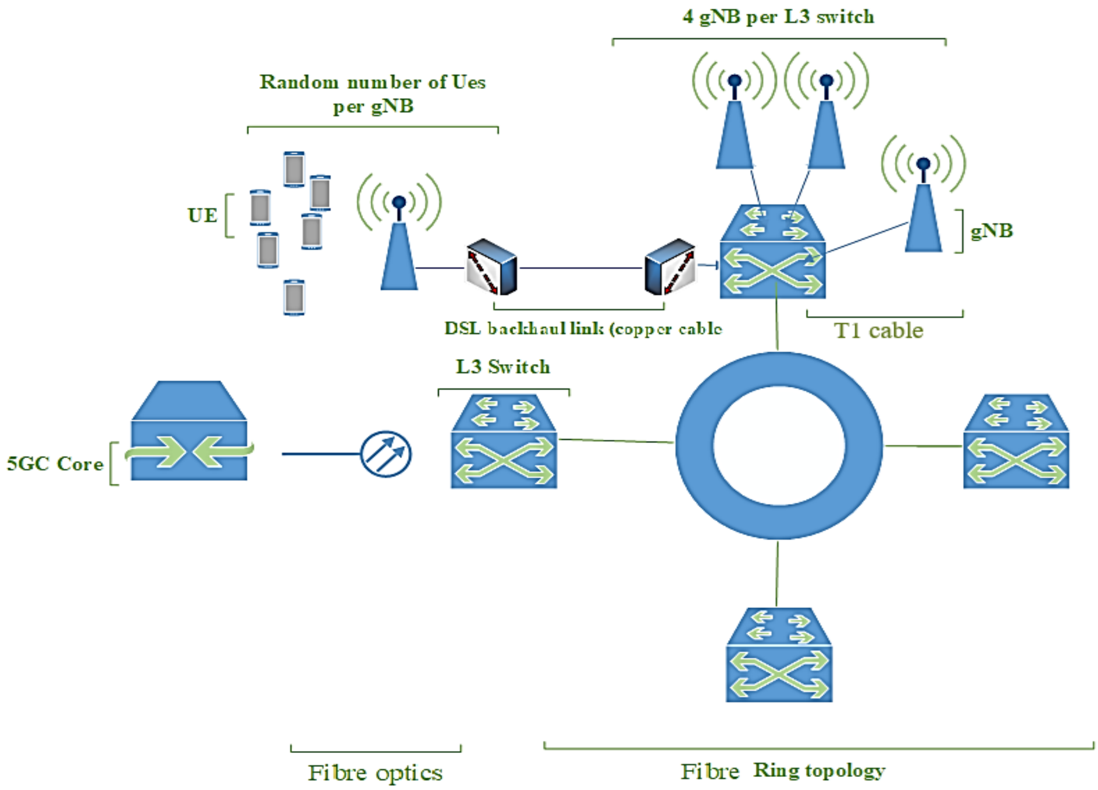

Figure 4.2: xDSL simulation network layout

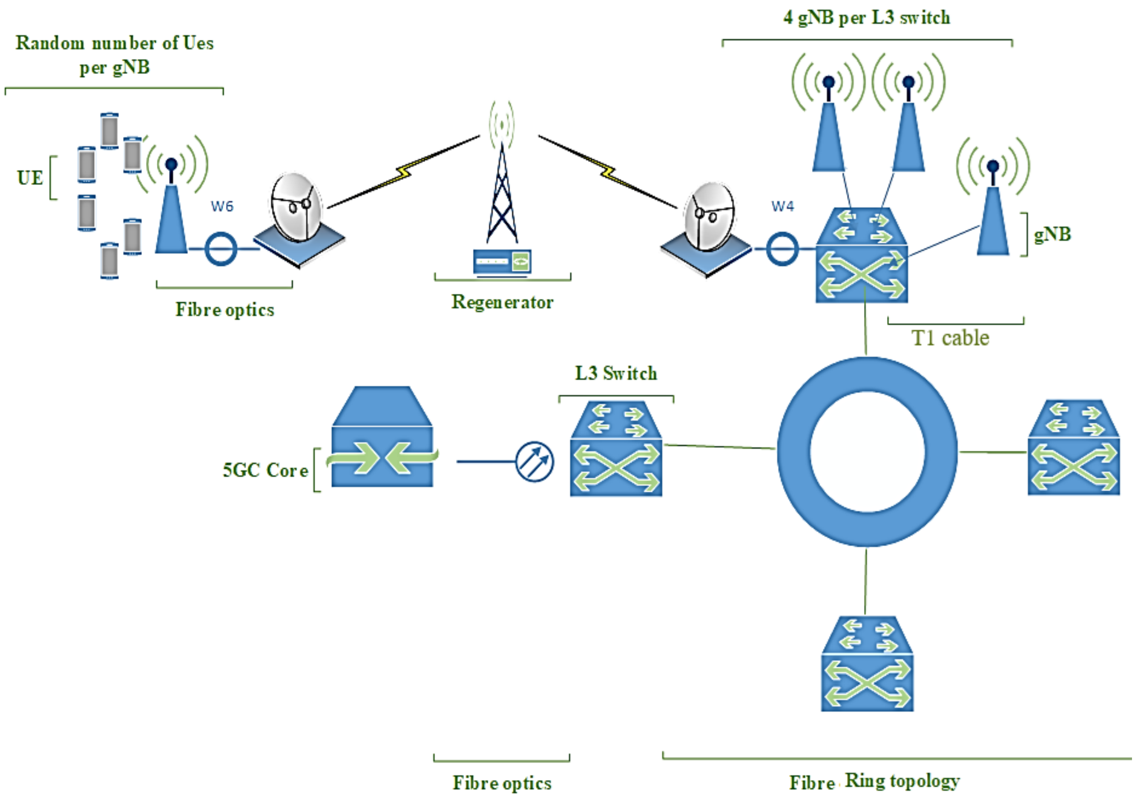

Figure 4.3: Microwave simulation network layout

4.2.4 mmWave backhaul scenario

Another potential wireless bamckhaul solution is mmWave technology of 60 GHz, and 70-80 GHz. It offers high capacity and reliability conditioned on LOS links. The simulation set up with mmWave backhaul from L3 Switch to each gNB, Fig 4.4. In this type of backhaul, the maximum distance can cover till 3 km hop length, as in Table 4.2 [10]. The velocity factor adopted to this scenario is 1.

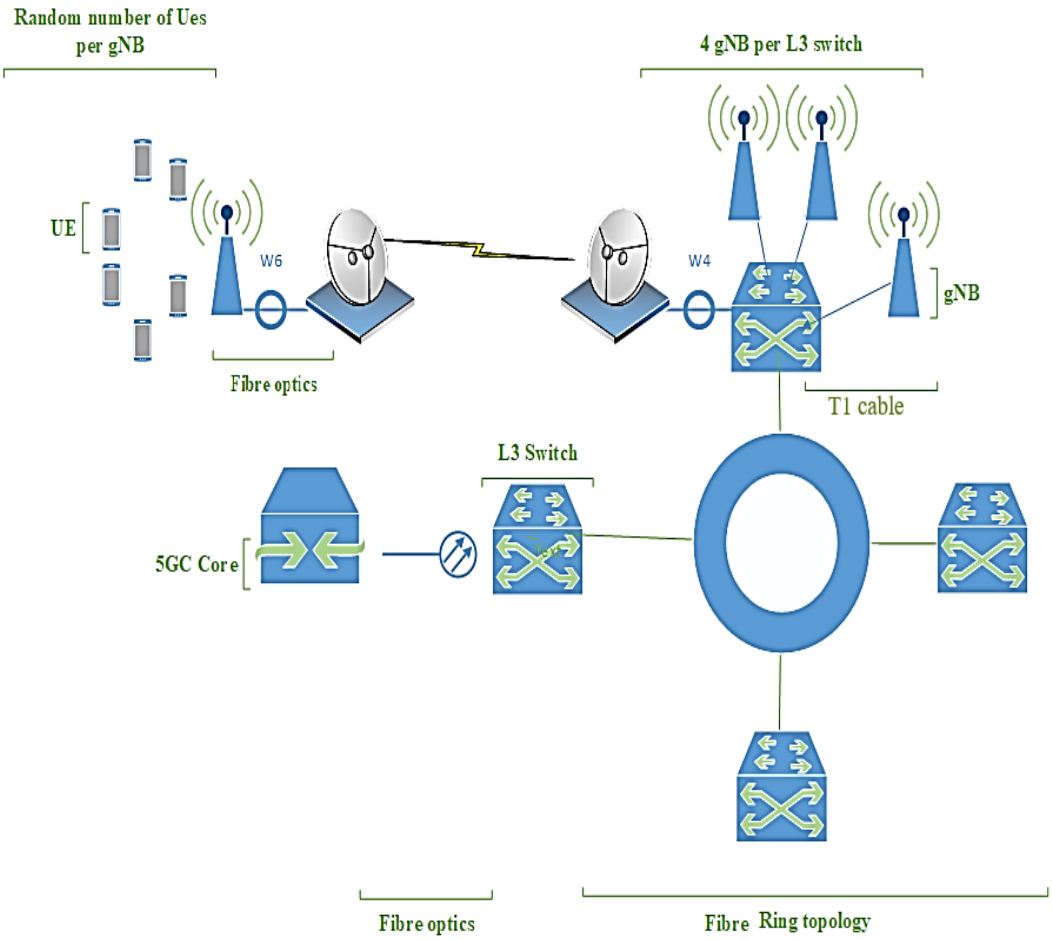

Figure 4.4: mmWave simulation network layout

4.3 Evolution cases and scenarios

Recommendations about connection bandwidth for a certain 5G scenario are obtained by simulating and monitoring the behavior of each link in the network with respect to the percentage of access users and the network delay between different communication technologies like DSL, Fiber, Microwave, and mmWave. The BWFs of L3-L3 and L3-gNB are considered in the study.

The scenarios presented in this study are utilized to evaluate the performance of 5G which supports different services and applications with different requirements. Following the 3GPP standard [11], each case is modeled based on the parameters shown in Chapter 3, Tables 3.5, 3.6 and 3.7, respectively. The data for each scenario are forwarded in the downlink direction from the core through a fiber optic, A ring topology of L3 switches towards the end user. The backhaul network is implemented based on the reference network model defined by one of the major cellular mobile networks in Iraq (ASIACELL) [3][1].

The number of hops required is calculated based on Equation 3.4 in section 3.3.2 of Chapter 3, it mainly depends on the maximum coverage distance of each technology, the distance is normalized by one hop length of each backhaul technology to allow comparison between them. The BWFs that had been adopted in the scenario are ranged from 0.4 to 1 for links L3-L3 that interconnect L3 Switches in the network, L3-gNB that connect each gNB to L3 Switch, and C-L3 that secure a connection between the core network and L3 Switch DWDM ring network.

4.3.1 Broadband in the crowd case

For this case, simulation parameters that been used are as in Table 4.3. Based on the user density of this case, the maximum number of users per cell is ranging from 250 to 500 users.

Percentage number of users without access

To satisfy the requirements of the maximum number of user access in each gNB, different BWFs are examined for each link in the network.

Simulations of various technologies, tested with users numbers ranging from 250 to 500 per cell, indicate distinct performance outcomes for the percentage users without access. When the BWF of the link L3-L3 fixed to 1 and the BWF of the link L3-gNB is ranged between 0.4 and 1, and thus for different number of users.

- When using xDSL, the results show that over 96 -98% of users can not accommodate in both links L3-L3, and L3-gNB.
- In contrast, microwave technology shows 70-84% of users without access,
- While fiber optics and mmWave technologies its around 35% of users can not access the network.

While fixing the BWF of the link L3-gNB to 1, and the BWF of link L3-gNB is ranged from 0.4 to 1 will show that

Table 4.3: Simulation parameters

Number of runs for averaging	10000
User Bit rate	25 M bps
Packet size	1500 Bytes
Number of cells (gNBs)	16
Number of cells per L3 Switch	4
User density	3000
Service area	7000 km^2
Core processing delay	0.05 ms
L3 Switch processing delay	0.01 ms
gNB processing delay	0.1 ms
UE processing delay	0.1 ms
Repeater processing delay	0.5 us
Re-generator processing delay	20 us
Fibre optic processing delay	50 ns
DWDM	600e9
Fibre optic velocity factor	0.8
Max delay	20 ms
Cell radius	12 km

- The results show that the percentage value is almost the same no matter of the BWF in the case of xDSL and microwave,
- While it decreases to reach 0% for 250 users and 3% for 500 users for the case of fibre and mmwave.

These results are illustrated in Fig. 4.5, and Fig. 4.6, Fig. 4.7, Fig. 4.8.

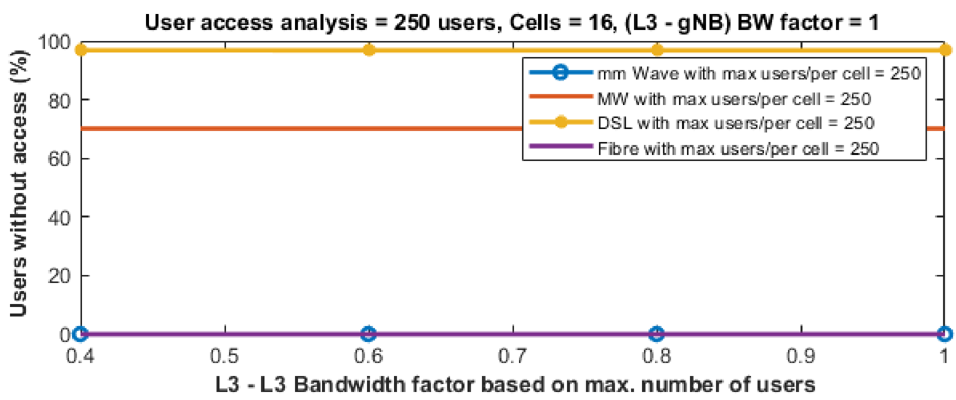

Figure 4.5: Percentage user access analysis of link L3-L3, 250 users

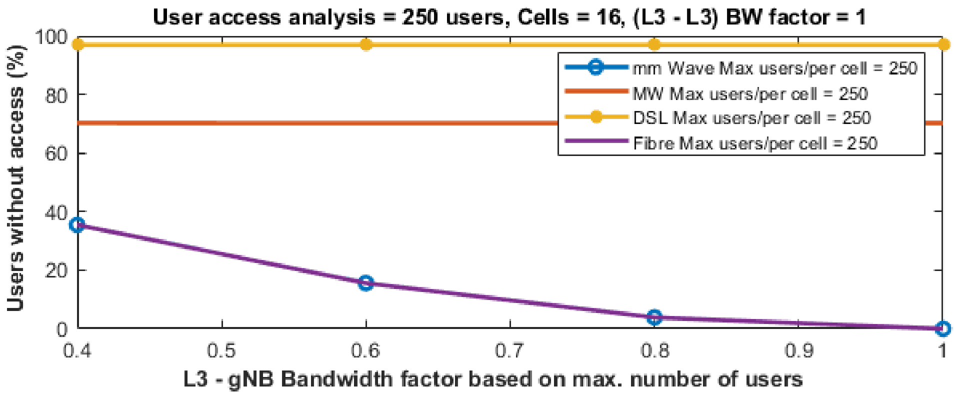

Figure 4.6: Percentage user access analysis of link L3-gNB, 250 users

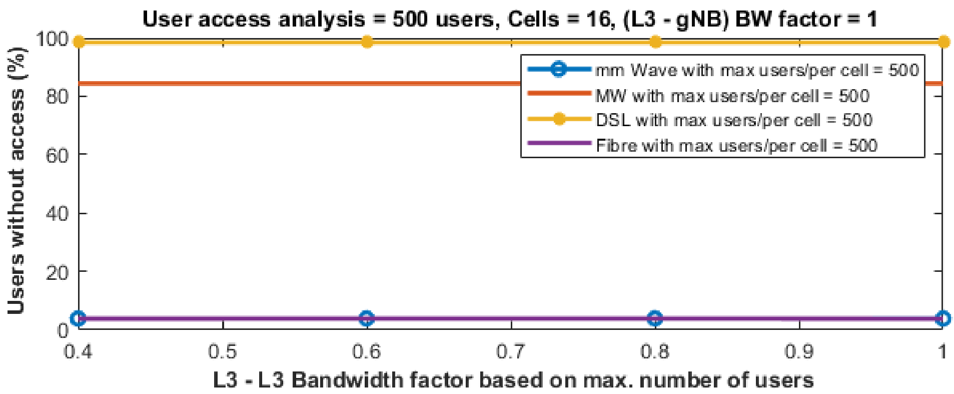

Figure 4.7: Percentage user access analysis of link L3-L3, 500 users

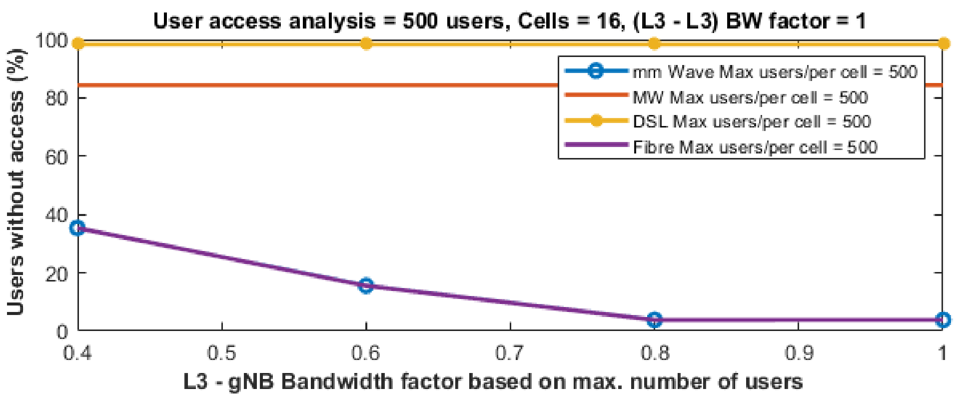

Figure 4.8: Percentage user access analysis of link L3-gNB, 500 users

Comparative Analysis of User Access Across Backhaul Technologies

The main parameters that affect the number of users the network could not be able to accommodate are the maximum capacity of the link based on the technology that will be used, the BWF examine in a certain point of simulation, user data rate for each case and finally the maximum number of users per cell. The following analysis will demonstrate the reasons behind the behavior of the network for each scenario:

- **Across technologies** According to the results,
  - Fibre and mmWave act as a best technologies to backhaul the traffic, for different number of maximum number of users and different values of BWFs for both links L3-L3, and L3-gNB. Thus because the maximum bandwidth of fibre and mmWave is 10 Gbps.
  - While microwave maximum bandwidth used for this simulation is 1 Gb/s the percentage number of usesr without access shows higher values with a very slight defernce when the BWF increased till 1 for different number of maximum users per cell.
  - And finally the xDSL with the limited maximum link bandwidth 100 Mb/s which leads to a higher percentage value of users without access for different number of users and different values of BWFs.

  The results illustrate that major impact comes from the BWF of the link L3-gNB and thus because its a last mile link that will deliver the service to the end users. When this link becomes congested due to the limited link capacity the immediate response is shown by eliminate the number of users can access the network to prevent service degradation.

  - For instance, when the BWF of the link L3-L3 is fixed to 1, for different number of users, the percentage number of users without access is showing the highest percentage value for xDSL.
  - While microwave is the next highest percentage value at the BWF of link L3-gNB in 0.4 and a slight decrease appear when the BWF value increased to 1.
  - Fibre and mmWave are both show a decreasing in the percentage number of users when the BWFs increase for different number of users.
  - In the other hand, when the BWF of the link L3-gNB is fixed to 1, for different values of the BWF of L3-L3 link the percentage number of users without access is showing the same high values for both xDSL and microwave, and the lowest values can be noticed in both fibre and mmwave.

Delay performance analysis

The simulation results for various technologies, considering maximum number of users per cell ranging from 250 to 500 per cell and a fixed BWF for the L3-L3 link to 1, reveal notable differences in network performance.

- When using xDSL, the average network packet delay at the L3-gNB link with all the BWF values is 29 ms for different number of users.
- For microwave technology, the delay ranges between 15 when the number of users is 250 and 19 ms when the number of users is 500.
- In contrast, both fibre optics and mmWave technologies is 11 ms when the number of users is 250 and 10 ms when the number of users is 500. The main reason behind this is that with an appropriate increase in the service rate, the system can handle more users with a lower queuing delay. However, if the service rate is not increased proportionally, the queuing delay will increase with the number of users. This highlights the importance of scaling the service capacity to match the increased load in order to maintain or improve performance in terms of queuing delay.

Fig. 4.9, Fig. 4.10 and illustrate that these values are dropping gradually when the BWF of link L3-gNB increase for fibre and mmWave while there are stable at the same value for both xDSL and microwave.

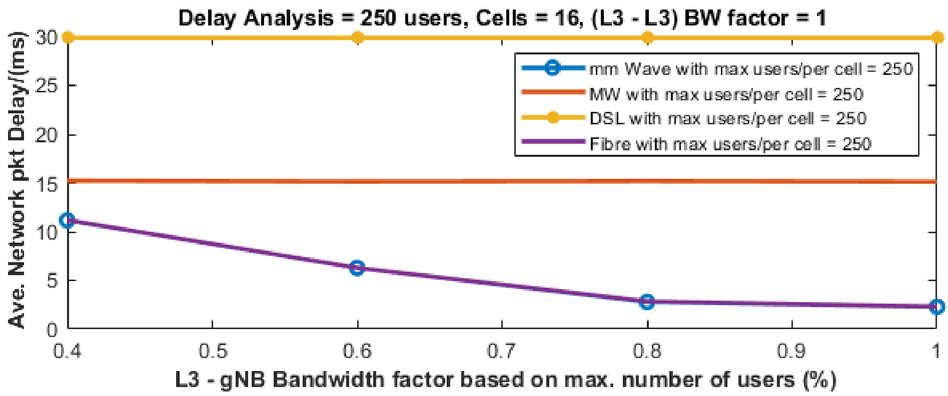

Figure 4.9: Average network packet delay (ms) of link L3-gNB

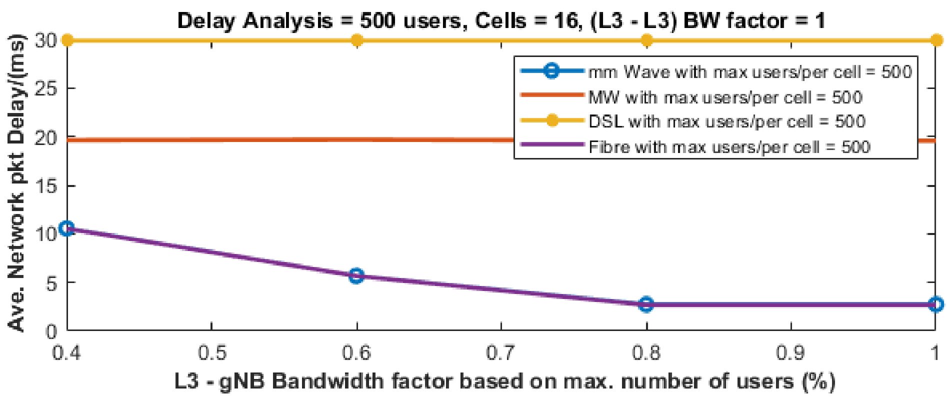

Figure 4.10: Average network packet delay (ms) of link L3-L3

However in the case when the link L3-gNB is fixed to 1, the results show that for different number of users

- When using xDSL the average network packet delay of the link L3-L3 at the value 0.4 is reaching (34 ms).
- Microwave around (26-28 ms) and finally (20-22 ms) for both fibre and mmWave.

Fig. 4.11, and Fig. 4.12 illustrate that for the whole technologies the average network delay is decreasing when the BWF of link L3-L3 is increasing.

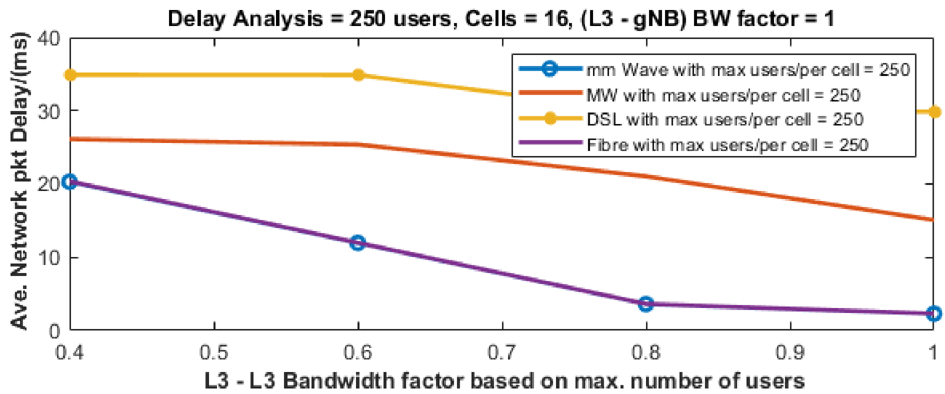

Figure 4.11: Average network packet delay (ms) of link L3-L3, users is 250

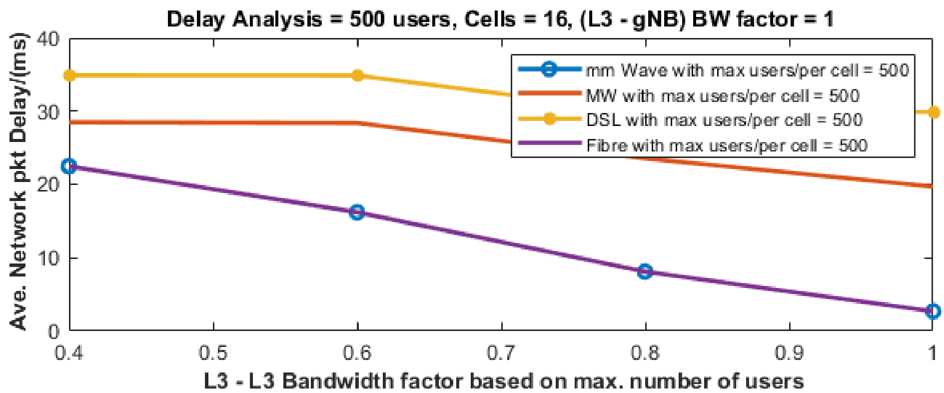

Figure 4.12: Average network packet delay (ms) of link L3-L3, users is 500

Comparative Analysis of End-to-End Delay Across Backhaul Technologies

Delay in this study depends propagation time (Tg), the processing time (Tp), and the transit time delay, which includes the queuing time (Tq), and the transmission time (Tt). the study approximate Tp based on Table 3.8, and Tg, Tg, Tq, and Tt is calculated based on the Equations in Chapter 3. The results report that the minor impact comes from the processing delay, and the propagation delay as both depends on the coverage area and the type of technology that has been adopted, while the major impact comes from the transmission and queuing delay where the link capacity and the number of users that need to be services are the most important parameters. The network will not be stable if the arrival rate higher than the services rate ($\lambda > \mu$). The following analysis will demonstrate the reasons behind the behavior of the network for each scenario.

- **Across technologies** The results indicate that
  - Fibre and mmWave are the most effective technologies for backhauling traffic in terms of end-to-end (E2E) delay. Although do not meet the strict limit values when the lowest BWF values is adopted, they still exhibit the lowest E2E downlink delay.
  - In contrast, xDSL and microwave show significantly higher E2E delay values across different BWFs and varying user numbers.
  - This discrepancy is due to the limited maximum capacity of xDSL and microwave compared to the higher capacities of fibre and mmWave, which influences the delay as the number of users per area increases due to the arrival rate become higher than the services rate and blockage will happen because the network at a certain point will be able to service a specific number of users.
- **Across BWFs** While the link between L3 and gNB significantly impacts the percentage of users without access, the L3-L3 link influences the end-to-end (E2E) delay. This is because the L3-L3 link is primarily responsible for backhauling traffic between the core network and end users. Any changes in this link will affect the average network delay.

  The results demonstrate that when the BWFs of the L3-L3 and L3-gNB links are at their lowest values, the E2E delay is at its highest for all technologies used in this study, regardless of the number of users.

  - However, as the BWFs increase, the average network E2E delay remains high for technologies with limited link capacity, such as xDSL and microwave,
  - But decreases for those with adequate link capacity to handle network load, like fibre and mmWave.

  A significant reduction in E2E delay is observed with the BWF of the L3-L3 link increased. The L3-gNB link likely serves as a last mile or access link while

L3-L3 link serves as a backbone, Changes in backbone links tend to have a more pronounced impact on E2E delay because they handle larger volumes of traffic and are more central in the data flow. Both xDSL and microwave may experience higher latency due to limited capacity, but both will be suitable for backhauling 5G traffic for another user case with the limited number of users, less user data rate and packet size, for instance xDSL work properly with services and application for maximum number of users 40 when the user data rate 10 Mbps and 1000 Bytes packet size, as in Fig.4.13 for percentage number of users and Fig.4.14 for the average network delay. While for microwave, it will work with more number of users around 150 users, user data rate 10 Mbps packet size 1500 Bytes, as in Fig.4.15 and Fig.4.16.

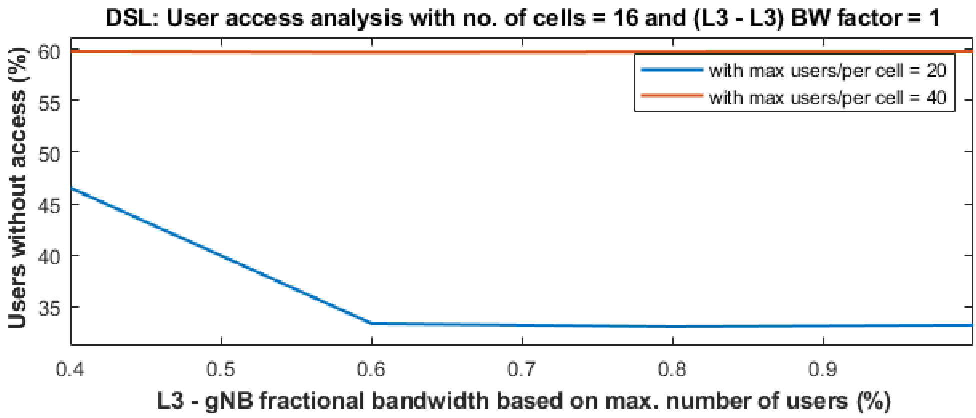

Figure 4.13: Link L3-gNB percentage number of users without access for xDSL

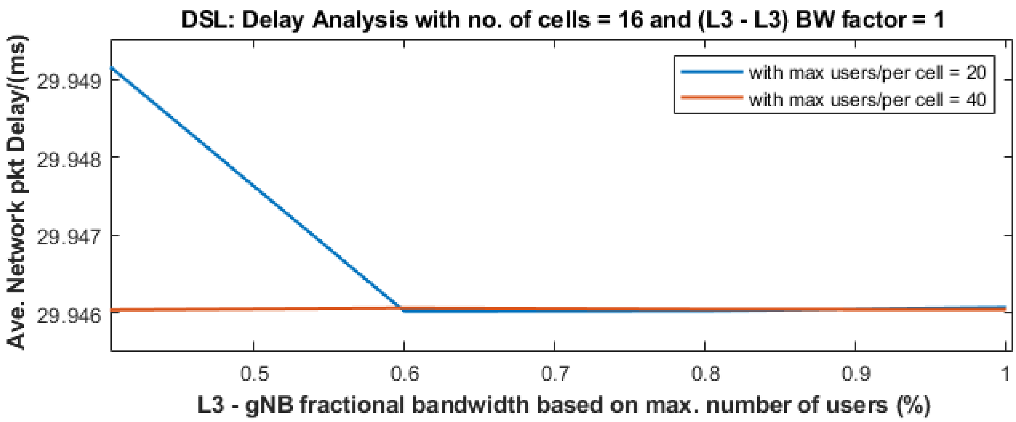

Figure 4.14: Link L3-gNB average network delay

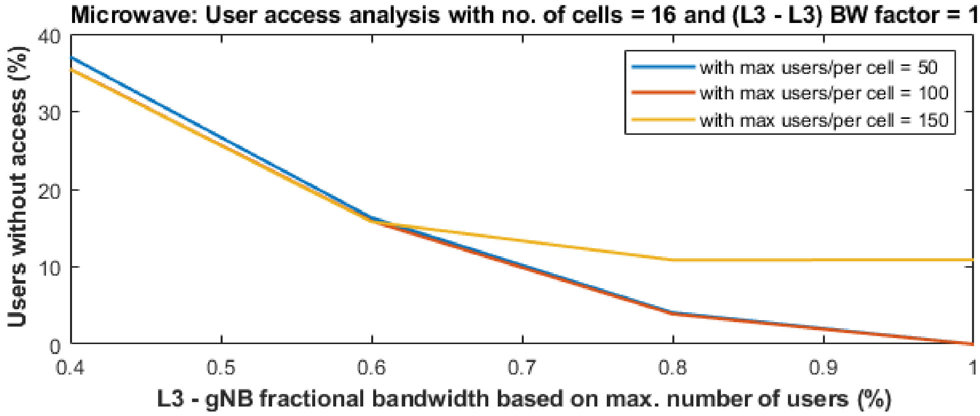

Figure 4.15: Link L3-gNB percentage number of users without acces for microwave

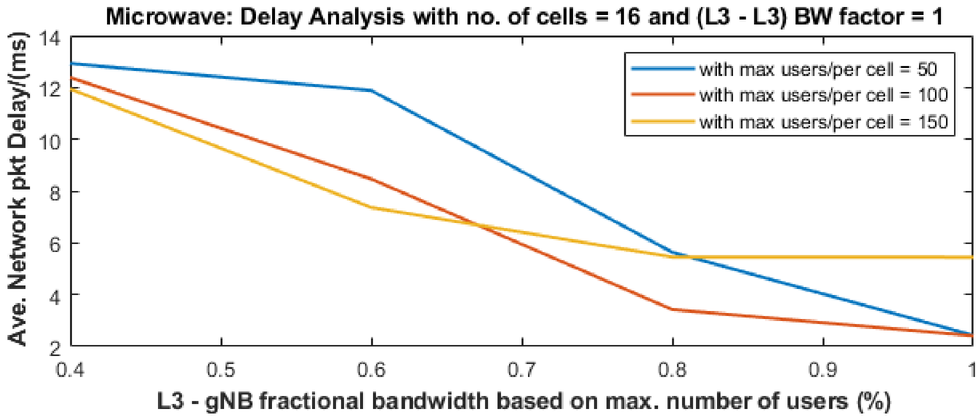

Figure 4.16: Link L3-gNB average network delay

Network Capacity analysis

Its the major factor that will influence the behavior of the network. The simulation results for different technologies and different number maximum users per cell reveal the following capacity outcomes.

- When using xDSL, the capacity reaches its maximum link capacity of 100 Mb/s at a BWF of 0.4, while microwave reaches 1 Gbps the maximum link capacity at the same BWF.
- In contrast, fibre and mmWave show significantly higher capacities, both fibre and mmWave is 2.5 Gbps, which increases to 5 Gbps when the maximum number of cells increased to 500 for the same BWF (0.4).
- In another hand when the BWF increased to 1 the, only Fibre and mmWave show an increasing in the required link capacity. For instance, when the number of maximum users per cell is 250, link capacity is 6.25 Gbps, and reach

its maximum limit at 10 Gbps when the number of users per cell increased to 500. As shown in Fig. 4.17, and Fig. 4.18.

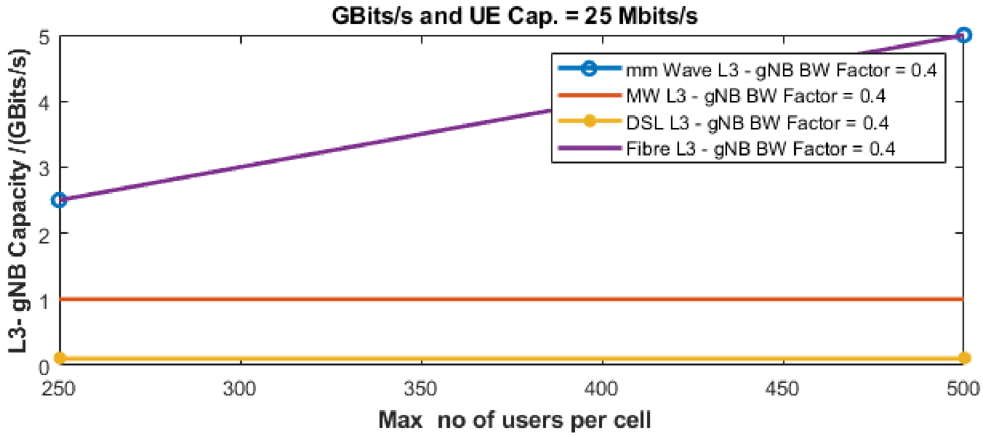

Figure 4.17: Link L3-gNB Capacity, BWF of link L3-gNB is fixed to 0.4

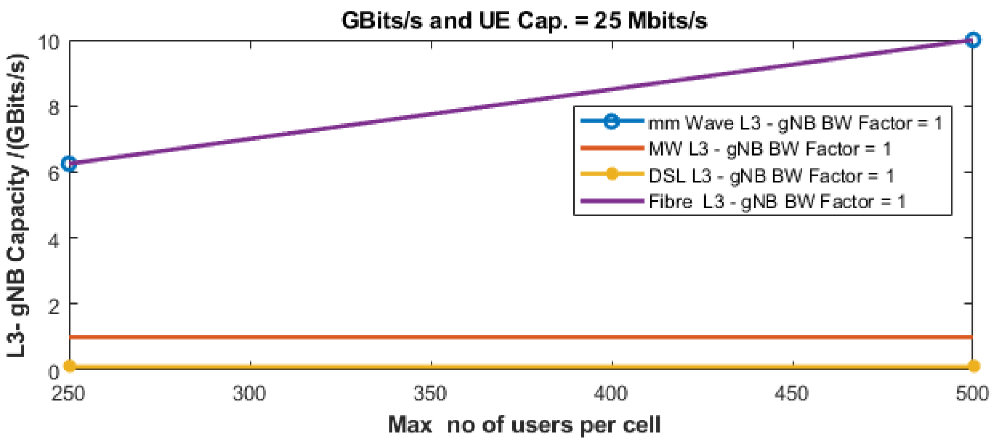

Figure 4.18: L3-gNB Capacity, BWF of link L3-gNB is fixed to 1

Comparative Analysis of Network Capacity Across Backhaul Technologies

As the capacity of the link can vary significantly based on the technology that been used. Based on the Equations in Chapter 3 the calaculations had been done and the comparison between different technologies has been made for different BWFs of link L3-gNB and for different maximum number of users as follow:

- **Across technologies** Based on the results,
  - Both fibre and mmWave are highly efficient as they show an identical high capacities, they show a linear increase in capacity for the maximum number of users from 250 to 500 for different values of BWFs.

- While xDSL and microwave both show a constant lower capacity compared to fibre and mmWave for different maximum number of users and BWF values. The reason behind this behaviour is the maximum link capacity limit for both xDsl and Microwave.

- **Across BWFs** For different BWFs different,
  - Both fibre and mmWave maintain high capacity when the BWF is 1 compared to the BWF 0.4 for different number of users. the maximum actual capacity for fibre and mmWave at 500 users is reaching its maximum value at (10 Gbps) when the BWF 1 compared to the BWF, thus because the BWF directly scale the available bandwidth, and the network capacity.
  - While for both xDSL and microwave show a limitation due to its limited maximum link capacity, which prevent significant capacity increase even when the BWF is high.

4.3.2 Summary

This chapter evaluated four backhaul technologies fiber, xDSL, microwave, and mmWave under the eMBB "broadband in a crowd" workload by varying the bandwidth factor (BWF) on the last-mile (L3–gNB) and backbone (L3–L3) links.
Admission is primarily governed by the L3–gNB BWF: increasing this ratio raises the share of users granted access, with xDSL and microwave saturating earlier than fiber and mmWave.
The end-to-end delay is influenced in part by the L3-L3 BWF: Increasing the backbone capacity reduces the waiting delay in all technologies, while fiber and mmWave consistently achieve the lowest delays. Crossed-BWF experiments confirm the bottleneck logic last-mile bandwidth limits admission, whereas backbone bandwidth limits delay so upgrading the non-limiting segment yields marginal benefit.

Implication: For eMBB deployments, fiber or mmWave are the practical candidates. To increase admission, raise L3–gNB BWF; to reduce delay, raise L3-L3 BWF. A pragmatic target is BWF 0.8 on the limiting link; below this level, drops and queuing delay rise sharply.

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Chapter 5

Satellite backhaul and analysis for Non Terrestrial Network (NTN)

5.1 Introduction

Fifth-generation (5G) telecommunication systems are expected to meet the world market demands of accessing and delivering services anywhere and anytime. The evolution of telecommunication technologies, the ever-increasing demand for new services, and the exponential growth of smart devices are fuelling the development of Non-Terrestrial Network (NTN) systems as an effective solution to complement TN in providing services over uncovered or under-served geographical areas. The primary motivation behind 5G NTN includes the low building and deployment cost of smaller satellites. Additionally, large coverage area and high throughput make satellites a promising solution for rural areas and mobile platforms. Satellites can support the existing TN by providing additional connectivity and bandwidth thereby improving service continuity in dense traffic areas [1].

Satellite networks were born independently from terrestrial systems owing to the different nature of satellite communications in terms of the covered distances, utilized radio spectrum, design, costs, applications, and targets. Satellite systems were initially intended to provide 1G analogue services, such as in voice and other low data rate applications, primarily in maritime scenarios (i.e., INMARSAT). In the early 90s, with the development of 2G technology, satellite communications were exploited to deliver aeronautical services to people traveling on aircraft as well as to provide coverage in certain land areas. Then, an integration of satellites with TN aimed to support the emerging 3G wireless system, also known as Universal Mobile Telecommunications System (UMTS). In 4G, the integration of satellite and terrestrial access technologies can help overcome several issues and one of them is the Non-LoS degradation through either integrated or hybrid networks. The integrated approach foresees that the TN can be considered as an alternative communication system to the satellite network. While 5G NTN, including satellites and Unmanned Aircraft Systems (UAS), ensures service continuity of machine to machine/ internet of things (M2M/IoT) devices or individuals traveling on moving platforms. It also guarantees service availability in critical communications and emerging sectors, such as maritime, aeronautical, and railway services. eMBB and mMTC are considered the main 5G service enablers for defining the use cases that should be supported by NTN. In terms of eMBB services, NTN aims to provide broadband connectivity in un/under-served areas and on moving plat forms (i.e., vessels and aircrafts), as well as to offer network resilience by combining terrestrial and NTN systems. While in mMTC, NTN supports connectivity for both wide and local area IoT services [2].

However, the placement of satellites in different orbits, such as LEOs, MEOs, and GEOs, with varying parameters, such as propagation delay and atmospheric interference, makes the 5G NTN a challenging task [3]. The NTNs are expected to play a vital role in 5G and beyond systems by covering different verticals, including transport, eHealth, energy, automotive, public safety, and many others.

5.1.1 NTN - current situation in the 3GPP standard

3GPP has initiated several study items on the possible impacts and solutions for NTN, as well as exploring a more advanced integration version combined with the upcoming terrestrial 5G networks. In contrast to the 1G to 4G cellular standards, the 5G standards portfolio provide strong heterogeneity support from many perspectives, including services, network technologies, and traffic characteristics.

3GPP started discussing NTN in Release-15, where the main focus was on deployment scenarios and channel models. The study was documented in 3GPP TR 38.811 [2]. The first main objective was to select some reference deployment scenarios of NTN and agree on key parameters, such as architecture, orbital altitude, frequency bands, and provides some alternative architectures for satellite integration in the 5G network. The study considers direct access satellite cases (bent-pipe satellite or base station onboard the satellite) or indirect access through a relay node (backhaul configuration) [4].

3GPP continued with a follow-up Release-16 study on solutions of adapting new radio (NR) to support NTN. The main objective was to identify a minimum set of necessary features that enable NR support for NTN (especially for satellite communication networks). This included architecture, higher layer protocols, and physical layer aspects. The outcome of the study is documented in 3GPP TR 38.821 [5].

Release-17 was completed under pandemic conditions and the satellite component included in it made the integration of NTN component with mobile systems possible. This standard was the result of a joint effort between stakeholders of both mobile and satellite industry, who both found benefits that: i) satellite operators can access a unified and large ecosystem and drive down the cost through economy of scale; and ii) mobile systems can achieve global service continuity and resiliency.

In Q2 2022, several 3GPP SIs and WIs started targeting Release-18 for providing the first step into 5G-A. They both focus on NR NTN based on the outcome of the Rel-16 study, in particular the 3GPP report TR 23.737. The main objective is to specify enhancements necessary for LEO and GEO based NTNs, while also targeting implicit support for High Altitude Platform Systems (HAPS) and air-to-ground networks.

Finally, Release-19 is considered as being the next phase on this development path and will be completed on 2025. Aiming to enhance the performance of NTN and its use cases. The main objectives are to provide improved coverage and optimized capacity, multicast and broadcast services (MBS), regenerative payload, and support for Reduced Capability (RedCap) terminals [6] Fig.5.1

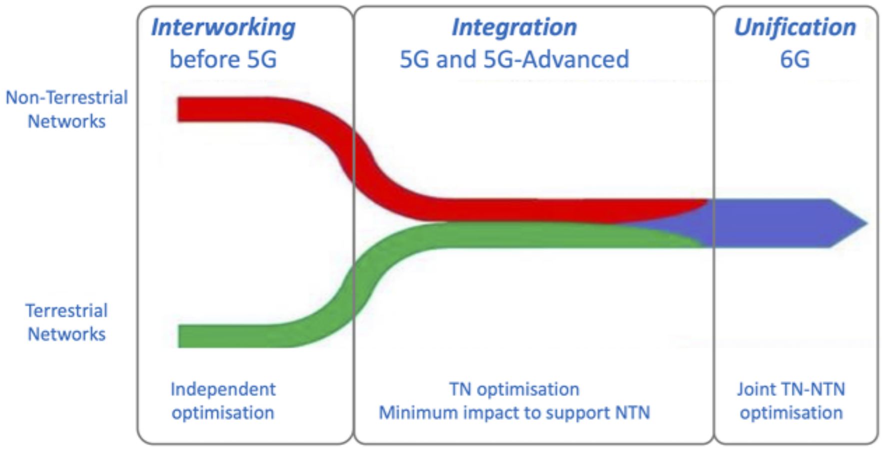

Figure 5.1: Satellite integration in the 3GPP eco-system: Vision [7]

ITU-R is also working on satellite 5G, where 5G systems are under the name of International Mobile Telecommunications-2020 (IMT-2020). The recommendations of the M series deal with the integration of TN and satellite mobile communication systems within IMT-2020. The world Radiocommunication Conference (WRC) considered regulation and standardization on spectrum sharing issues that have become a pressing need in ultra-dense systems. Because the interference coordination is necessary between Geostationary Orbits (GSO) and non geostaionary orbits (NGSO) and between different NGSO systems sharing the same frequency bands, WRC-19 has regulated the use of the bandwidths for various systems and the coordination between GSO and NGSO satellite systems. The next WRC-23 is expected to allocate new bands to inter-satellite links (ISLs) and mobile satellite services.

Moreover, IEEE is developing standards for drones. In particular, the IEEE P1936.1 standard (May 2022) deals with application scenarios for UAVs/drones and the IEEE P1937.1 standard (October 2021) deals with interface requirements, including a two-way communication interface [8].

The goals of these efforts has been to further optimize satellite access performance, address new bands with their specific regulatory requirements, and support new capabilities and services as the evolution of 5G continues.

5.1.2 NTN description

Beyond satellites, Non-terrestrial networks (NTN) refer to networks, or segments of networks, using an airborne or spaceborne vehicle for transmission. It may have different deployment options according to the type of the NTN platform involved.

The classification of space borne platforms typically depends on three main parameters, including altitude, beam footprint size, and orbit. NTN platforms may be classified as space-borne platforms and can be differentiated:

- HEO High earth Orbit
- GEO Geostationary Earth Orbit
- MEO Medium Earth Orbit
- LEO/vLEO Low/ very low Earth Orbit

vLEO/LEO and MEO are also known as Non-GEO (NGSO) satellites for their motion around Earth with a lower period than the Earth rotation time; in fact, it varies from 1.5 to 10 hours.

While the airborne category encompasses UAS platforms, which are typically placed at an altitude between 8 and 50 km and include HAPS at 20 km altitude. Similar to the GEO satellite, the UAS position can be kept fixed in the sky at a given point on the ground. The UAS beam footprint size ranges from 5 to 200 km [9].

5G NTN provides connectivity services to user terminals through satellite connections, and can also provides a connection between terrestrial gNB and 5G core network, which known as NTN backhaul.

The main concern of this study is the space-borne platform, in another word GEO and NGEN satellite and its integration with the TN. Fig.5.2 is showing NTN satellite backhauling.

5.1.3 Satellite and 5G NR network architecture

The satellite network was integrated with the terrestrial 5G core network using an indirect access (backhaul) architecture to enable the implementation of a satellite-based 5G network. The satellite backhaul architecture then formed the basis for the subsequent use case demonstrations, each incorporating individual MEC Multi-access Edge Computing at the edge to optimize performance for specific applications, as shown in Figure 5.2 [7].

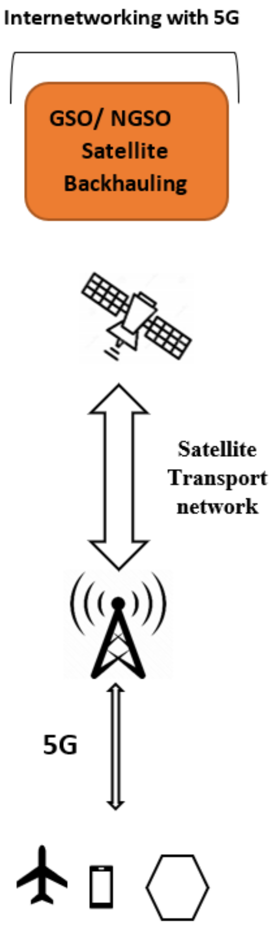

Figure 5.2: Satellite backhauling [7]

The architecture options that are being discussed within 3GPP for NTN serves as the basis for the analysis performed, in particular the options that were categorized based on either the type of satellite payload, i.e., transparent or regenerative, and the type of user access link, i.e. direct or through an on-ground Relay Node (RN), as shown in Fig. 5.3, 5.4, 5.5, and 5.6, as follows:

a. The satellite includes full or part of a gNB to generate/ receive a "Satellite-friendly" NR signal to/ from the Relay Nodes. This requires sufficient on-board processing capabilities to be able to deploy gNB or a Relay Node functionality (see Fig.5.3).

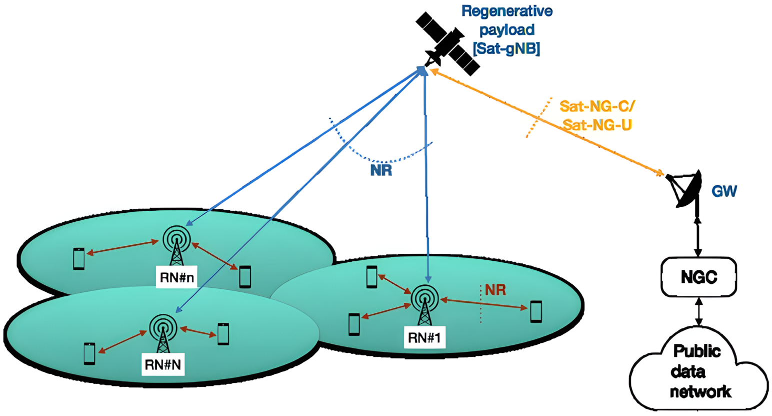

Figure 5.3: Satellite simulation layout - a [10]

b. The satellite will relay a "Satellite friendly" NR signal between the gNB and the Relay Nodes in a transparent manner (see Fig.5.4).

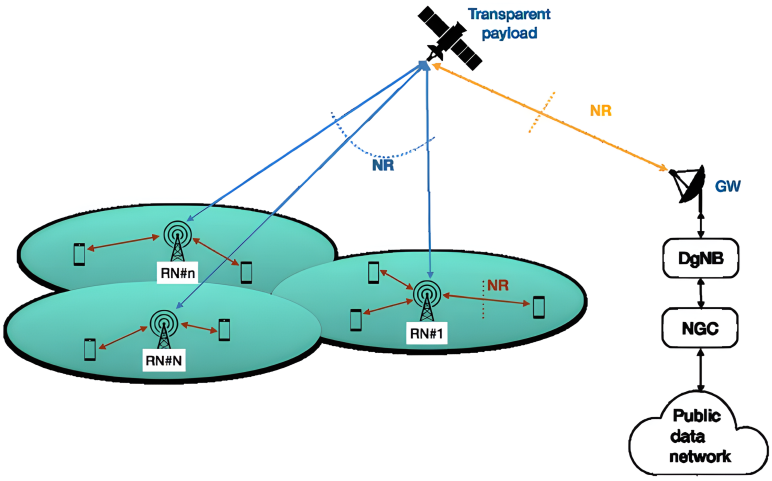

Figure 5.4: Satellite simulation layout - b [10]

c. The satellite includes a whole one or part of a gNB to generate/receive a "Satellite friendly" NR signal to/from the UEs. This requires sufficient on-board processing capabilities to be able to deploy gNB or Relay Node functions (see Fig.5.5).

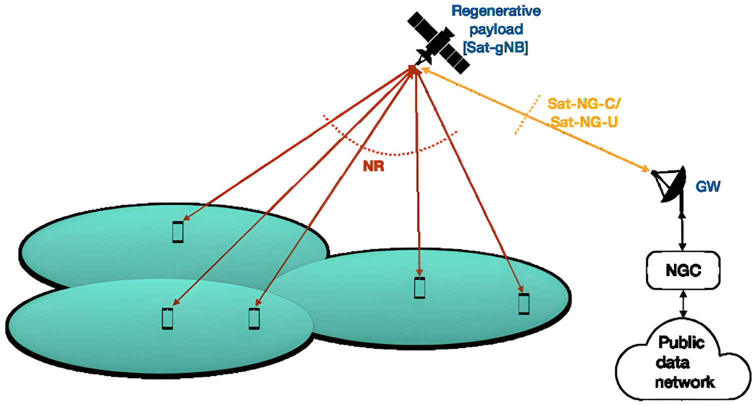

Figure 5.5: Satellite simulation layout - c [10]

d. The satellite will relay a "Satellite friendly" NR signal between the gNB and the UEs in a transparent manner (see Fig.5.6).

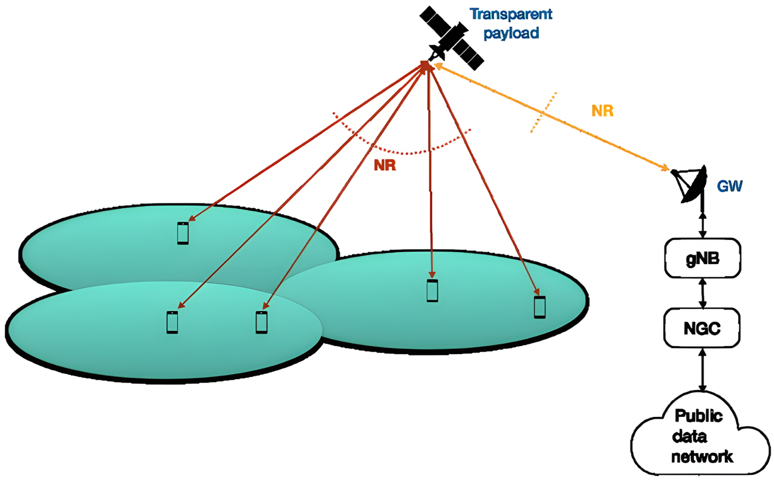

Figure 5.6: Satellite simulation layout - d [10]

The layout in (a) is adopted and simulated to analyze the behavior of the network for this study. The reason why is a follows:

- It is a more suitable approach for reaching end users in extremely remote or infrastructure-poor areas.
- This setup is particularly beneficial for extending coverage to remote or undeserved areas, as it allows the satellite to manage connections with UEs directly or relay them to terrestrial gNBs.
- This layout is efficient for providing coverage in developing regions where terrestrial infrastructure may be limited or underdeveloped.

5.2 Satellite based approaches

Satellite communication has recently been included as one of the key enabling technologies for 5G backhauling, especially for the delivery of bandwidth demanding applications in 5G. Therefore, one of the key objectives of 5G use cases is to assure the Quality-of-Experience (QoE) of these applications' users in dynamic and challenging network scenarios [11].

5.2.1 Modeling approach

Over the past few decades, GEO satellite systems have been deployed to support broadband services, backhauling, disaster recovery, and emergency services. Today, there is a considerable renewed interest in planning and developing Non-GEO satellite systems for backhauling the traffic of the new mobile technology generations. Although satellite is one of the most cost effective technologies for backhaul mobile traffic in rural areas, long propagation delay and frequent disruptions of satellite links bring several challenges, especially to map the 5G quality of service requirements for traffic. Satellite provides backhaul capacity across the globe without exploiting expensive microwave radio towers, in addition to the significant advantages the new generation of satellite HTS will provide [12].

Recent research has shown that backhaul has an advantage compared with terrestrial technologies in the field of mobility, because it can provide basic connectivity to users in wide regions without sufficient coverage by TNs.

LEO/vLEO satellite networks promise high-capacity backhaul, seamless coverage, and flexible access. However, it has been nearly 30 years since the first such constellation, Iridium, was launched.

Several projects on LEO satellite constellation have been proposed since then, but very few were successful. When it comes to high-performance connectivity, high throughput per terminal, predictable low latency, high network availability, and flexibility, MEO, such as O3b mPower, may play a vital role in future broadband networks [13].

Mobility management of LEO/vLEO satellites is, therefore, much more challenging than GEO or MEO systems. The mobility of LEO/vLEO satellite systems is rather similar to cellular radio systems with a few differences. In both systems, the relative position between the cells and the mobile hosts changes continuously, requiring handover of the mobile hosts between adjacent cells [14].

In this research, a MATLAB design is focused on the satellites for backhauling 5G traffic from core network to the end user. It primarily adopts the most promising satellite orbits vLEO, LEO, and MEO to meet the requirements of 5G services and applications The design considers a 5G standalone network, deployed to deliver the services from the Core to each gNB that connected to the network through satellite network. E2E delay statistics and capacity planning based on users access statistics are both considered. Observing link utilization that meet the 3GPP delay requirements provides a reliable method for proposing the most efficient backhaul technology to deploy 5G network in developing countries.

5.2.2 MATALB model details

In this subsection, studies and analyses are conducted for the use of both MEO and LEO/vLEO satellites to backhaul the traffic from core to the end use in terms of delay, capacity, and the percentage number of users without access.

MATLAB simulation was carried out based on the network layout in Fig. 5.7 [15]. The model is set up using Core - L3 switch - ground station - satellite - base station equipment. By observing the output traffic delays, the required link capacity is determined from various random scenarios. The assumed actual link delay and bandwidth were computed for the communication links between Core and L3 switches - several ground stations - satellite - base station equipment. Random distribution of users were distributed with an expected maximum number of users of i, where i depends on the scenario that will be simulated. A simulation model was formed based on the data rate requirements of individual scenarios and the model was employed to compute user access statistics and delay for each scenario based on available bandwidth in the links. Simulations were repeated a fixed number of times (1000) and the results were averaged to have confidence in them.

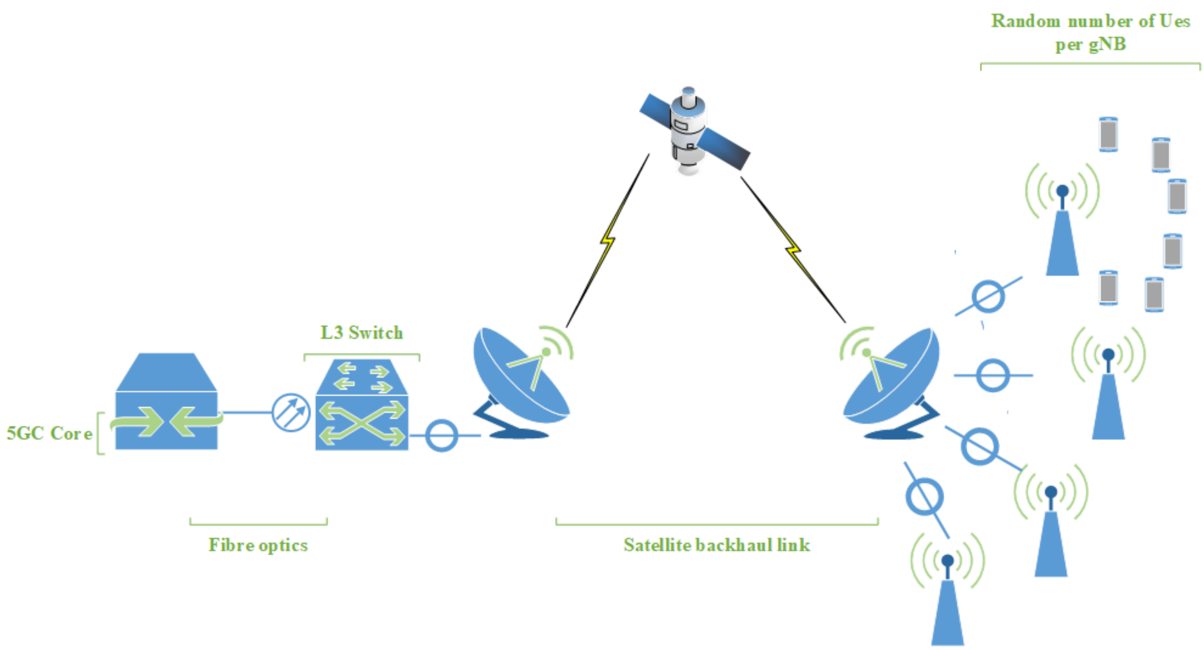

Figure 5.7: Satellite simulation model

E2E Delay statistics

Although MEO and LEO/vLEO satellite constellations are envisioned as a complementary or integrated part of 5G and future 6G networks for broadband or massive access, given their capabilities of full earth coverage in inaccessible or very isolated environments, end users are interested in reduced delays when compared with other services to ensure timely updates for a real status monitoring or acceptable Quality of Service (QoS). Besides propagation and transmission delays, queuing delays pose their own inherent challenges, since these depend not only on transmission and processing capabilities of the satellites, but also on the incoming traffic of the aggregated services. In this study, it is considered that the total E2E (DL) delay ($\mathfrak{D}$) can be calculated based on equations in Chapter 3, Subsection 3.3.1.

In terms of satellite, handover time delay T_{HO} will also considered in order to support continuous communications over satellite system, handover from one satellite to the nearest one may happen. To estimate the number of handover that may happened in any satellite network, the coverage time per satellite T_{coverage} is considered and is calculated based on Equation 5.1 (5.1a - 5.1c)

$$T_{\text{coverage}} = \frac{\text{D}}{\text{Satellite velocity}} \tag{5.1a}$$

Where D is the distance the satellite would have traveled while providing coverage for the gNBs considered, and it calculated based on Equation 5.1b. As shown in Fig. 5.8

$$D = 2 \cdot d_1 - a \tag{5.1b}$$

a is the length/width of the gNBs covered by the specific satellite, d_1 is the half foot print on earth for the satellite, and is calculated based on Equation 5.1c.

$$d_1 = \frac{\text{Altitude}}{\tan(\theta)} \tag{5.1c}$$

Where θ is the inclination angle.

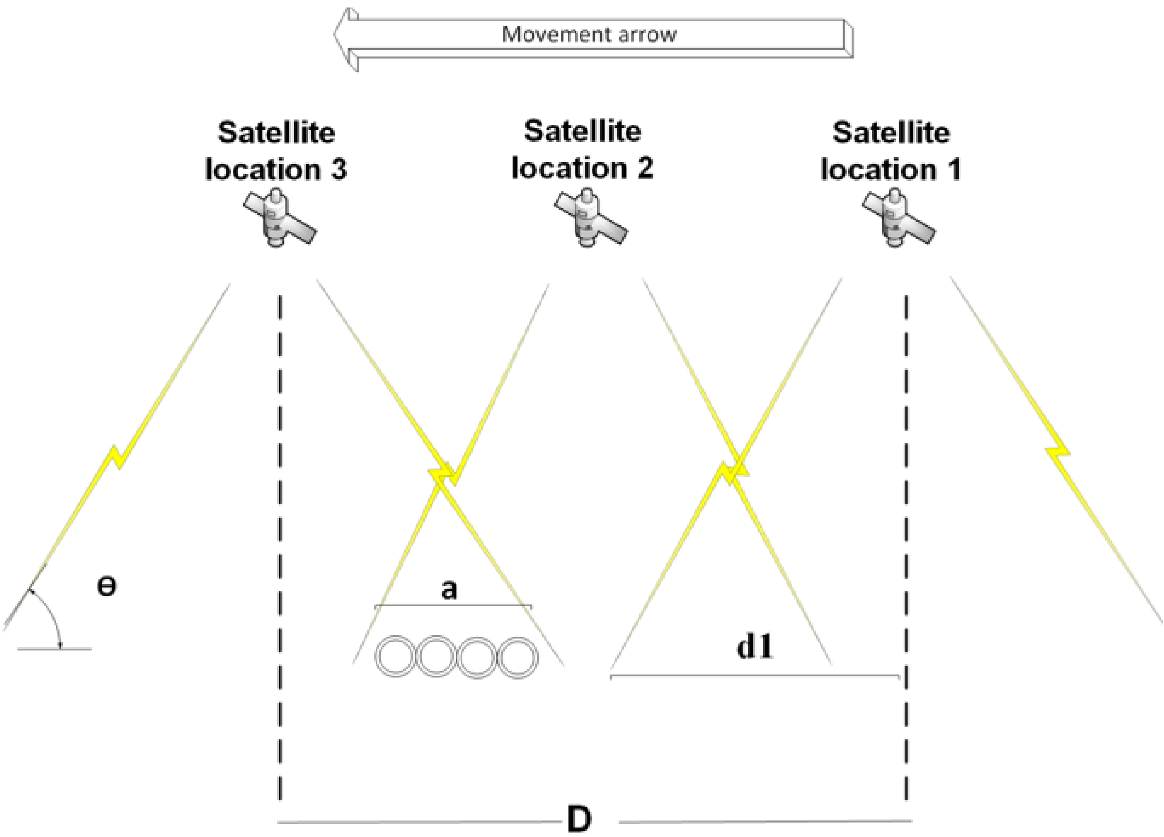

Figure 5.8: Satellite coverage time

Capacity planning based on users access statistics

The network capacity requires optimization in order to improve the quality of service (QoS). It mainly depends on the top design parameters. Network topology and routing algorithm have un neglectable influence on network capacity as essential top design elements. The distribution of network users is wide-range, uneven and time-varying considering the possible mobility of them, which would contribute the 'all-to-all' traffic model for MEO and LEO/vLEO satellite network. Each satellite could receive data packets with destination to every other MEO or LEO/vLEO satellite in the network at the same time, hints that the network does not have a specific source node or destination node. Moreover, the construction parameters of satellite constellation changes over time owing to the movements of satellites and mobile users, which could not be predicted by a static and continuous formula. The capacity improvement then becomes an optimization problem with complicated environments and multi-constraint demands [16]. To calculate the link capacity C will consider the Equations in Chapter 3 Subsection 3.3.2.

5.3 Modelling and simulation

As the main aim of this study is introducing 5G technology and beyond to the developing countries by propose a solution for their legacy infrastructure, it focuses on the backhaul scenario where the satellite is not used to connect directly to the 5G User Equipment (UE), but through gNBs. The design is focused on a 5G standalone network (SN).

All three types of satellites MEO, LEO and vLEO are simulated in order to study the behaviour of the network for each one, the parameters adopted in this simulation for each satellite are based on Table 5.3. The scenarios presented in this study are utilized to evaluate the performance of 5G that supports different services and applications with different requirements. Following the 3GPP standard [17], the broadband in the crowd case is the selected one as an example of the eMMB 5G use case, as follow:

- **Broadband in a crowd case** the case for stationary, pedestrian, and users in vehicles, for example, in offices, city centers, shopping centers, residential areas, rural areas and in high speed trains. The passengers in vehicles can be connected either directly or via an onboard base station to the network. eMBB can boost the mobile broadband capacity to provide access to multimedia, human-centric services and data contents. One major example of this case is the stadium, which is considered a challenging core case for operators in providing their services and building their brand and reputation by delivering a reliable high capacity and low latency service [17][18]. This case is simulated based on the values in Table 5.1.

Table 5.1: KPI parameters for broadband in the crowd applications [19]

Max. delay (ms)	**Data rate (Mbps)**	**Packet size (Byte)**	**UE density**	**Service area (km^2)**
5	25	1500	3000	7000

The simulation was set up with a random number of users per cell (gNB), and will not exceed the maximum number of users assumed per cell for simplicity. The selected case is the one that adopted to simulate and analyze the performance of the network and user experiences in this study. A fixed high transit delay was assumed when there is a high arrival rate compared to the service rate at a node of 20 ms, and this when the arrival rate become higher than the service rate so the over all delay will become high, and handover delay is also estimated at value (50-100 ms) [20]

[21] and it depends on the number of handover that will happened in each satellite orbit that will calculated based on equations in Section 5.2

For this case, simulation parameters used are as in Table 5.2. Based on the user density of this case, the maximum number of users per cell ranges from 500 to 1000.

Table 5.2: Simulation parameters

Number of runs for averaging	10000
User Bit rate	25 (Mbps)
Packet size	1500 (Bytes)
Number of cells (gNBs)	16
Cell raduis	12 (km)
User density	3000
Service area	7000 (km^2)
Core processing delay	0.05 (ms)
gNB processing delay	0.1 (ms)
UE processing delay	0.1 (ms)
Sat-gNB max. link capacity	10 (Gbps)
Max delay	20 (ms)

By simulating and monitoring the behavior of each link in the network shown in Figure 5.7, the analysis considers the percentage of access users and the network delay. Recommendations about connection bandwidth for a certain 5G scenario are obtained by simulating and monitoring the behavior of each link in the network with respect to the users statistics and the network delay.

Different orbits are simulated in the study, starting from MEO, LEO, and vLEO. All parameters that have been adopted in the simulation are based on Table 5.3, while the coverage time of each orbit has been calculated based on Equation 5.1.

Table 5.3: Satellite simulation parameters for MEO, LEO, vLEO [21][22]

Orbits	**Inclination angle (θ)**	**Coverage time per satellite (s)**	**Footprint diameter (km)**	**Orbital altitude (km)**	**Velocity (km/h)**
MEO	55–80°	4500–36500	10000–15000	8000–24000	18000
LEO	70–98°	200–500	8000	320–2000	28080
vLEO	55–90°	15–100	6000	100–500	28080

5.4 Simulation Results for Satellite-Based Backhaul Scenarios

Simulations of various numbers of users ranging from 500 to 1000 per cell, indicating distinct performance outcomes for the percentage users without access. When simulating each scenario for each orbit, the results are as follows.

5.4.1 MEO

The simulation results for the satellite based MEO backhaul scenario, in terms of user drop rate and end-to-end delay, indicate the following:

Percentage number of dropped users

For MEO satellite, Fig.5.9, Fig.5.10, Fig.5.11, and Figure 5.12 show that the percentage number of users without access is high when both BWF links have the lowest values and start to decrease when the BWFs start to increase. However, both of them have the same impact on the percentage number users. The figures illustrate the following.

- The major impact comes from the BWF of link Sat-gNB. It is showc clearly when when increasing the BWF of link Sat-gNB, the number of users access are improved regardless the value of link Core-Sat BWF. While increasing the BWF of link Core-Sat will also improve user access, but the rate of improvement may vary based on other factors.
- Users density has significantly impact the results, as the figures illustrate that a higher maximum users per cell typically leads to higher initial percentages of users without access. This occurs because greater user density places additional strain on the network. For instance, when the BWF of link Core-Sat is fixed with 1000 maximum users per cell or more, the percentage number of dropped users will be high no matter whether the BWF has increased or decreased. However, when the maximum number of users per cell is 500, the percentage number of users without access will decrease to reach its lowest value at BWF 0.8.

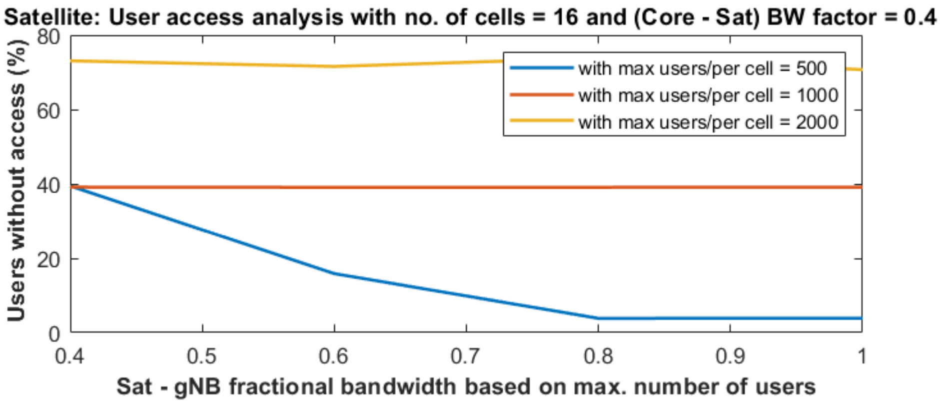

Figure 5.9: Percentage user access analysis of link Sat-gNB, BWF of link Core-Sat is fixed to 0.4, MEO

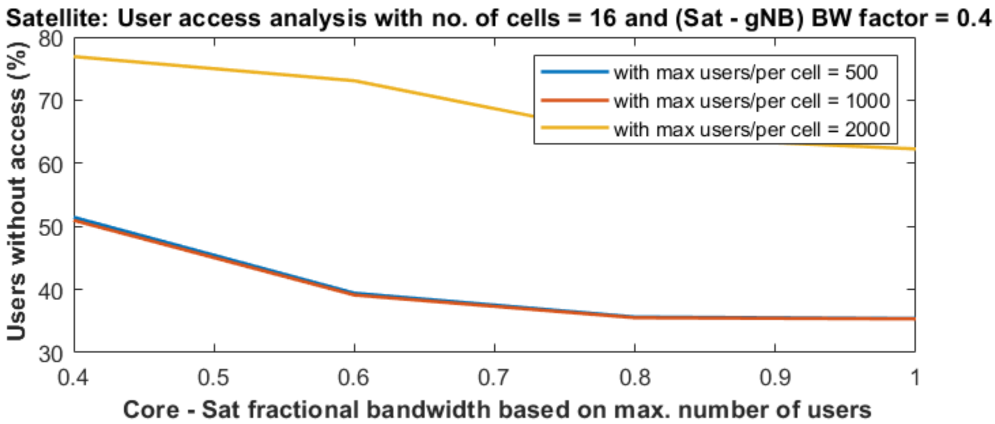

Figure 5.10: Percentage user access analysis of link Core-Sat, BWF of link Sat-gNB is fixed to 0.4, MEO

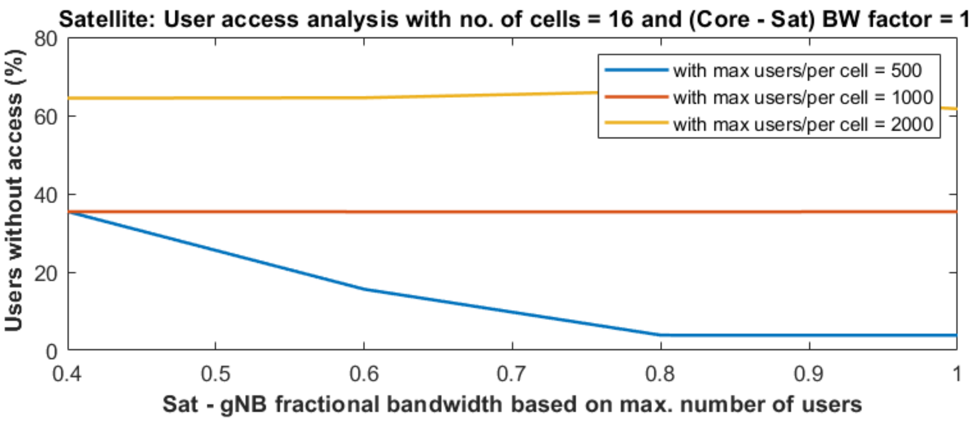

Figure 5.11: Percentage user access analysis of link Sat-gNB, BWF of link Core-Sat is fixed to 1, MEO

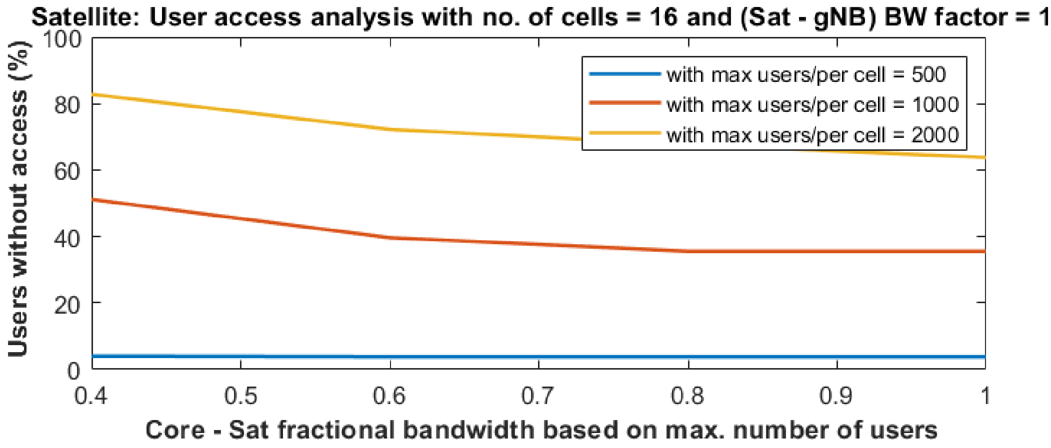

Figure 5.12: Percentage user access analysis of link Core-Sat, BWF of link Sat-gNB is fixed to 1, MEO

End-to-End Delay Analysis in the MEO Satellite Backhaul Scenario

In terms of delay, the results in Figure 5.13, Figure 5.14, Figure 5.15, and Figure 5.16 show that:

- Both BWFs impact the average network packet delay. However, the primary impact comes from the Sat-gNB link, as increasing its BWF value reduces the average packet delay, regardless of the Core-Sat link's BWF value. This effect is observed when user density is low. However, as user density increases, both links significantly influence the average network packet delay.
- Average network delay is high for different values of BWFs for both links.
- The lowest average network packet delay is 7 ms when the BWF of the link Core-Sate is fixed to 0.4 and for link Sat-gNB at the value 0.8, which is considered as an acceptable value based on 3GPP standards.

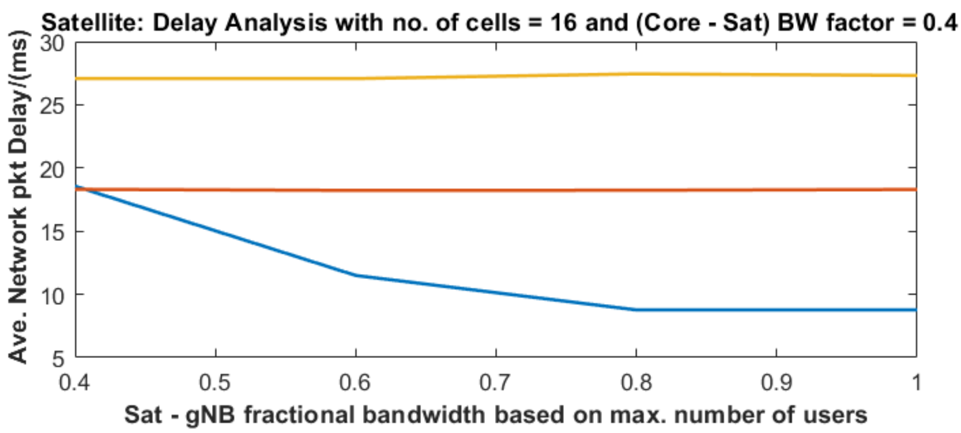

Figure 5.13: Average network packet delay of link Sat–gNB; BWF of link Core–Sat fixed to 0.4 (MEO).

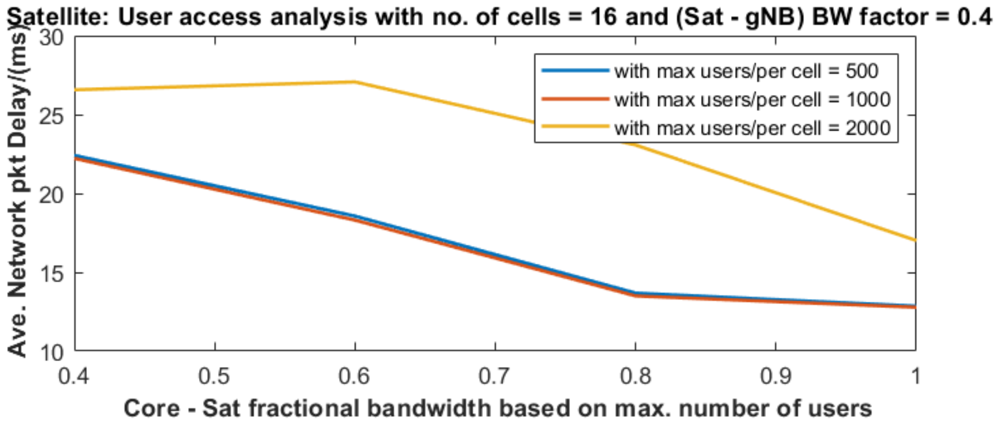

Figure 5.14: Average network packet delay of link Core–Sat; BWF of link Sat–gNB fixed to 0.4 (MEO).

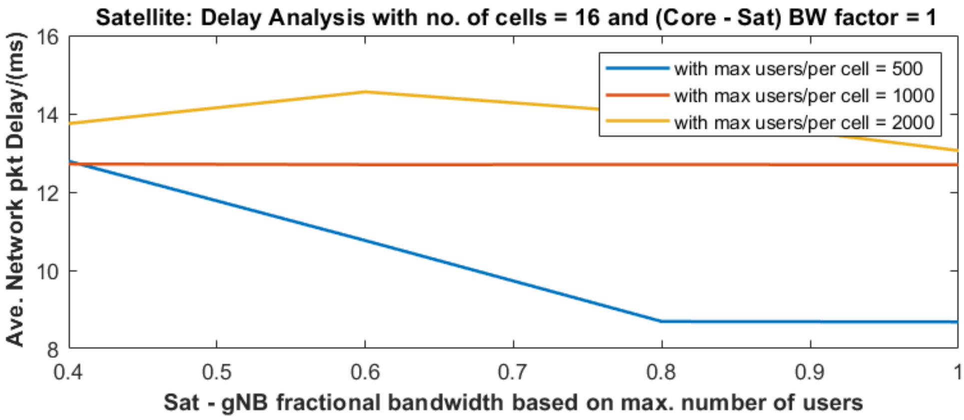

Figure 5.15: Average network packet delay of link Sat–gNB; BWF of link Core–Sat fixed to 1 (MEO).

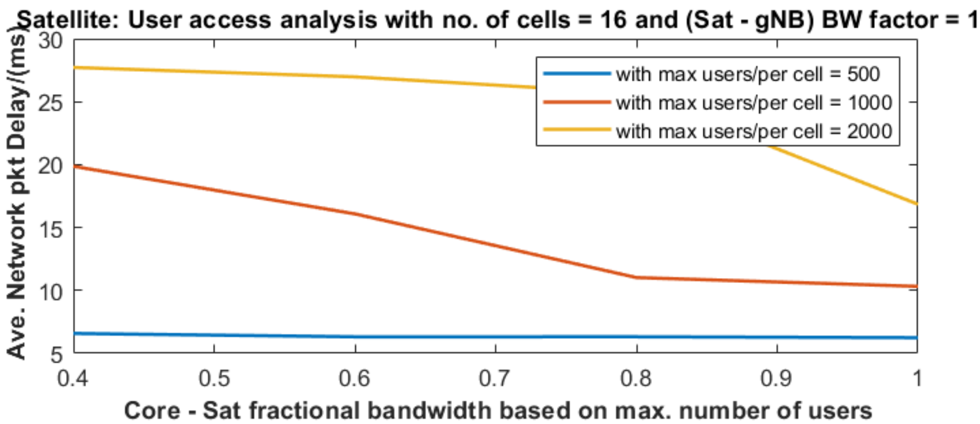

Figure 5.16: Average network packet delay of link Core–Sat; BWF of link Sat–gNB fixed to 1 (MEO).

5.4.2 LEO

The simulation results for the satellite based LEO backhaul scenario, in terms of user drop rate and end-to-end delay, demonstrate that:

Percentage number of dropped users

For LEO satellite, the results in figures Figure 5.17, Figure 5.18, Figure 5.19, and Figure 5.20 show that:

- The major impact comes from the BWF of Sat-gNB, as increasing it decreases the percentage of users without access in different scenarios. However, the rate of improvement varies.
- When the number of maximum users per cell is 500, the graphs show a more rapid decrease in the percentage of users without access as the Sat-gNB BWF increases.
- A slower rate of decline is observed with increasing BWF of the Sat-gNB link, compared to the scenario with 1000 users per cell or more.

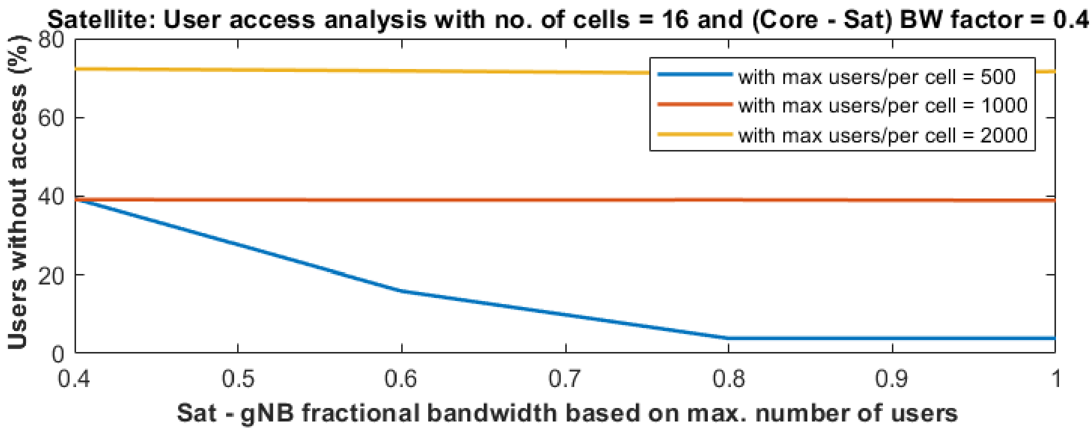

Figure 5.17: Percentage user–access analysis of link Sat–gNB; BWF of link Core–Sat fixed to 0.4 (LEO).

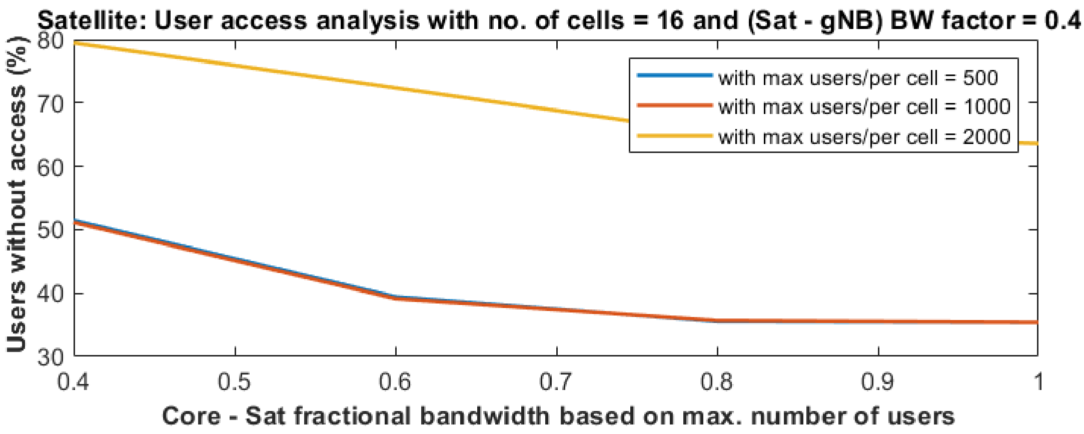

Figure 5.18: Percentage user–access analysis of Core–Sat; BWF of link Sat–gNB fixed to 0.4 (LEO).

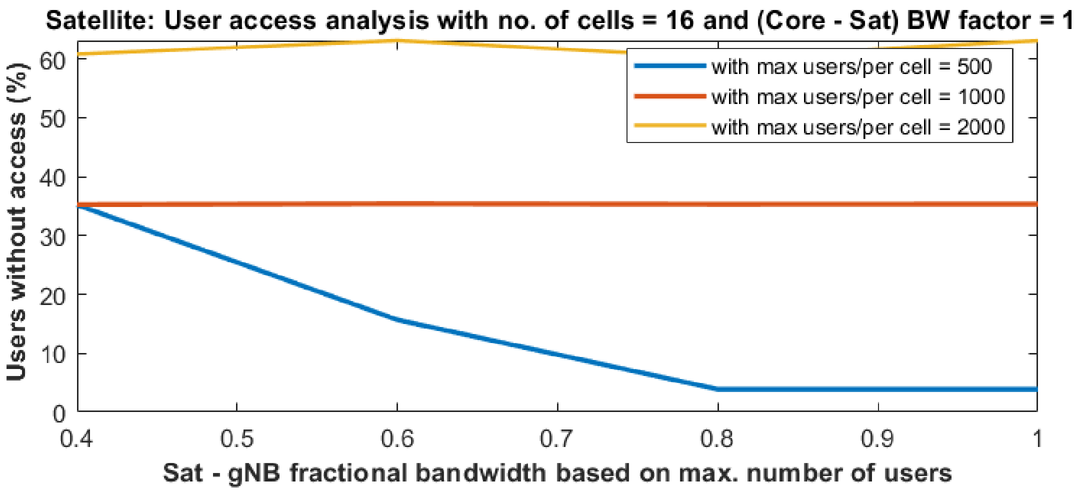

Figure 5.19: Percentage user–access analysis of link Sat–gNB; BWF of link Core–Sat fixed to 1 (LEO).

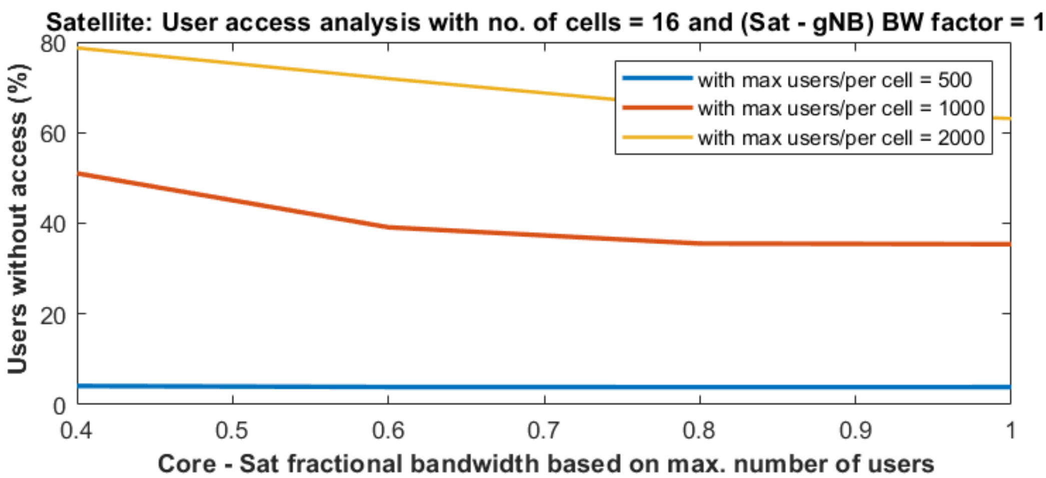

Figure 5.20: Percentage user access analysis of link Core–Sat; BWF of link Sat–gNB fixed to 1 (LEO).

End-to-End Delay Analysis in the LEO Satellite Backhaul Scenario

In terms of delay, the results in Figure 5.21, Figure 5.22, Figure 5.23, and Figure 5.24 show that:

- The major impact comes from link Sat-gNB on the average delay of the network regardless of the rate of the link Core-Sat.
- BWF of the link Core-Sat has also an impact on the average network delay, but it is a slight one and will vary based on the other factors in the network.
- The density of users also has an impact on the average delay.
- The lowest average network delay is 7 ms. This happened when the BWF of link Sat-gNB is 0.8 regardless to the BWF value of the link Core-Sat.

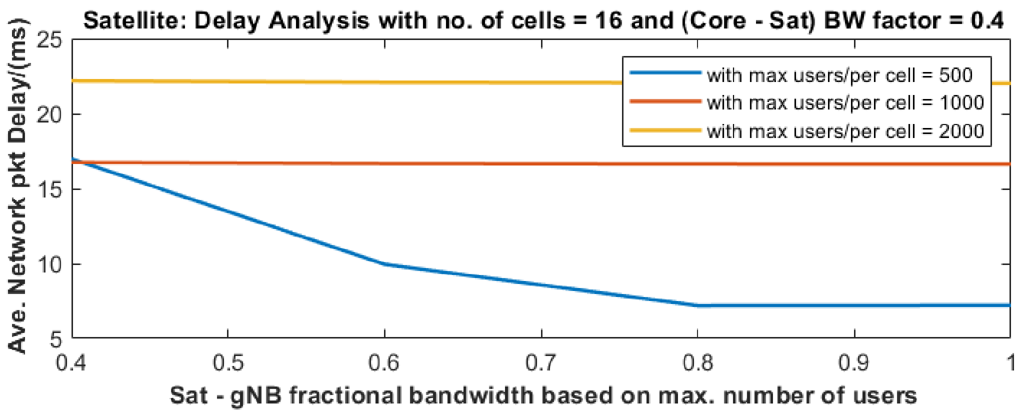

Figure 5.21: The average network packet delay of link Sat-gNB, BWF of link Core-Sat is fixed to 0.4, LEO

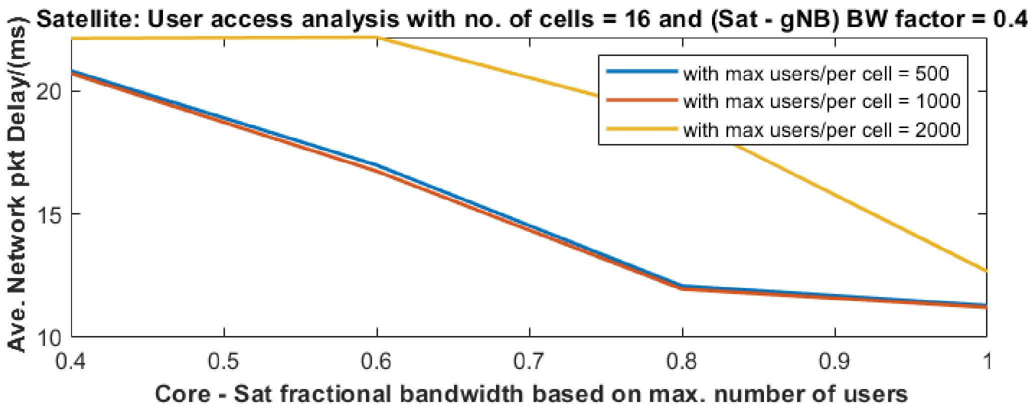

Figure 5.22: The average network packet delay of link Core-Sat, BWF of link Sat-gNB is fixed to 0.4, LEO

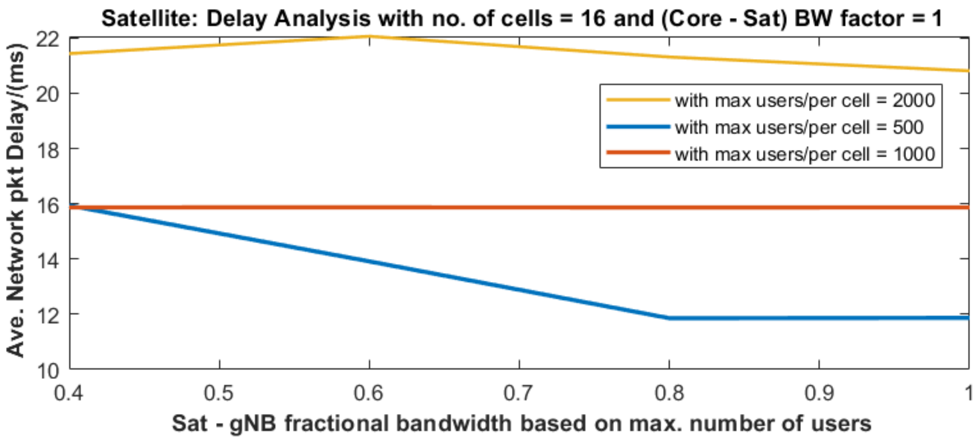

Figure 5.23: The average network packet delay of link Sat-gNB, BWF of link Core-Sat is fixed to 1, LEO

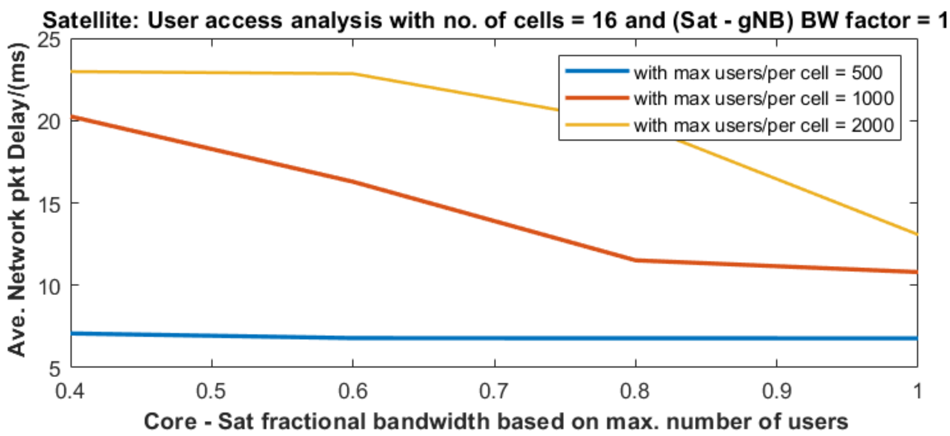

Figure 5.24: The average network packet delay of link Core-Sat, BWF of link Sat-gNB is fixed to 1, LEO

5.4.3 vLEO

The simulation results for the satellite based vLEO backhaul scenario, focusing on the percentage of dropped users and end-to-end delay, reveal that:

Percentage number of dropped users

For the vLEO satellite, the results in Figure 5.25, Figure 5.26, Figure 5.27 and Figure 5.28 show that:

- The major impact comes from the BWF of the link Sat-gNB, while less effect comes from the BWF of the link Core-Sat.
- With a maximum of 500 users per cell, increasing link BWF will improve user experience, whereas with 1000 this will lead to a higher initial percentage of

users without access regardless of the BWF rate.

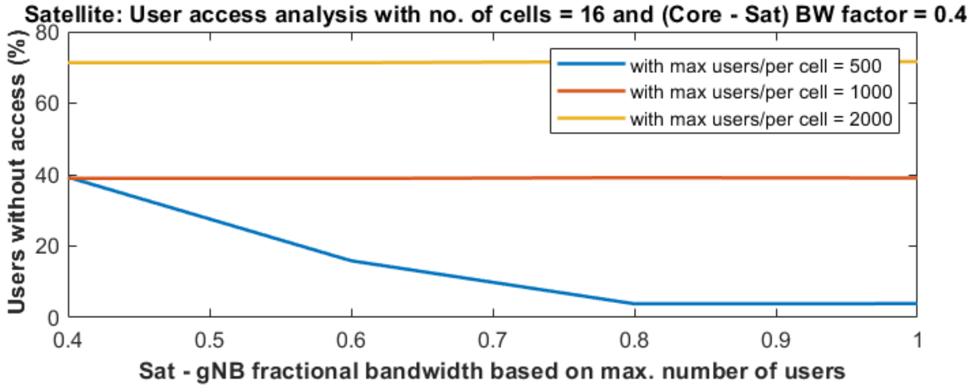

Figure 5.25: Percentage user access analysis of link Sat–gNB; BWF of link Core–Sat is fixed to 0.4 (vLEO).

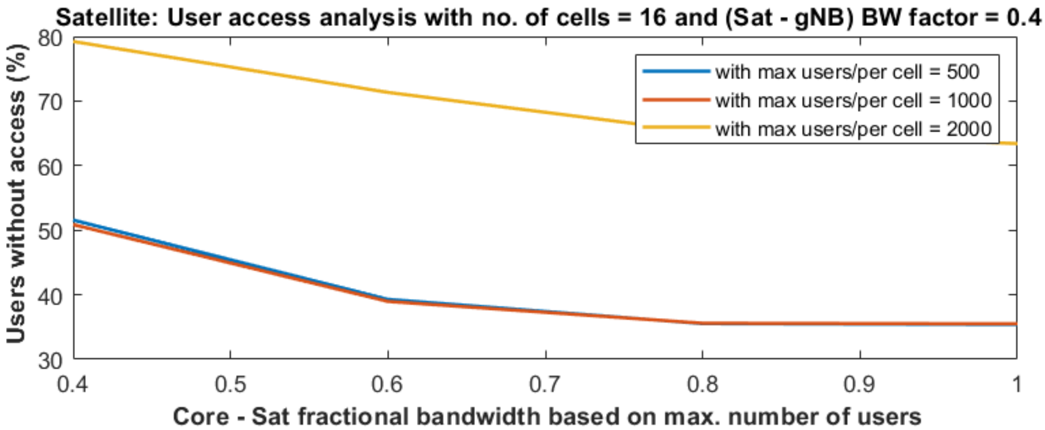

Figure 5.26: Percentage user access analysis of link Core–Sat; BWF of link Sat–gNB is fixed to 0.4 (vLEO).

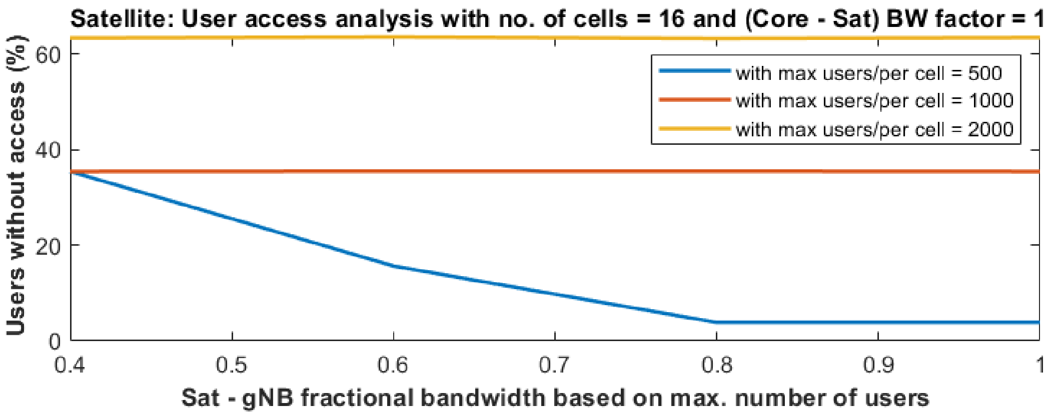

Figure 5.27: Percentage user access analysis of link Sat–gNB; BWF of link Core–Sat is fixed to 1 (vLEO).

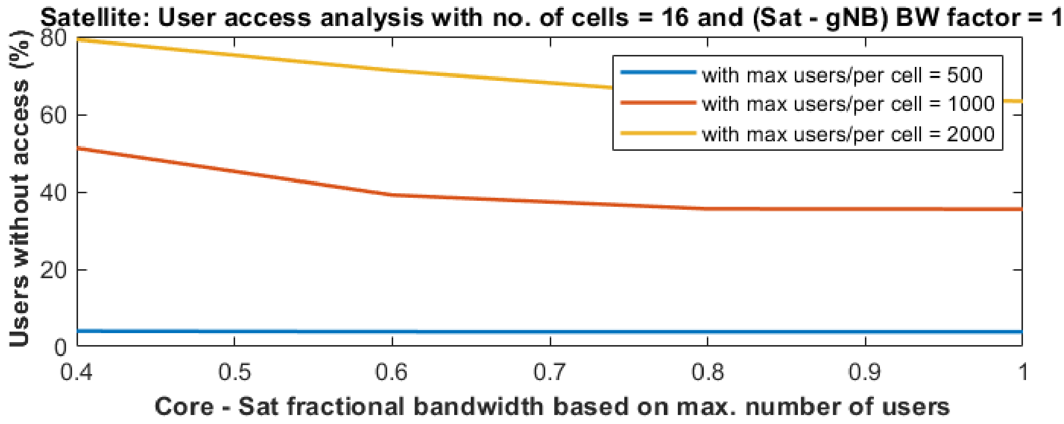

Figure 5.28: Percentage user access analysis of link Core–Sat; BWF of link Sat–gNB is fixed to 1 (vLEO).

End-to-End Delay Analysis in the vLEO Satellite Backhaul Scenario

In terms of delay, the results in Figure 5.29, Figure 5.30, Figure 5.31, and Figure 5.32 show that: show that:

- Allocating more bandwidth by increasing Sat-gNB BWF will improve network performance. However, increasing Core-Sat will have less impact and may vary based on other factors, such as Sat-gNB BWF.
- The density of users will affect the average network delay, as the figures illustrate that when the maximum number of users is 500, adjusting the BWFs will decrease the average delay. However, when the number of users is increased to 1000 or more, increasing link bandwidth will show no effect on the network performance.

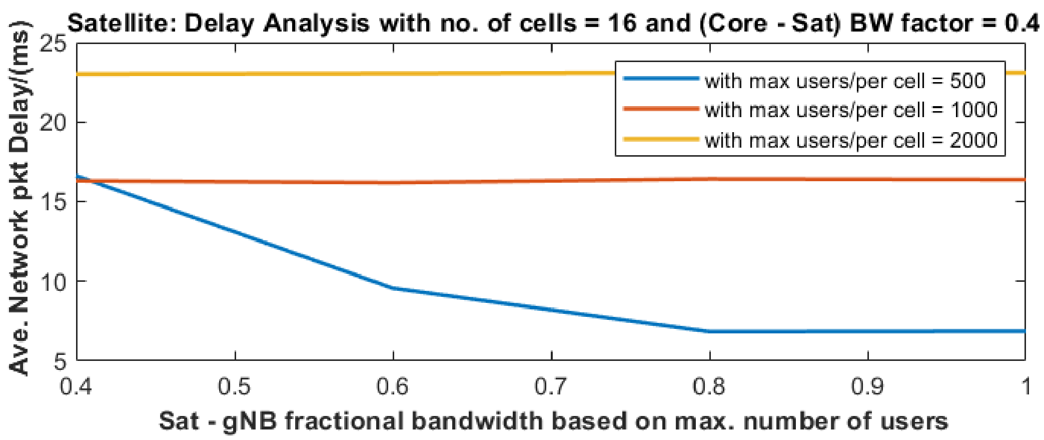

Figure 5.29: The average network packet delay of link Sat-gNB, BWF of link Core-Sat is fixed to 0.4, vLEO

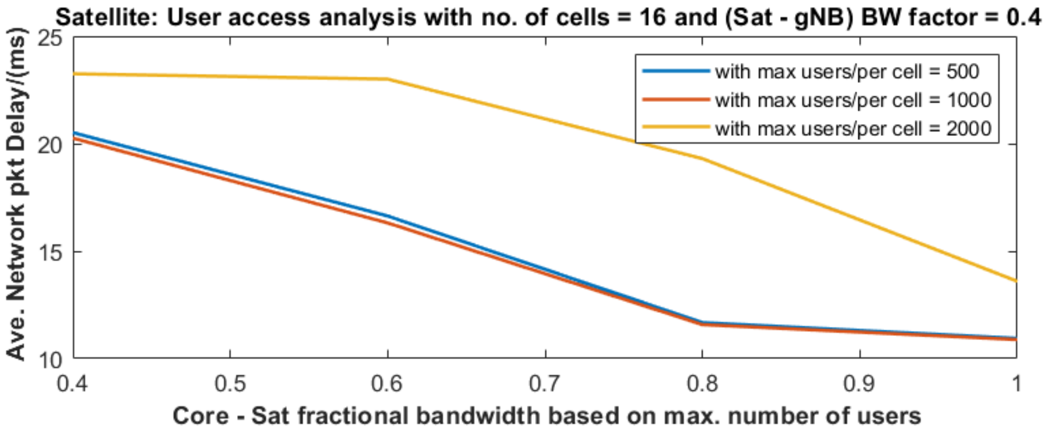

Figure 5.30: The average network packet delay of link Core-Sat, BWF of link Sat-gNB is fixed to 0.4, vLEO

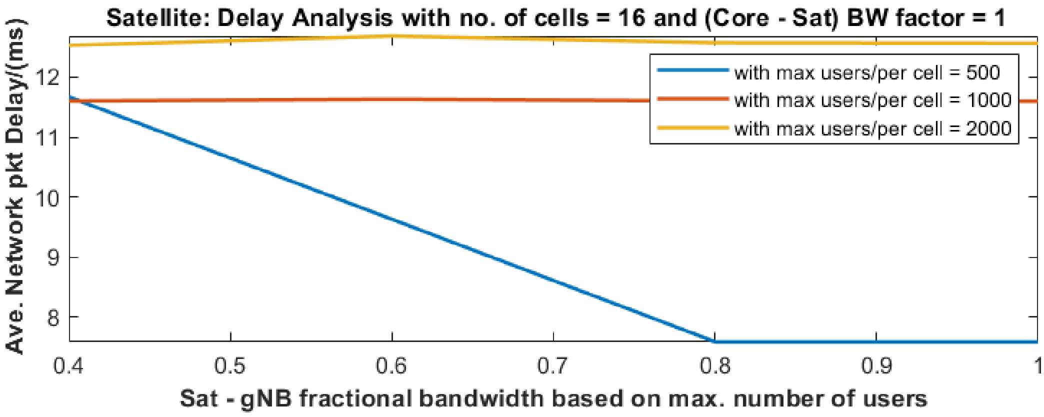

Figure 5.31: The average network packet delay of link Sat-gNB, BWF of link Core-Sat is fixed to 1, vLEO

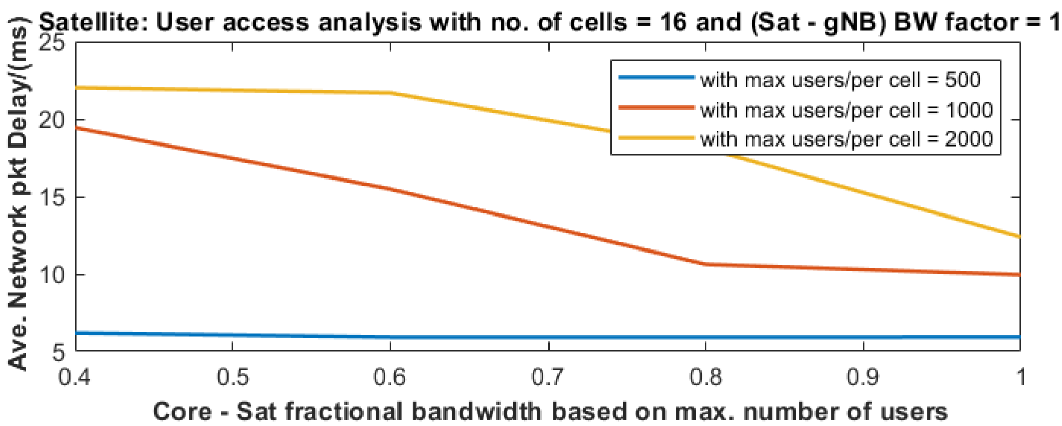

Figure 5.32: The average network packet delay of link Core-Sat, BWF of link Sat-gNB is fixed to 1, vLEO

5.5 Comparison and Discussion

The analysis presenting presented in this study is supported by the observed trend and patterns of each figure. The potential impact of factors including bandwidth, average end-to-end delay and user density have been considered. The insights provided in this study can be valuable to network operators, providers, provider, and investors who plan to introduce 5G technology and beyond in developing nations. By understanding the trade-offs between bandwidth allocation, user density, and network performance, they may make informed decisions to improve user experience and network efficiency.

- Based on the 5G scenario adopted in this study, handover delay is not considered as the coverage time greater than the service time required for each satellite orbit unless a live streaming application is considered, then handover will play a vital role to secure continuous of the service. For example, if vLEO orbit is used, handover is required every 15s as a minimum coverage time. This is because the coverage time is greater than the time required for handover from one satellite to the nearest one, which is between 50 and 100 ms in order to guarantee the continuity of services.

- For all satellite orbits, user density have the same impact on the network performance for both average network delay and the percentage number of users without access. For instance when the maximum number of users per cell is 500 users increasing BWFs will improve the performance, while when when its 1000 or more the performance will not change, thus indicating that the network capacity has been reached.

- The results show that the BWF of link Sat-gNB is playing a vital role in the network performance in terms of average network delay and percentage number of users without access. For instance, when its BWF was at its lowest value (0.4), figures for both average delay and percentage number of users without access showed its highest rate and improved when the BWF increased regardless of the BWF of link Core-Sat.

- The BWF of link Core-Sat has less impact on improving the network performance and may vary based on other factors.

- By comparing the result from all the orbits, for different maximum number of users, and different BWFs for all the links in network, the greater the average packet delay, the greater the higher average network packet delay n MEO satellite, and the lowest in vLEO satellite due to the high propagation delay in the case of MEO. Figure 5.33, and Figure 5.34 illustrate one of the cases where Core-Sat link is fixed to 0.4.

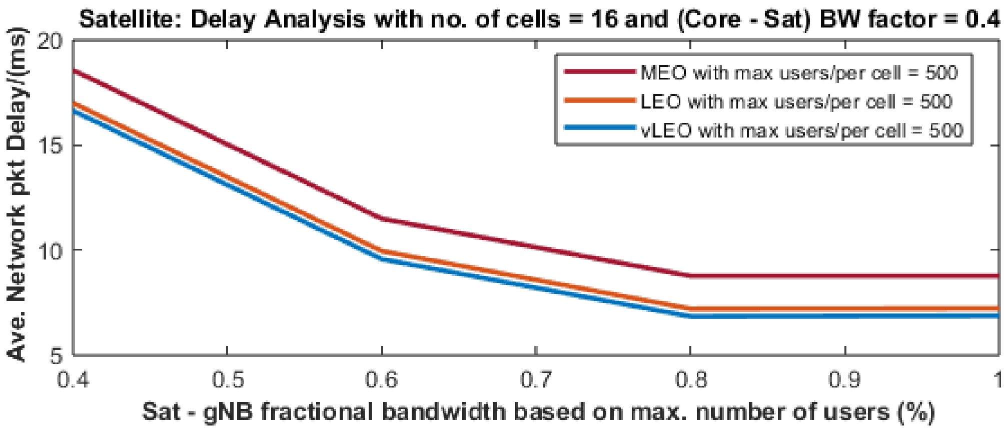

Figure 5.33: The average network packet delay of link Sat-gNB, BWF of link Core-Sat is fixed to 0.4, Users is 500

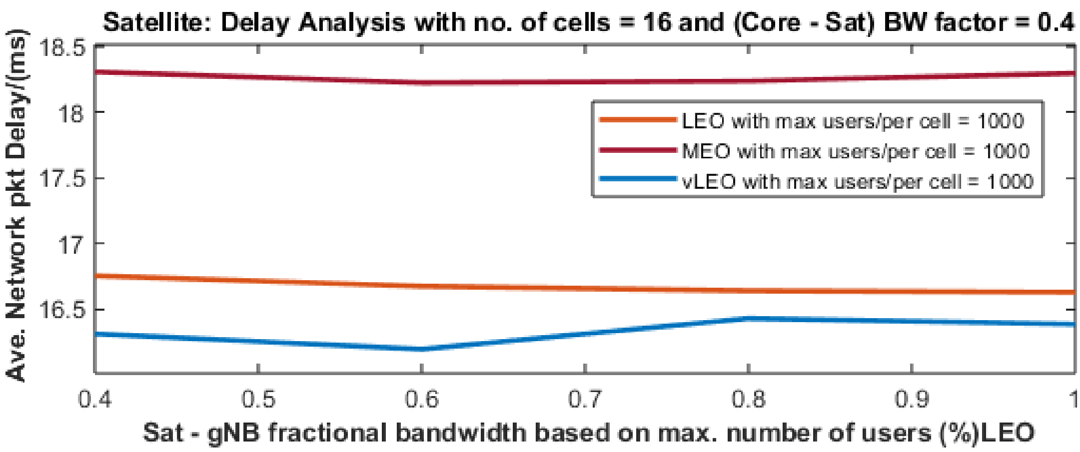

Figure 5.34: The average network packet delay of link Sat-gNB, BWF of link Core-Sat is fixed to 0.4, users is 1000

In addition, Figure 5.35, and Figure 5.36 show that all the orbits exhibit the same behavior in terms of the percentage number of users without access. The reason behind this performance is that this study estimates the same maximum link capacity for all the orbits.

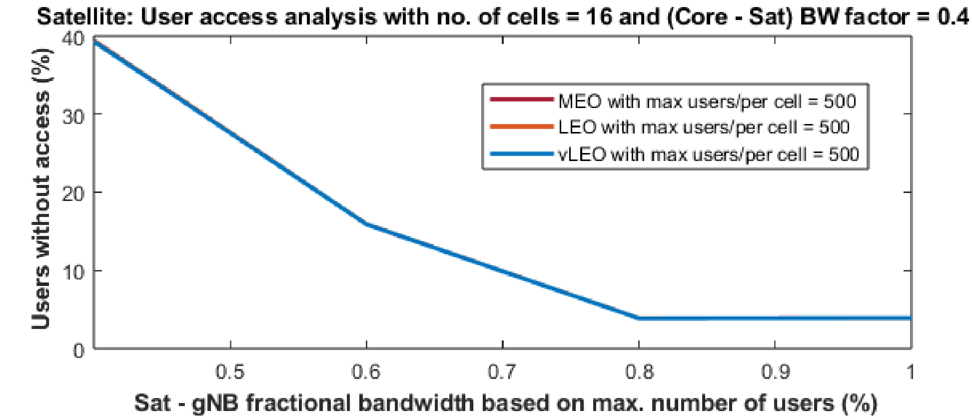

Figure 5.35: The average network packet delay of link Sat-gNB, BWF of link Core-Sat is fixed to 0.4

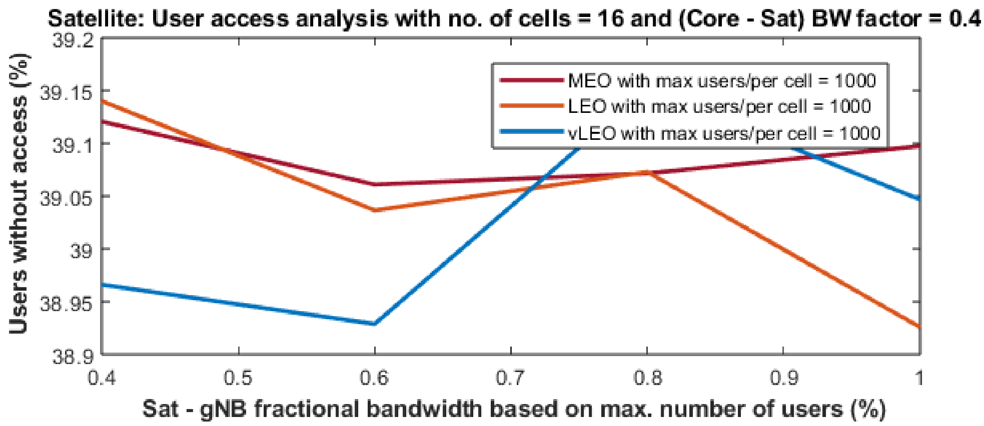

Figure 5.36: The average network packet delay of link Core-Sat, BWF of link Core-Sat is fixed to 0.4

The models presented in this article offer practical solutions for optimizing performance and supporting the design of 5G deployment in developing countries.

In conclusion, LEO/vLEO satellites will play an important role in delivering 5G services and applications that require low latency, such as broadband in crowded areas and medical monitoring, while MEO satellites may play a vital role in other 5G services and applications that require a large service coverage area and high user density. As a result, their expansion plan will include upgrades in terms of capacity growth and corresponding bandwidth requirements, such as spectrum and backhaul.

5.6 Summary

Satellite backhaul was evaluated across MEO, LEO, and vLEO under the eMBB “crowd” load by varying the bandwidth factor (BWF) on Sat–gNB and Core–Sat and the users-per-cell. Admission is chiefly controlled by Sat–gNB BWF: higher values reduce the share of users without access, with the largest gains at moderate BWF and lower density. End-to-end delay is also most sensitive to Sat–gNB unless Core–Sat is the tighter segment. Orbit choice mainly tunes propagation delay: for equal capacities, vLEO yields the lowest delay, MEO the highest. Higher user density drives earlier saturation.

Implication: Provision the limiting link to about BWF 0.8 before other upgrades; select vLEO/LEO for delay-sensitive eMBB and MEO where broader coverage outweighs latency.

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Chapter 6

Summary and future works

This chapter presents a summary of the key findings of the two research models presented within this thesis. Section 6.1. presents a brief outline of the overall thesis including its aims, objectives and applications. The following sections 6.2 to 6.4. present a description of the model setup and the key findings of each individual model design. Finally, section 6.5 discusses potential future works.

6.1 Thesis Overview

This thesis entailed investigation into how to introduce 5G technology to the developing countries by examining different backhaul technologies in terms of delay and bandwidth utilization. It aimed to facilitate the work of those who planning to invest in 5G and beyond in developing countries, helping developing countries to cope with the rest of the world in terms of new technologies, proposed a solution to solve their infrastructure issues, considering E2E delay and user statistics to optimize BW utilization. MATLAB simulation model of 5G network has been implemented based on one of the major mobile providers in one of the developing countries. Multiple wire backhaul like xDSL and fibre optics and wireless backhaul like mm Wave, microwave, and satellite have been adopted. The network behavior has been examined for each technology in terms of user access statistic, and one way E2E time delay to provide a clear view between bandwidth allocation, user access, and delay in regard to providing the research community with the solid basis for future studies relevant to this research topics.

To closely approximate real-world conditions, for any network, the simulation taken into account the critical variables such as user density, coverage area and the accurate number of gNBs as knowing the total area and gNB coverage area will help to determine their required amount of gNBs, the technologies employed for backhauling traffic, and the respective link capacities of those technologies. By considering these factors, this assure that the simulation reflected the complexities of real network environments, thereby ensuring the optimization results are relevant and applicable to practical scenarios. The structure of this thesis is as follow:

- Chapter 1 - Introduction

The chapter explained the significance of the research, discussed the research aims and objectives, de- scribed the research methodology, introduced the research contributions of the knowledge, presented the research structures and outlines, and finally depicted the publications that contributed to the work of the research.

- Chapter 2 - Literature review

  In this chapter, the obstacles and challenges that may face those who plan to invest, deploy or develop 5G technology in developing countries were illustrated.

- Chapter 4 - Simulation study for exploring network behavior for various backhaul technologies

  In this chapter, different terrestrial technologies have been adopted, testing and analyzing. The results are comparing to propose a suitable solution for backhauling 5G traffic in developing countries.

- Chapter 5 - Satellite backhaul and analysis

  In this chapter, the the role of satellite networks in 5G technology and how it will integrate with the NTN were highlighted

6.2 Key contributions

- Development of a system model to analyze different technologies. a MATLAB simulation models developed for different backhaul technologies, terrestrial and non terrestrial, wire and wireless based on one of the major mobile technology providers in one of the developing countries.

- Comparison of different terrestrial backhaul technologies to aid 5G deployment in developing countries. The performance of each terrestrial technology evaluated by simulating and examining each models in terms of delay, the number of users that can access the network, and the maximum bandwidth utilization. The key findings is that by adopting a hybrid model topology based on the exiting network, will help determine the required backhaul technology. Because in developing countries there will be existing fibre infrastructure and incorporating this infrastructure in a hybrid setup using the models developed in this study will cooperate in selecting a proper technology.

- Investigation of satellite based backhaul technologies to aid 5G deployment in developing countries. The study mainly adopted the most promising satellite's orbits, vLEO, LEO and MEO to that cope with 5G services and applications requirements. The key findings is that LEO/vLEO satellites will play an important role in delivering 5G services and applications that require low latency, such as broadband in crowded areas and medical monitoring, while MEO satellites may play a vital role in other 5G services and applications that require a large coverage area and high user density. This model offer a practical solution for optimizing performance and supporting the design of 5G deployments in developing countries.

6.3 Conclusions

To summarise, there is no one solution to 5G backhaul, i.e. no unique technology to meet 5G backhaul requirements. The main point is that to build future backhaul, current transport networks must be optimised, incumbent solutions, such as HTS must be developed and new technologies, such as mmWave, sub-6GHz, IAB, and others, must be investigated.

For developing countries, there are different scenarios to be considered involving a number of factors, including the existing 3G or 4G network infrastructures, the available financial resources for deploying a 5G network and the population density in a certain geographic area. A hybrid model topology based on the existing networks and financial considerations based on specific needs/ requirements will play an important role in determining the backhaul network topology. Because in some developing countries there will be existing fiber infrastructure and incorporating this infrastructure in a hybrid setup using the models developed in this research will help to determine the required backhaul technologies/investments with minimum expenditure. The models presented in this study offer practical solutions for optimizing performance and supporting the design of 5G deployments in developing countries.

As a result, their expansion plan will include upgrades in terms of capacity growth and corresponding bandwidth requirements, such as spectrum and backhaul.

6.4 Future Work

Suggestions for future works are presented below:

- To use AI for traffic forecasting for users growth predication for short and long term surges in users. Load distribution across different cells for mobile network. In terms of satellite backhaul AI can help in optimizing handover between satellites and latency prediction based on different parameters.
- Merging satellites from different orbits to backhaul the traffic.

- To incorporate energy consumption metrics for different components to evaluate the trade offs between performance and energy.
- To investigate round trip latency for each technology, as this will help giving a clear vision in regards to the network performance.
- To further develop a network slicing and virtualization to provide isolated virtual networks for different use case and to enhance flexibility and manageability in the network.
- Plan the network jointly with traffic using band-aware link budgets—explicitly model path loss, rain fade, and gas absorption for each band (Ku/Ka/Q/V for satellite backhaul; FR1/FR2 for access) and validate the impact with scenario-based simulations.
- Finally, examine the economic implications of latency reduction strategies and consider the regulatory bodies to ensure that latency requirements align with policy objectives.

Appendix

MATLAB Code

```
%  This model incorporates both bandwidth and delay
   aspects in 5G with
%  random number of users. Simulations are done with
   varying number
%  frcational bandwidth w.r.t maximum number of users.
   Each results is
%  avarged over a number of runs.
%
   ------------------------------------------------------------------

%% General defs.
clear;
clc;
dataDirectory = '\\ikb\home\90\0835690\My Documents\
   MATLAB\new path';
%dataDirectory = pwd;
Bit_rate_UE  = 25*10^6;        % User bit rate, 10 MBits/s
Pkt_size_UE  = 1500*8;         % User pkt size, bits
Pkt_rate_UE  = Bit_rate_UE/Pkt_size_UE;    % Pkt rate for
    user
Ave_runs     = 1000;          % Number of runs for
   averaging
Disp_run     = 1000;
Speed_c      = 3*10^8;       % EM wave speed in free space
Vfactor_fibre= 0.8;          % Velocity factor for the
   fibre
Fibre_BW     = 600e9;        % (Iraq DWDM 600 Gbps- 1Tbps)
```

```
    DWDM link bandwidth based on the paper Backhauling 5g
    small cells: A radio resource management perspective
delta_1       = 1e-9;            % to avoid errors due to
   very small numbers
Max_delay     = 10e-3;           % To limit excessive delay
    at Core, L3, gNB etc (for teh diaplay).
Min_UEs       = 10;
%Fibre_PC      = 0.02e-3;

% DSL backhaul
Vfactor_DSL    = 0.65;
DSL_Bw         = 100e6;        % 100 Mbps based on
   reference 36 paper Under standing qos applicability in
    5g transport networks

DSL_PC_d       = 0.02e-3;        % (This same as MW
   processing delay equipments as Dr Nila guidance)
   Backhaul challenges and emerging research directions

Rep_PC_d       = 500e-9;        % in s presentation
   Equipment latency is important but not the most
   important factor  AVIAT networks
Rep_reg_PC_d   = 20e-6;        % in s presentation
   Equipment latency is important but not the most
   important factor  AVIAT networks
Dist_DSL       = 1.5e3;
                                                       %
   Backhauling 5g small cells: A radio resource
   management perspective
Rep_regen_flag= 0;

   % To switch between repeater and regenerator

%% 5G
num_cells_x          = 4;
                                                     %
   Allways use even numbers
num_cells_y          = num_cells_x;
num_cells            = num_cells_x*num_cells_y;
```

```
                                % Number of cells
Cell_radius          = 12e3;
                                                   % Cell
    radius in m   (30 km)
num_L3               = num_cells_x/2*num_cells_y/2;
                            % Number of L3 switches used
   to connect gNBs to core
L3_PC_d              = 0.001e-3;
                                              % L3
   default processing time delay (s)(provide by vender;
   Can be the time required to process one packet in each
    swtich)
gNB_PC_d             = 0.1e-3;
UE_PC_d              = 0.1e-3;
%% Delay and bandwidth

%% Core Location
Core_x = 3e5;

   % core cooredinate
Core_y = 3e5;

   % core cooredinate
Core_PC_d = 0.05e-3;
%% L3 Switch Location - one for 4 cells and Core -L3
   switch delays

num_gNB_per_L3 = 4;

   % Number of gNBs for each L3 switch
l3 = 1;
for  n = 1:2:num_cells_x-1
  for m = 1:2:num_cells_y-1
    L3_Switch{l3}.x    = 2*n*Cell_radius;
                                         % L3 Switche's x
       coordinates
    L3_Switch{l3}.y    = 2*m*Cell_radius;
                                         % L3 Switche's y
       coordinates
```

```
    % Delay Calculatiosn between Core and L3 switch. L3
       switches are arranged in a ring configuration
    if l3 == 1
      Dist_Core_L3    = sqrt((Core_x-L3_Switch{l3}.x).^2 +
         b@x...
                             (Core_y-L3_Switch{l3}.y).^2);
                                                    %
                               Distance from Core to the
                               first L3 switch
    else
      Dist_L3n1_L3n2 = sqrt((L3_Switch{l3}.x - L3_Switch{
         l3-1}.x).^2 + ...
                              (L3_Switch{l3}.y - L3_Switch{
                                l3-1}.y).^2);       %
                                Distance from the first L3
                                 switch to other switch in
                                 a ring pattern (L1-L2)
                                and (L1-L2-L3) and so on.
      Dist_Core_L3    = Dist_Core_L3 + Dist_L3n1_L3n2;
                               % Add the distance from (L1
         -L2) to (L2-L3) to get the overall distance from
          (L1-L3) for example
    end;

    L3_Switch{l3}.PC_d = L3_PC_d * l3;
                                            % Because its
       ring, the processing time of L3 will * (l) the
       number of switches
    L3_Switch{l3}.PG_d = Dist_Core_L3/(Speed_c*
       Vfactor_fibre);              % Progation delay
       between Core and L3_switch
    l3 = l3 + 1;
  end % m
end %n

g = 1;
for ii = 1:num_cells_x
  for jj = 1:num_cells_y
```

```
    gNB{g}.x = (2*ii-1)*Cell_radius; % x coordinate of
       gNB location
    gNB{g}.y = (2*jj-1)*Cell_radius; % y coordinate of
       gNB location
    gNB{g}.L3 = floor((ii-1)/2)*(num_cells_y/2) + floor((
       jj-1)/2) + 1;     % Determine the gNBs that attach
        to a specific L3 switch

    % Delay calculation between Core and gNB

    L3_ind = gNB{g}.L3;
    DistL3_gNB = sqrt((L3_Switch{L3_ind}.x - gNB{g}.x)^2
       + (L3_Switch{L3_ind}.y - gNB{g}.y)^2);
    gNB{g}.PG_d = L3_Switch{L3_ind}.PG_d + DistL3_gNB /(
       Speed_c* Vfactor_DSL); % Propagation delay between
        Core and the gNB

    % Number of hop between L3 switch and gNB
    Num_repeaters = floor(DistL3_gNB /Dist_DSL);
                                   % Calculate the number
       of hops based on distance

    g = g + 1;
  end % jj
end % ii

num_L3_Switch = l3 - 1;
num_gNB       = num_cells;

%---------------------------------------------------%
% Simulation with diffrent maximum users per cell   %
%---------------------------------------------------%
% A bandwidth factor is used to analyse the number of
   servisable users with
% random number of users and fixed gNB bandwidth.

BW_factL3_gNB_min = 0.9; BW_factL3_gNB_max = 1;
   BW_factL3_gNB_step = 0.05;
BW_factL3_L3_min  = 0.9;  BW_factL3_L3_max = 1;
```

```
   BW_factL3_L3_step   = 0.05;
Max_UE_ind = 1; BWf_L3_L3_ind = 1;

%% Simulation for Diffrent maximum number of users per
   cell

for Max_UEs_cell = 200 : 200 : 200
  disp(['Max UE per cell = ', num2str(Max_UEs_cell)])
  Cap_gNB_U  = Bit_rate_UE;                                  %
     Capacity for gNB - User link
  BWf_L3_gNB_ind = 1; BWf_C_L3_ind = 1; BWf_L3_L3_ind =
     1;
  % Data_BW_Delay
  % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,1) =
     Max num of users
  % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,2) =
     BW Factor L3 - L3
  % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,3) =
     BW Factor L3 - gNB
  % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,4) =
     Dropped usrs
  % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,5) =
     total delay

  %% Simulation for diffrent bandwidth factors
  for BW_factorL3_gNB = BW_factL3_gNB_min :
     BW_factL3_gNB_step : BW_factL3_gNB_max
    disp(['BW factorL3_gNB = ', num2str(BW_factorL3_gNB)
       ])

    BWf_L3_L3_ind = 1;
    Cap_L3_gNB  = BW_factorL3_gNB*Max_UEs_cell*
       Bit_rate_UE;                 % Capacity for L3 -
       gNB link

     if Cap_L3_gNB > DSL_Bw
        Cap_L3_gNB = DSL_Bw; % Add max delay to the
           current delay and continue
```

```
end

for BW_factorL3_L3 = BW_factL3_L3_min :
   BW_factL3_L3_step : BW_factL3_L3_max
    disp(['BW_factorL3_L3 = ', num2str(BW_factorL3_L3
       )])
    Data_BW_Delayd(Max_UE_ind,BWf_L3_L3_ind,
       BWf_L3_gNB_ind,1) = Max_UEs_cell;
    Data_BW_Delayd(Max_UE_ind,BWf_L3_L3_ind,
       BWf_L3_gNB_ind,2) = BW_factorL3_L3;
    Data_BW_Delayd(Max_UE_ind,BWf_L3_L3_ind,
       BWf_L3_gNB_ind,3) = BW_factorL3_gNB;
    Cap_L31_L32 = BW_factorL3_L3*num_gNB_per_L3*
       Cap_L3_gNB*(num_L3_Switch-1);   % Capacity for
        the links connecting L3 switches in the ring
    BW_factorC_L3 = 1;
    Cap_Core_L3 = BW_factorC_L3*num_gNB_per_L3*
       Cap_L3_gNB*num_L3_Switch;       % Capacity for
        Core - L3 ring link
    %% multiple runs for averaging
    for run = 1 :  Ave_runs
                                                     %
       Averaging loop (random user allocation per
       cell)
        if rem(run,Disp_run) == 0 disp(['Run number '
           ,num2str(run)]); end;
        Total_UEs   = 0;
        Dropped_UEs = 0;

           % Dropped users due to bandwidth
           limitation

        %% Assignment of random number of users per
           cell,defs of user loactions, gNB delays
           calcs.
        for g = 1:  num_gNB
            gNB{g}.UEs      = Min_UEs + round((
               Max_UEs_cell-Min_UEs)*rand); % Number
               of users in a cell (Keep inside the
```

```
      ave loop)
    gNB{g}.PC_d      = gNB_PC_d;
                                                  %
      Processing delay: Based on the
      reference paper
    % gNB dropped users based on BW
    gNB_BW      = Cap_L3_gNB;
                                                     %
      gNB Bandwidth to service all users
      attached to it
    Total_UEs   = Total_UEs + gNB{g}.UEs;
    if (gNB{g}.UEs*Bit_rate_UE) > gNB_BW
        gNB_UEs = round(gNB_BW/Bit_rate_UE);
                                  % gNB actual
          users
        Dropped_UEs = Dropped_UEs + (gNB{g}.
          UEs - gNB_UEs);
        gNB{g}.UEs  = gNB_UEs;

    end
end; % for g defs

%% L3 Switches: Calculation of queing,
   processing delays etc. for all L3 switches
for l3 = 1 : num_L3_Switch    L3_Switch{l3}.
   UEs = 0; end;
% Calculation of number of users who needs to
    be serviced by
% the L3 switch
for g = 1:  num_gNB
    L3_ind                = gNB{g}.L3;
    L3_Switch{L3_ind}.UEs =  L3_Switch{L3_ind
      }.UEs + gNB{g}.UEs;
end;
% Dropped users at L3 switch
for l3 = 1 : num_L3_Switch
    if l3 == 1 L3_cap = Cap_Core_L3; else
      L3_cap = Cap_L31_L32; end;
    if (L3_Switch{l3}.UEs*Bit_rate_UE) >
```

```
            L3_cap
             L3_UEs = round(L3_cap /Bit_rate_UE);
             L3_Switch{l3}.dUEs = L3_Switch{l3}.
                UEs - L3_UEs;
             L3_Switch{l3}.UEs  = L3_UEs;
             Dropped_UEs        = Dropped_UEs +
                L3_Switch{l3}.dUEs;

        end;
    end;

    % L3_Switch (queuing+transmision) delay
    for l3 = 1 : num_L3_Switch
        for l31 = l3+1 : num_L3_Switch
            L3_Switch{l3}.UEs = L3_Switch{l3}.UEs
                + L3_Switch{l31}.UEs; % because
                of the ring set-up more user
                traffic go through different L3
                switches
        end;
        Arrival_rate_lam        =  L3_Switch{l3}.
           UEs*Pkt_rate_UE;  % Arrival rate in
           pkts/s at the L3 switch
        Service_fract_alpha     =  1;
        Service_rate_mu         =
           Service_fract_alpha*Cap_L31_L32/
           Pkt_size_UE;
        rate_diff               = (
           Service_rate_mu-Arrival_rate_lam);
        if rate_diff > delta_1  L3_Switch{l3}.
           TQ_d = 1/(rate_diff);
        else L3_Switch{l3}.TQ_d = Max_delay; end;
    end;
display (L3_Switch{l3}.TQ_d)
    %% CORE: Dropped users, Processing and quing
       delays
    if (L3_Switch{1}.UEs*Bit_rate_UE) >
       Cap_Core_L3
        Core_UEs  = round(Cap_Core_L3 /
```

```
            Bit_rate_UE);
        Core_dUEs = L3_Switch{1}.UEs - Core_UEs;
        Dropped_UEs         = Dropped_UEs +
            Core_dUEs;
    end;
    Arrival_rate_lam     = L3_Switch{1}.UEs*
        Pkt_rate_UE;
    Service_fract_alpha = 1;
    Service_rate_mu      = Service_fract_alpha*
        Cap_Core_L3/Pkt_size_UE;
    rate_diff            = (Service_rate_mu-
        Arrival_rate_lam) + delta_1;
    if rate_diff > delta_1  Core_TQ_d = 1/
        rate_diff;                 % Need to refine
        this according to [22]
    else Core_TQ_d = Max_delay; end;

    %% User Delay calculations
    for g = 1 : num_gNB
        % gNB dropped users based on BW
        gNB_BW      = Cap_L3_gNB;
                                                  %
            gNB Bandwidth to service all users
            attached to it
        Total_UEs   = Total_UEs + gNB{g}.UEs;
        if (gNB{g}.UEs*Bit_rate_UE) > gNB_BW
            gNB_UEs = round(gNB_BW/Bit_rate_UE);
                                      % gNB actual
                users
            Dropped_UEs = Dropped_UEs + (gNB{g}.
                UEs - gNB_UEs);
            gNB{g}.UEs   = gNB_UEs;
        end
        %  gNB (queuing + transmision) delay
        Arrival_rate_lam      =  gNB{g}.UEs*
            Pkt_rate_UE;              % Arrival rate
             in pkts/s at the gNB switch
        Service_fract_alpha  =  1;
        Service_rate_mu      =
```

```
    Service_fract_alpha*Cap_L3_gNB/
    Pkt_size_UE;
%gNB{g}.TQ_d          =  0*1/(
    Service_rate_mu-Arrival_rate_lam);   %
     Assuming no quing delay at gNB
gNB{g}.TQ_d          = delta_1;

%%  Simulation for users within a cell (
    gNB)
for u = 1 : gNB{g}.UEs
    loc_ang = 2*pi*rand;
    UE{u}.r = Cell_radius*rand;
    UE{u}.x = gNB{g}.x + UE{u}.r*sin(
       loc_ang);               % UEs x
       coordinates
    UE{u}.y = gNB{g}.y + UE{u}.r*cos(
       loc_ang);               % UEs y
       coordinates

    % User - gNB Prop. delay calculation
    Dist        = sqrt((gNB{g}.x - UE{u}.
       x)^2 + (gNB{g}.y - UE{u}.y)^2);
    UE{u}.PG_d   = gNB{g}.PG_d+ Dist/
       Speed_c;                 % Core to
       User propogation delay
    UE{u}.PC_d   = UE_PC_d;
                                         %
       Based on 3GPP guidance

    % Total delay (Propgation,Processing,
        Queuing, transmission)on DL for
       user
    L3_ind       = gNB{g}.L3;

    %% Adding the number of mmWave to the
        total delay
    UE{u}.delay = UE{u}.PC_d + UE{u}.PG_d
        + ...
                 gNB{g}.PC_d + gNB{g}.
```

```
                        TQ_d + ...
                      Core_PC_d + Core_TQ_d;
                                        %
                        Total delay for the
                        user

All_delay(u,1) = UE{u}.PG_d;
                                    %
   Propagation delay
All_delay(u,2) = Core_PC_d + gNB{g}.
   PC_d + UE{u}.PC_d; % Processing
   delay
All_delay(u,3) = Core_TQ_d + gNB{g}.
   TQ_d;                % Quieuing
   delay

for l3 = L3_ind : -1 : 1

   % As it is a ring setup all L3
   proc. delays contribute

    UE{u}.delay = UE{u}.delay +
       L3_Switch{l3}.PC_d + L3_Switch
       {l3}.TQ_d;
    All_delay(u,2) = All_delay(u,2) +
        L3_Switch{l3}.PC_d;
    All_delay(u,3) = All_delay(u,3) +
        L3_Switch{l3}.TQ_d;

end;
 %   Additional delays due to
    repeaters
UE{u}.delay = UE{u}.delay + DSL_PC_d
   + Rep_PC_d*Num_repeaters ...
                + Rep_regen_flag*((
                   Rep_reg_PC_d -
                   Rep_PC_d + Max_delay
                   )*Num_repeaters);
                   % MW_equip_PC_d*1:
```

```
                            for Tx at L3 switch
                            and RX and gN
        All_delay(u,2) = All_delay(u,2) +
           DSL_PC_d*1 + Rep_PC_d*
           Num_repeaters + Rep_regen_flag*((
           Rep_reg_PC_d-Rep_PC_d)*
           Num_repeaters);
        All_delay(u,3) = All_delay(u,3) +
           Rep_regen_flag*Max_delay*
           Num_repeaters;
        UE_delay(u)  = UE{u}.delay;


        % for plotting user locations
        if run == Ave_runs
           gNB{g}.UE{u}.x = UE{u}.x;
           gNB{g}.UE{u}.y = UE{u}.y;
        end
    end % u

    %  UE_delay
    gNB{g}.ave_d         = mean(UE_delay);
                                     % Average
       delay in a cell
    clear UE delay

       % Need to clear otherwise earlier
       information will be there
    gNBs_delay(g)        = gNB{g}.ave_d;
    gNBs_All_delay(g,:) = mean(All_delay,1);
    clear All_dealy
end % g

% Dropped user stats
Dropped_UEs_Perc_runs(run)= Dropped_UEs/
   Total_UEs*100;

% User delay stats
Ave_delay_runs(run)        = mean(gNBs_delay);
```

```
                                        % Averaged over number
                of gNBs
            Ave_All_delay_runs(run,:) = mean(
                gNBs_All_delay,1);
            clear gNBs_delay; clear L3_Switch{:}.dUEs;
                clear gNBs_All_delay;

        end % average runs
        %  Stats averaged over runs
        Data_BW_Delayd(Max_UE_ind,BWf_L3_L3_ind,
            BWf_L3_gNB_ind,4)   = mean(
            Dropped_UEs_Perc_runs);
        Data_BW_Delayd(Max_UE_ind,BWf_L3_L3_ind,
            BWf_L3_gNB_ind,5)   = mean(Ave_delay_runs);
        Data_BW_Delayd(Max_UE_ind,BWf_L3_L3_ind,
            BWf_L3_gNB_ind,6:8) = mean(Ave_All_delay_runs
            ,1);


        BWf_L3_L3_ind = BWf_L3_L3_ind+1;

    end; % BW_factorL3_L3

    BWf_L3_gNB_ind = BWf_L3_gNB_ind+1;
    % Save relevant data arrays to MAT files
    % Saving the first set
    %save(fullfile(dataDirectory, 'Data_BW_L3_gNBM.mat'),
        'Data_BW_L3_gNBM');
    %save(fullfile(dataDirectory, 'Data_BW_L3_L3M.mat'),
       'Data_BW_L3_L3M');
    % save(fullfile(dataDirectory, 'Data_BW_L3_L3M.mat'),
        'Data_BW_L3_gNB_slice');
    end % BW factorL3_gNB

    Max_UE_ind = Max_UE_ind + 1;
end % Max_UEs_cell

Max_UE_ind       = Max_UE_ind -1;
Max_L3_L3_ind    = BWf_L3_L3_ind - 1;
```

```
Max_L3_gNB_ind  = BWf_L3_gNB_ind - 1;
Title_txt       = 'DSL';
L3_L3_plot_ind  = 1; if L3_L3_plot_ind > Max_L3_L3_ind
   L3_L3_plot_ind = Max_L3_L3_ind; end;   % Can change
   this ind to have plots at diffrent L3_L3 factor
L3_gNB_plot_ind = 1; if L3_gNB_plot_ind > Max_L3_gNB_ind
    L3_gNB_plot_ind = Max_L3_gNB_ind; end;% Can change
   this ind to have plots at diffrent L3_gNB factor


%%  Display of location of gNBs, L3_Switches and users

 % Data_BW_Delay
 % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,1) =
    Max num of users
 % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,2) = BW
     Factor L3 - L3
 % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,3) = BW
     Factor L3 - gNB
 % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,4) =
    Dropped usrs
 % Data_BW_Delay(Max_UE_ind,L3_L3_ind, L3_gNB_ind,5) =
    total delay

%% UEs, L3s and gNB distribution plot
figure  % 1
for g = 1 : num_cells
  viscircles([gNB{g}.x gNB{g}.y],Cell_radius);
  if g == 1 hold on; end
  plot(gNB{g}.x,gNB{g}.y,'ko')
  for u = 1 : gNB{g}.UEs
      plot (gNB{g}.UE{u}.x,gNB{g}.UE{u}.y,'bx')
  end;
end

for i = 1 : (num_cells_x/2)*(num_cells_y/2)
  plot(L3_Switch{i}.x,L3_Switch{i}.y,'bx','MarkerSize',
     10, 'LineWidth',2)
  plot(L3_Switch{i}.x,L3_Switch{i}.y,'go','MarkerSize',
```

```
     10, 'LineWidth',2)
end

%% (gNB - L3 BW factor) vs (users without access &
   overall dealy) plots with varying max users per cell
   with fixed (L3 - L3 BW factor)

if BWf_L3_gNB_ind > 2
    figure  %2
    subplot(2,1,1)
    for p = 1 : Max_UE_ind
            plot(squeeze(Data_BW_Delayd(p,L3_L3_plot_ind
               ,:,3)),squeeze(Data_BW_Delayd(p,
               L3_L3_plot_ind,:,4)), ...
            'DisplayName',append('with max users/per cell
                = ',num2str(Data_BW_Delayd(p,
               L3_L3_plot_ind,1,1))))
        if p == 1 hold on; end;
     end;
    xlabel('\bf L3 - gNB fractional bandwidth based on
       max. number of users (%)')
    ylabel('\bf Users without access (%)')
    title(['\bf ',Title_txt,': User access analysis with
       no. of cells = ', num2str(num_cells), ' and (L3 -
       L3) BW factor = ',num2str(Data_BW_Delayd(1,
       L3_L3_plot_ind,1,2))])
    legend
    subplot(2,1,2)
    for p = 1 : Max_UE_ind
            plot(squeeze(Data_BW_Delayd(p,L3_L3_plot_ind
               ,:,3)),squeeze(Data_BW_Delayd(p,
               L3_L3_plot_ind,:,5))*1e3, ...
            'DisplayName',append('with max users/per cell
                = ',num2str(Data_BW_Delayd(p,
               L3_L3_plot_ind,1,1))))
        if p == 1 hold on; end;
    end;
    %axis([0.5 1 0 10])
    xlabel('\bf L3 - gNB fractional bandwidth based on
```

```
        max. number of users (%)')
    ylabel('\bf Ave. Network pkt Delay/(ms)')
    title(['\bf ',Title_txt,': Delay Analysis with no. of
        cells = ', num2str(num_cells), ' and (L3 - L3) BW
        factor = ',num2str(Data_BW_Delayd(1,
       L3_L3_plot_ind,1,2))])
    legend
end;

%% (L3 - L3 BW factor) vs (users without access & overall
    ) plots with varying max users per cell with fixed (
   gNB - L3 BW factor)
if BWf_L3_L3_ind > 2
    figure %3
    subplot(2,1,1)
    for p = 1 : Max_UE_ind
        plot(squeeze(Data_BW_Delayd(p,:,L3_gNB_plot_ind
           ,2)),squeeze(Data_BW_Delayd(p,:,
           L3_gNB_plot_ind,4)), ...
            'DisplayName',append('with max users/per cell
               = ',num2str(Data_BW_Delayd(p,1,
              L3_gNB_plot_ind,1))))
        if p == 1 hold on; end;
     end;
    xlabel('\bf L3 - L3 fractional bandwidth based on max
       . number of users')
    ylabel('\bf Users without access (%)')
    title(['\bf ',Title_txt,': User access analysis with
       no. of cells = ', num2str(num_cells), ' and (L3 -
       gNB) BW factor = ',num2str(Data_BW_Delayd(1,1,
       L3_gNB_plot_ind,3))])
    legend
    subplot(2,1,2)
    for p = 1 : Max_UE_ind
        plot(squeeze(Data_BW_Delayd(p,:,L3_gNB_plot_ind
           ,2)),squeeze(Data_BW_Delayd(p,:,
           L3_gNB_plot_ind,5))*1e3, ...
            'DisplayName',append('with max users/per cell
               = ',num2str(Data_BW_Delayd(p,1,
```

```
              L3_gNB_plot_ind ,1))))
         if p == 1 hold on; end;
      end;
     xlabel('\bf L3 - L3 fractional bandwidth based on max
        . number of users')
     ylabel('\bf Ave. Network pkt Delay/(ms)')
     title(['\bf ',Title_txt,': User access analysis with
        no. of cells = ', num2str(num_cells), ' and (L3 -
        gNB) BW factor = ',num2str(Data_BW_Delayd(1,1,
        L3_gNB_plot_ind,3))])
     legend
end;
display (Data_BW_Delayd(:,1,:,5))

%% (Max no of users) vs (users without access & overall
   delay) plots with varying gNB - L3 factor with fixed (
   L3 - L3 BW factor)
if BWf_L3_L3_ind > 2
     figure %4
     subplot(2,1,1)
     for p = 1 : Max_L3_gNB_ind
         plot(squeeze(Data_BW_Delayd(:,L3_L3_plot_ind,p,1)
            ),squeeze(Data_BW_Delayd(:,L3_L3_plot_ind,p,4)
            ), ...
              'DisplayName',append('with gNB - L3 factor =
                 ',num2str(Data_BW_Delayd(1,L3_L3_plot_ind,
                 p,3))))
         if p == 1 hold on; end;
      end;
     xlabel('\bf Max  no of users per cell')
     ylabel('\bf Users without access (%)')
     title(['\bf ',Title_txt,': User access analysis with
        no. of cells = ', num2str(num_cells), ' and (L3 -
        L3) BW factor = ',num2str(Data_BW_Delayd(1,
        L3_L3_plot_ind,1,2))])
     legend
     subplot(2,1,2)
     for p = 1 : Max_L3_gNB_ind
         plot(squeeze(Data_BW_Delayd(:,L3_L3_plot_ind,p,1)
```

```
        ),squeeze(Data_BW_Delayd(:,L3_L3_plot_ind,p,5)
        )*1e3, ...
         'DisplayName',append('with gNB - L3 factor =
            ',num2str(Data_BW_Delayd(1,L3_L3_plot_ind,
            p,3))))
      if p == 1 hold on; end;
   end;
   xlabel('\bf Max  no of users per cell')
   ylabel('\bf Delay/(ms)  ')
   title(['\bf ',Title_txt,': Delay analysis with no. of
       cells = ', num2str(num_cells), ' and (L3 - L3) BW
       factor = ',num2str(Data_BW_Delayd(1,
     L3_L3_plot_ind,1,2))])
   legend
end;

%% (gNB - L3 BW factor) vs (Propagation & Queuing Delay)
   plots with varying max users per cell with fixed (L3 -
    L3 BW factor)
if BWf_L3_gNB_ind > 2
   figure % 5
   subplot(2,1,1)
   for p = 1 : Max_UE_ind
       plot(squeeze(Data_BW_Delayd(p,L3_L3_plot_ind,:,3)
         ),squeeze(Data_BW_Delayd(p,L3_L3_plot_ind,:,6)
         )*1e3, ...
      'DisplayName',append('with max users/per cell = ',
        num2str(Data_BW_Delayd(p,L3_L3_plot_ind,1,1))))
      if p == 1 hold on; end;
   end;
   %axis([0.5 1 0 10])
   xlabel('\bf L3 - gNB fractional bandwidth based on
     max. number of users')
   ylabel('\bf Ave. propagation Delay/(ms)')
   title(['\bf ',Title_txt,': Delay Analysis with no. of
       cells = ', num2str(num_cells), ' and (L3 - L3) BW
       factor = ',num2str(Data_BW_Delayd(1,1,
     L3_gNB_plot_ind,2))])
   legend
```

```
    subplot(2,1,2)
     for p = 1 : Max_UE_ind
        plot(squeeze(Data_BW_Delayd(p,L3_L3_plot_ind,:,3)
           ),squeeze(Data_BW_Delayd(p,L3_L3_plot_ind,:,8)
           )*1e3, ...
       'DisplayName',append('with max users/per cell = ',
          num2str(Data_BW_Delayd(p,L3_L3_plot_ind,1,1))))
        if p == 1 hold on; end;
     end;
    %axis([0.5 1 0 10])
    xlabel('\bf L3 - gNB fractional bandwidth based on
       max. number of users (%)')
    ylabel('\bf Ave. Queuing Delay/(ms)')
    title(['\bf ',Title_txt,': Delay Analysis with no. of
        cells = ', num2str(num_cells), ' and (L3 - L3) BW
        factor = ',num2str(Data_BW_Delayd(1,1,
       L3_gNB_plot_ind,2))])

    legend
end;
```