Tampere University

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GENERAL OVERVIEW OF 4G AND 5G WITH FIELD MEASUREMENTS AND PERFORMANCE COMPARISON

Master’s Thesis
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ABSTRACT

Omar Dawood Al-Gburi: General Overview of 4G and 5G with field measurements and performance comparison.
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This Master of Science thesis aims to review and compare 4G Long-Term Evolution (4G) of wireless cellular technology versus Fifth Generation (5G) of wireless cellular technology from different points of view. The main perspectives of comparison are the overall architecture, used frequency bands, frame structures, and frame configurations, the network capabilities of maximum data throughput, and latency theoretically. On the other hand, comparing the field measurements of data throughput and latency, then concluding and originating the reasons behind the mismatching between the theoretical expectations and the obtained values of measurements. The compared cellular network technologies in the theoretical part are 4G, 5G NSA, and 5G SA. In contrast, in the actual measurements, the operated cellular networks are only 4G and 5G NSA.

The conducted measurements in this thesis were performed in two environments, Urban and Suburban areas. The propagation environments were indoor, outdoor Non-Line of Sight, and outdoor. The measurements were performed in Tampere, Finland. Because of the continuous deployment of 5G networks and upgrade of 4G networks (because of 5G), three rounds of measurements have been performed.

The first round of measurements took sixteen days. The measurements were discarded after checking them because of the upgrading and deployment of networks. The second round of measurements took five days. This round was discarded for the same reasons as before. The third round of measurements took eight days. This round of measurements was successful; therefore, it was considered and progressed.

The utilized cellular network in measurement progress was “Elisa”. The 5G phase during the time of measurements was still being deployed, and thus 5G coverage was not available in some locations or times during the measurements. Therefore, more capacity, coverage, and better performance are still expected in the future (5G is not ready yet for typical coverage and expected capacity).

OnePlus 8 5G was used as User Equipment (UE) to perform both 4G and 5G measurements. The UE has been forced to operate on 4G mode during the measurements of 4G and on 5G mode during the 5G measurements. Static locations have been chosen to perform the measurements of each of 4G and 5G.

The results and their analysis are giving an idea about 4G and 5G cellular networks performance in Urban and Suburban areas with indoor, Non-Line of Sight, and Line of Sight outdoor propagation environments. That idea can be beneficial for understanding the 4G and 5G cellular networks performance and in 4G and 5G performance-enhancing in specific areas or spots, networks planning and deploying of 4G and 5G. The measurements and the scenarios of conducting them can form a foundation for more expanded and complicated scenarios and more intense measurements. The overall results have shown that 5G offers 11 % less latency, 18 % higher upload throughput, and 30 % higher download throughput, than 4G. The overall results have shown that 5G offered an overall 16 % less latency, 22 % higher upload throughput, and 37 % higher download throughput than 4G in the Urban area. The overall results have shown that 5G offered an overall 8 % less latency, 13 % higher upload throughput, and 24 % higher download throughput than 4G in the Suburban area. Overall, the 5G service in outdoor propagation environments was much better than 4G. In comparison, the case is opposite in indoor propagation environments unless the 5G received signal level is high enough to guarantee good 5G service quality and performance at UE (location 11).

Keywords: NSA, 5G, 4G, SA, 5G NR, LTE, 4G vs. 5G, Wireless Cellular Network, Measurements, Latency, Upload, Download, Throughput, Urban, Suburban, Indoor, Outdoor, Master of Science.

PREFACE

This Master of Science Thesis has been written to fulfill the Master of Science Degree in Electrical Engineering graduation requirements at Tampere University.

First, I would like to express my acknowledgments to my supervisors and examiners, Dr. Joonas Säe and Prof. Mikko Valkama, for providing me with this topic for my master thesis. The thesis topic was in response to my request to meet my desire and aspiration. I want to express my deep respect and appreciation for Dr. Joonas Säe, which this thesis would not have been achieved without his continuous guidance and supervision.

Second, I would like to thank everyone who stood beside me and supported me during my study and thesis work.

Finally, I dedicate this success with endless gratitude to the most precious people in my life, my father, my mother, and my brother. My father is the best role model ever in my life who was and still keeps me motivated to turn my dreams into a reality. My mother, source of serenity and peace in my life, this success is to keep the smile on her face. My brother who has supported me continuously.

In Tampere, Finland, on 1st March 2021

Omar Dawood Al-Gburi

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LIST OF ABBREVIATIONS

1G	First Generation of wireless cellular technology
2G	Second Generation of wireless cellular technology
3D	Three Dimension
3D-MIMO	Three Dimension Multi-Input Multi-Output
3G	Third Generation of wireless cellular technology
3GPP	3rd Generation Partnership Project
4G	Fourth Generation of wireless cellular technology
5G	Fifth Generation of wireless cellular technology
5G NR	Fifth Generation New Radio
5GC	Fifth Generation Core network
6G	Sixth Generation of wireless cellular technology
ACK	Acknowledged
AF	Application Function
AI	Artificial Intelligence
AM	Acknowledged Mode
AMF	Access and Mobility management Function
AMPS	Advanced Mobile Phone System
AR/VR	Amended Reality and Virtual Reality
ARQ	Automatic repeat ReQuest
AuC	Authentication Center
AUSF	AUthentications Server Function
BLER	Block Error Rate
BLRR	Block Retransmission Rate (measurements notation)
BPSK	Binary Phase Shift Key
BS	Base Station
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver
CA	Carrier Aggregation
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CDN	Content Delivery Network
CH	Channel
CN	Core Network
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CSI	Channel State Information
D	Downlink (in frame configuring notation)
D2D	Device-to-Device communications
DAPS	Dual Active Protocol Stack
DC	Dual Connectivity
DCI	Downlink Control Information

DL	Downlink
DL-SCH	Downlink Synchronization Channel
DM-RS	Demodulation Reference Signal
DRX	Discontinuous reception
DSS	Dynamic Spectrum Sharing
DwPTS	Downlink Pilot Time
eCP	extended Cyclic Prefix
EDGE	Enhanced Data rates in GSM Environment
EHC	Ethernet Header Compression protocol
EIR	Equipment Identity Register
eMBB	enhanced Mobile BroadBand
eNB	E-UTRAN Node B
EN-DC	E-UTRA-NR Dual Connectivity
en-gNB	EN-DC gNB
EPC	Enhanced Packet Core
EPDCCH	Enhanced Physical Downlink Control Channel
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FD-MIMO	Full Dimensional-Multi-Input Multi-Output
FEC	Forward Error Correction
FM	Frequency Modulation
FOFDMA	Fired Orthogonal Frequency Division Multiple Access
FR1	Frequency Range 1
FR2	Frequency Range 2
FR3	Frequency Range 3
Gbps	Giga bits per second
GERAN	GSM EDGE Radio Access Network
GFDMA	Generalized Frequency Division Multiple Access
GGSN	Gateway GPRS Support Node
GHz	Gigahertz
GMSc	Gateway MSc
gNB	next generation Node B
GP	Guard Period
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GSMA	GSMA Association
HARQ	Hybrid Automatic repeat ReQuest
HLR	Home Allocation Register
HSS	Home Subscriber Server
IAB	Integrated Access Backhaul
IIoT	Industrial Internet of Things
IMS	IP Media Subsystem
IMT	International Mobile Telecommunications
IMT-Advanced	International Mobile Telecommunications Advanced

IoT	Internet of Things
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISI	Inter-symbol Interference
IT IS	Intelligent Transport Systems
ITU-R	International Telecommunications Union-Radiocommunications Sector
ITU-T	ITU Telecommunication Standardization Sector
kbps	kilo bit per second
kHz	kilohertz
KPIs	Key Performance Indicators
LAA	License Assisted Access
LAS-CDMA	Large Area Synchronized Code Division Multiple Access
LMDS	Local Multipoint Distribution Service
LoS	Line of Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LTE-A Pro	Long Term Evolution Advanced Pro
LWA	LTA-WLAN Aggregation
M2M	Machine to Machine communications
MAC	Medium Access Control protocol layer
MBMS	Multimedia Broadcast and Multicast Services
Mbps	Mega bits per second
MC-CDMA	Multi-carrier Code Division Multiple Access
MCH	Multicast Channel
MEC	Multiple access Edge Computing
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
mMIMO	massive Multi-Input Multi-Output
MMS	Multimedia Message Service
mMTC	massive Machine Type Communications
mmWaves	millimeter Waves
MN	Master Node
MPDCCH	MTC Physical Downlink Control Channel
MS	Mobile Station
MSC	Mobile Switching Center
MSG	Master Cell Group
MTC	Machine Type Communications
MTSO	Mobile Telephone Switching Office
MU	Mobile User
NAK	Not Acknowledged
NB	Narrowband
NEF	Network Exposure Function
NFC	Near Field Communications
NFV	Network Function Virtualization
NG	New Generation

NGRAN	New Generation Radio Access Network
NLoS	Non-Line of Sight
NOMA	Non-Orthogonal Multiple Access
NPBCH	Narrow Physical Broadcast Channel
NPDCCH	Narrowband Physical Downlink Control Channel
NPDSCH	Narrowband Physical Downlink Shared Channel
NPRACH	Narrowband Physical Random-Access Channel
NPUSCH	Narrowband Physical Uplink Shared Channel
NR	New Radio
NSA	Non-Standalone
NSS	Network Switching Subsystem
NSSF	Network Slice Selection Function
NTT	Nippon Telegraph
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Orthogonal Multiple Access
OMC	Operation and Maintenance Center
OSI	Open System Interconnection model
P	PING (measurements notation)
PA	Power Amplifier
PBCH	Physical Broadcast Channel
PCF	Policy Control Function
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PCRF	Policy and Charging Resource Function
PD	Ping on Downlink (measurements notation)
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol layer
PDF	Probability Density Function
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
P-GW	Packet data network Gateway
PHICH	Physical Hybrid ARQ Indicator Channel
PHY	Physical
PING	Latency measurement (measurements notation)
PMCH	Physical Multicast Channel
PMI	Precoding Matrix Indicator
PRACH	Physical Random-Access Channel
PRB	Physical Resource Block
PSBCH	Physical Sidelink Broadcast Channel
PSCCH	Physical Sidelink Control Channel
PSDCH	Physical Sidelink Discovery Channel
PSFCH	Physical Sidelink Feedback Channel
PSLCH	Physical Sidelink Channel
PSSCH	Physical Sidelink Shared Channel
PSTN	Public Switching Telephone Network

PU	Ping on Uplink (measurements notation)
PUCCH	Physical Uplink Control Channel
PUCH	Physical Uplink Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Key
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
RI	Rank Indicator
RLC	Radio Link Control layer
RN	Relay Node
RN	Radio Network
RNC	Radio Network Control
RNS	Radio Network Subsystem
ROHC	Robust Header Compression
R-PDCCH	Relay Physical Downlink Control Channel
RRC	Radio Resource Control
RRE	Radio Resources Entity
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RTT	Round Trip Time
RX	Receive
S	Special (in frame configuring notation)
SA	Standalone
SAP	Service Access Point
SC	Subcarrier
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCG	Secondary Cell Group
SCH	Synchronization Channel
SCMA	Sparse Code Multiple Access
SCs	Subcarriers
SDN	Software-Defined Network
SDU	Service Data Unit
SFN	System Frame Number
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway
SINR	Signal to Interference and Noise Ratio
SL	Sidelink
SMF	Session Management Function
SMS	Short Message Service
SN	Sequence Number

SN	Secondary Node
SNR	Signal to Noise Ratio
SON	Self-Organized Network
SPDCCH	Short Physical Downlink Control Channel
SPUCCH	Short Physical Uplink Channel
SR	Scheduling Request
SSB	Synchronization Signal Block
SSMA	Spread Spectrum Multiple Access
S-SSB	Sidelink - Synchronization Signal Block
STDV	Standard Deviation
SUCES	Successfulness
TB	Transport Block
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
TMS	Traffic Management Solution
TTI	Transmission Time Interval
TX	Transmit
U	Upload (in frame configuring notation)
UAV	Unnamed Arial Vehicles
UCI	Uplink Control Information
UDM	Unified Data Management
UE	User Equipment
UHD	Ultra-High Definition
UL	Uplink
UL-SCH	Downlink Synchronization Channel
UM	Unacknowledged Mode
UMTS	Universal Mobile Telecommunications Service
UPF	User Plane Function
UpPTS	Uplink Pilot Time Slot
URLLC	Ultra-Reliable Low Latency Communications
UTRAN	UMTS Terrestrial Radio Access Network
V2X	Vehicle to everything
VLR	Visitor Location Registry
VOIP	Voice Over Internet Protocol
VOLTE	Voice Over Long-Term Evolution
VR	Virtual Reality
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

LIST OF SYMBOLS AND VARIABLES

#	Number of
%	Percentage (measurements notation)
5G_4G	Measurement parameter of eNB on 4G side during 5G measurement (measurements notation)
CAR	number of utilized Carriers (measurements notation)
L_(nth)G_RF_%	Locational Radio Frequency Bands Utilization Percentage of nth (measurements notation)
L_AVG	Locational Average measurement (measurements notation)
M	(M) is for modulation order (measurements notation)
p	antenna port

Δf	Subcarrier Spacing
$N_{\mathrm{symb}}^{\mathrm{retune}}$	Number of symbols in a guard period for narrowband or wideband retuning
T	Time
T_{f}	Time duration of one radio frame
T_{slot}	Time duration of one slot
T_{subframe}	Time duration of one subframe

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1. INTRODUCTION

Communication is an essential need in our daily lives. It is the key to understand and exchange information among people. Since the ancient ages, people have developed very primitive and basic methods of communication and exchange information. In the past, communication tools were limited, where people used smoke signals and hand signs to communicate. After that, spoken language was used, making it more comfortable and informative to communicate than smoke signals or hand signs. After that, characters had been drawn to represent the language in stones, wood, and some other substances, so that other people could get information indirectly. Since then, people went a long way in this evolution. Now the communication process is almost instantaneous with incomparable information amount exchange per time unite. Today people would not have to wait years, months, or even minutes to receive information or a message. Emails and messages can reach the recipient in just a matter of seconds or even less.

Mobile telecommunication in the recent past (last few decades) has experienced a tremendous evolution. The mobile telecommunication evolution includes data rate, latency, network size, and technology supporting and maintaining it. This evolution has enabled the use of wireless communications for other purposes than voice calls. It became possible to transfer enormous data through cellular networks, starting with pictures, videos, video calls, and data files and remotely controlling machines by humans. Moreover, new communications types were innovated, like Machine to Machine communications (M2M), with low latency and high communications reliability. On the other hand, wireless network complexity has increased as the singed functionalities are becoming more complex. In the coming chapters, there is a detailed historical and technical overview of cellular networks' evolution, mostly focused on 4G and 5G, in addition to more related discussions.

This thesis aims to review and compare 4G Long-Term Evolution (4G) cellular networks versus Fifth Generation New Radio (5G NR) cellular networks from different perspectives. In short, those perspectives are the overall architecture, the used frequency bands, the structures and configurations of the frame, the network capabilities of maximum data throughput, and the latency. On the other hand, comparing the actual field measurements of data throughput and latency then conclude and originate the reasons behind the mismatching between the theoretical expectations and the obtained values of measurements. The compared cellular network technologies in the theoretical part are 4G, 5G NSA, and 5G SA. In contrast, in the actual measurements, the operated cellular networks are only 4G and 5G NSA.

The risen problems and challenges in 5G wireless cellular networks of using higher frequencies and maintaining tremendous amounts of data exchange, reliability, and keeping mobility of the wide diversity of terminals require new approaches, techniques, and designs. Overviewing the newly involved and used technologies and innovations in 5G NR will produce clear concepts of overcoming the risen challenges of the New Generation Radio Access Network (NGRAN) level.

The accompanying challenges of NGRAN can be represented by:

- The dynamic frame structure reformation.
- The different frame configurations management.
- The managing of interference whether it occurs in the same cell or among neighbor cells.
- The management of signal fades.

Compared with 4G, the case is different in the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). By moving to the Core Network (CN) of both 5G NR and 4G, there are different kinds and sets of challenges. In Fifth Generation Core network (5GC) architecture, new virtual entities and software-based functions are added. In comparison, there were no similar entities and related software or challenges to be handled in Enhanced Packet Core (EPC) of 4G. As a result, the expected performance differences and network capabilities of 4G and 5G will be reviewed in detail, in addition to the transition and deployment scenarios of 5G and the accompanying advantages and disadvantages of each scenario. Eventually, in this thesis, a review and comparison between real performed measurements in 4G and 5G wireless cellular networks will take place. Additionally, the theoretical expectation of the performance of both 4G and 5G cellular networks can be compared with the real measurements. Despite 5G wireless cellular networks deployment is ongoing, the comparison between the theoretical expectations of performance and the actual measurements can scratch the surface and give sight or an idea about the real physical limits and capabilities of 5G. At the same time, that comparison can show the accompanying challenges that must be handled and what should be done further to raise those limits and boost the network performance.

2. EVOLUTION TIMELINE OF CELLULAR NETWORK TECHNOLOGIES

To dive deeply into the different aspects of the various cellular network technologies and discuss their various challenges and solutions, some briefed background about cellular communications evolution must be reviewed. The following sections brief a historical perspective of a cellular communications technology evolution.

Before starting to review the evolution of cellular communication network technologies, some general concepts should be overviewed from different perspectives:

- The technologies utilized in a specific generation of wireless cellular communications. Generally, hardware technologies from the network parts and User Equipment (UE) points of view.
- The frequencies and frequency bands, the frame structure, and the frame configurations utilized in a specific generation of wireless cellular communications.
- The protocols utilized in communications and data conveyance management in the wireless part, inside the different parts, levels, network interfaces, et cetera in a specific generation of wireless cellular communications.

2.1 First Generation (1G) Technology

Motorola produced the first handheld mobile cell phone on April 3rd, 1973, in New York [1]. This phone was made by Motorola engineer Martin Cooper [1]. The first launch of a commercial automated wireless mobile phone communications system in the world was 1G, by Nippon Telegraph and Telephone (NTT) in Tokyo, Japan in 1979, where the 1G wireless mobile communications system is an analog technology which was developed in 1980. The channel capacity was 30 kbps, frequency band 824-894 MHz, and data rate up to 2.4 kbps. The First Generation mobile networks were built to provide essential voice services to customers. The 1G was based on a technology called Advanced Mobile Phone System (AMPS) with Frequency Division Multiple Access (FDMA) modulation. [2]

Generally, in 1G, analog technology was used with no data capabilities. Digital signaling had been used in the processing stages of data to connect the radio towers to the rest of the telephone system [5]. On the other hand, analog signaling was used in modulating voice calls to a higher frequency 150 MHz (Frequency Modulation, FM), transmitting and receiving stages [5]. The standard cell size in 1G is 2-20 km [5]. Figure 1 below shows the architecture of a standard 1G wireless network.

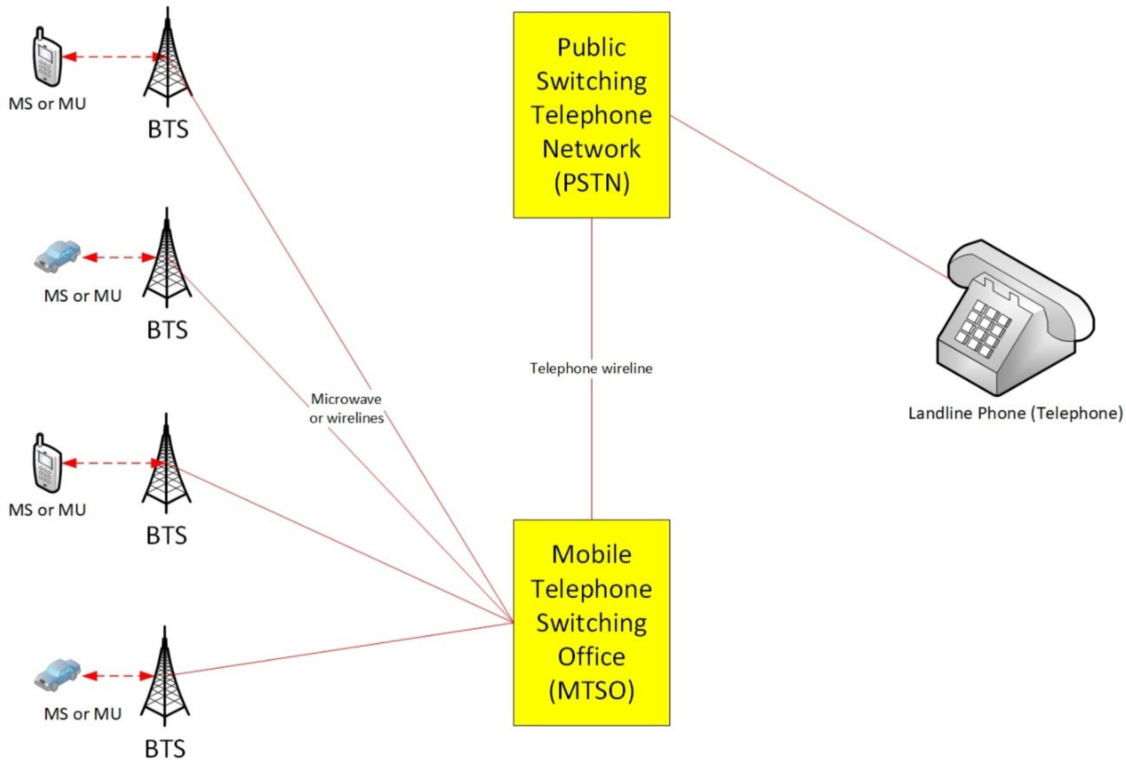

Figure 1. *The architecture of AMPS. It was redrawn based on [5].*

2.2 Second Generation (2G) Technology

The Second Generation was introduced in the late 1980s; after eleven years, the first launch of the Global System for Mobile network GSM was launched by Radiolinja in Finland [6]. The voice call quality of 2G was improved significantly compared to the voice quality of 1G [2]. The Second Generation of wireless cellular technology had relied on digital technology to progress the data, which enabled new and more efficient services. An example of the more efficient services is the voice call quality to compare 1G technology and 2G technology. In 1G, there was no possibility of error correction of the received signals.

In comparison, the used digital technology in 2G enabled the conversion of the analog wave of sound to digital data with a transmission rate of 64 kbps by the mobile station itself. The operation of encoding the speech signal was done through a digital algorithm called a “codec”. The codec functionality is to encode and decode according to several encoding and decoding standards. In short, the encoding and decoding techniques are operating with an error correction level which enabled fixing the occurred errors in the received signals at the mobile station partially or fully [7].

The bandwidth (BW) of 2G is 30 kHz – 200 kHz. New techniques were used to improve the BW and spectral efficiency by multiple access schemes allocation like Frequency Division Multiple Access (FDMA), TDMA, and Code Division Multiple Access (CDMA). Short Message Service SMS and Multimedia Messaging Service (MMS) became secured by encrypting them; also, the global roaming system was enabled in 2G. Mobile subscribers had become able to use their mobile phones abroad in different countries with more quality and bigger capacity [2]. Global System for Mobile Communication (GSM) was the most widely utilized. The Second Generation of wireless cellular technology was commercially launched on GSM standard in Finland in 1991. More advantages were obtained from 2G in comparison with 1G. For example, the cell size of GSM became up to 35 km [3,5], while it was 2 km – 20 km in 1G [5]. Figure 2 below shows the architecture of 2G GSM.

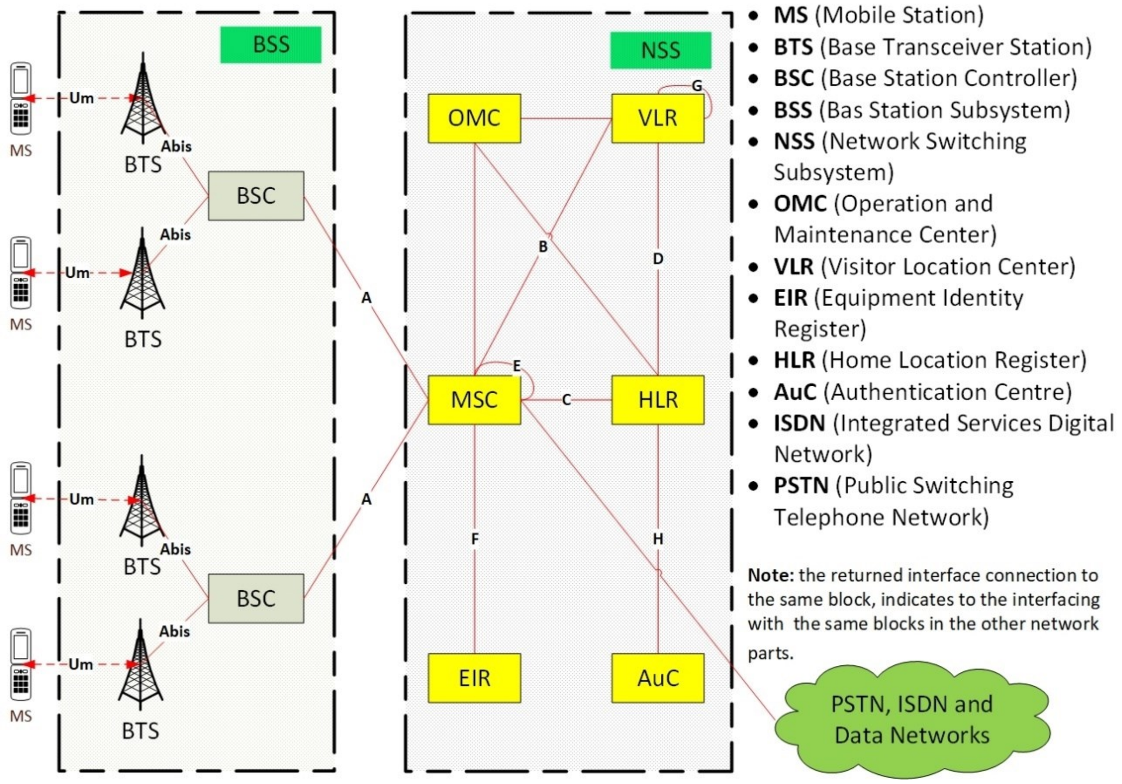

Figure 2. *The architecture of the 2G GSM network. It was redrawn based on [5,8,10].*

As the improvement progress was still ongoing, more upgrades and features were added to the 2G networks. New technologies were used in 2G, like General Packet Radio Service (GPRS) and Enhanced Data rates in GSM Environment (EDGE). General Packet Radio Service provides packet-switching protocols, short setup time for Internet Service Provider (ISP) connections, and the possibility of charging the subscriber according to the amount of data sent rather than connection time.

The General Packet Radio Service allows variable data transmission rates and supports a continuous link with the network. General Packet Radio Service was a significant step towards the Third Generation (3G) of wireless cellular Technology [2].

2.3 Third Generation (3G) Technology

In 2000, the 3G wireless mobile communication system was introduced. The first test Release of Wideband Code Division Multiple Access (WCDMA) technology was in May 2001 [9]. The first commercial Release for 3G mobile technology was on October 1st, 2001; Japan both was released by NTT DoCoMo [9]. The Third Generation of wireless cellular technology offers advanced services to the users compared with 1G and 2G. In addition to voice communication, there were data services, access to television videos, web browsing, email, video conferencing, paging, fax, and maps. [2]

From channel BW's perspective, 5 MHz was standardized, which offered a high-speed internet, video chatting, et cetera. The structural details of the 5 MHz BW are 0.58 MHz as guard band included in both sides of the channel BW therefore, 1.16 MHz for the guard band in total, which leaves 3.84 MHz utilized channel BW for data. An organization called 3rd Generation Partnership Project (3GPP) had defined the 3G, in which it fulfills the International Mobile Telecommunications (IMT-2000) standards [2].

In Europe, the 3G was called as Universal Mobile Telecommunication System (UMTS). International Mobile Telecommunications is the ITU Telecommunication Standardization Sector (ITU-T) name for the 3G system, while the name of the American 3G variant is Code Division Multiple Access 2000 (CDMA2000). A new 3G standard from China was also accepted by IMT2000, for instance, Time Division – Synchronous Division Multiple Access (TD-SCDMA). Regarding the air-interface technology for UMTS, Wide Code Division Multiple Access had been utilized. [2]

The 3G provided dedicated digital networks to deliver broadband and multimedia services. Data rate and Quality of Service (QoS) have noticeably improved; the credit goes to internet and Internet Protocol (IP) network technology. Some disadvantages were raised like, 3G UEs consume more power than most of 2G UE models, and 3G wireless cellular networks were less economical to be set-up, operated, and maintained. On the other hand, 3G systems were to offer increased data rates from 144 kbps to 384 kbps for broad coverage areas and 2 Mbps for local coverage areas, the areas that are close to the base station antenna. [2,5]

Figure 3 below shows the architecture of the 3G UMTS network.

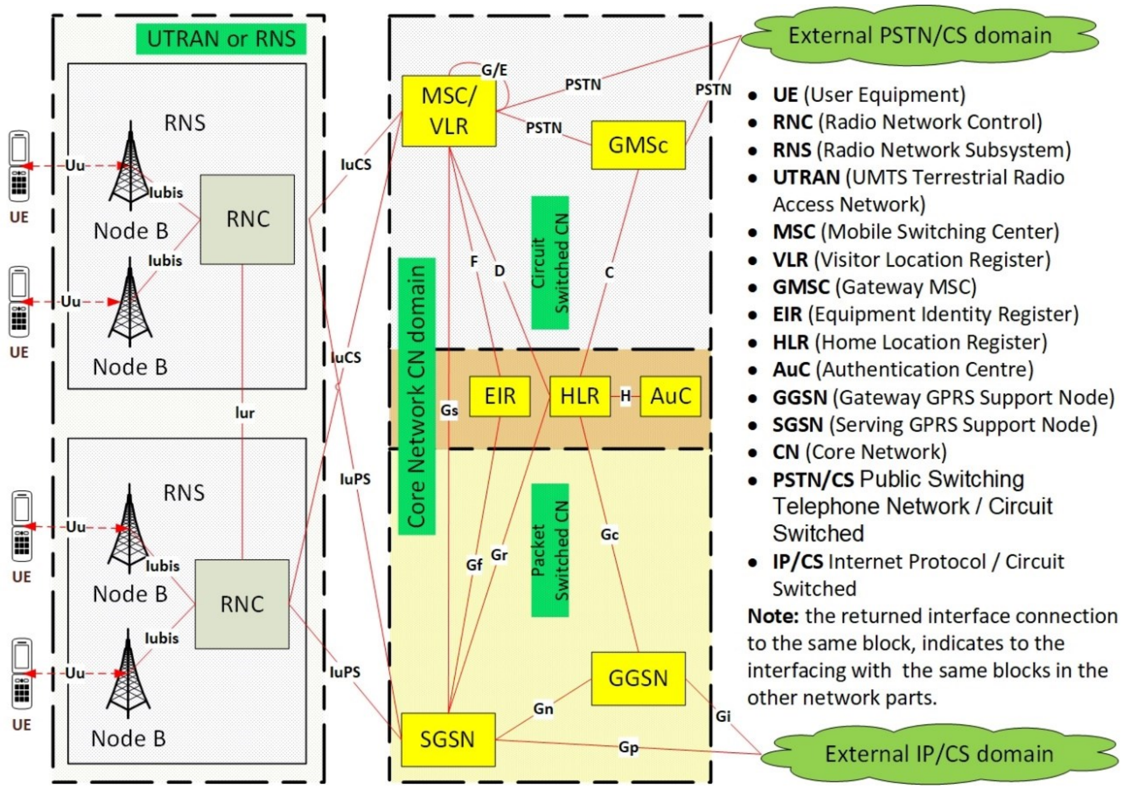

Figure 3. *The architecture of the 3G UMTS mobile network. It was redrawn based on [10].*

2.4 Fourth Generation (4G) Technology

After producing the historical overview of the 4G cellular network, the term 4G will be used to refer to Long Term Evolution (LTE) for simplicity.

In the late 2000s, 4G was launched commercially by TeliaSonera telecom operator for the first time globally on December 14th, 2009, in Stockholm and Oslo [11]. The aim was to provide and support packet-switched traffic with seamless mobility, QoS and minimize latency [12]. This approach enables multiservice support (voice, data, and multimedia) through packet connection [12]. Multiservice is mainly leaned on IP-based network systems. As known, increasing the data rate is one of these evolution targets. Moreover, higher capacity, more security features (higher security), lower the cost of services for voice and data services, multimedia, and the internet.

The advantage of using IP is to have a common platform for all the technologies developed until the 4G network launch. As there were different mobile network technologies simultaneously, the UE must roam automatically among the various network technologies. As a result, UE of 4G has the freedom of mobility and the ability to stay connected even in areas where no 4G coverage is found, where the UE switches to roam other wireless cellular technologies 3G or 2G. The 4G technology has integrated with different wireless networks of Orthogonal Frequency Division Multiplexing (OFDM), Multicarrier Code Division Multiple Access (MC-CDMA), Large Area Synchronized Code Division Multiple Access (LAS-CDMA), and Network-Local Multipoint Distribution Service (Network-LMDS). That integration had led to enable the roaming capability in UE of 4G. The intersystem handover among different wireless technologies must be smooth, not to be any interruption. [2,5]

The LTE and Wireless Interoperability for Microwave Access (WiMAX) were considered as 4G technologies. The Fourth Generation of wireless cellular technologies was designed to offer a peak data rate of approximately 100 Mbps [2]. More details in chapter 3. Figure 4 below shows the architecture of the 4G wireless cellular network.

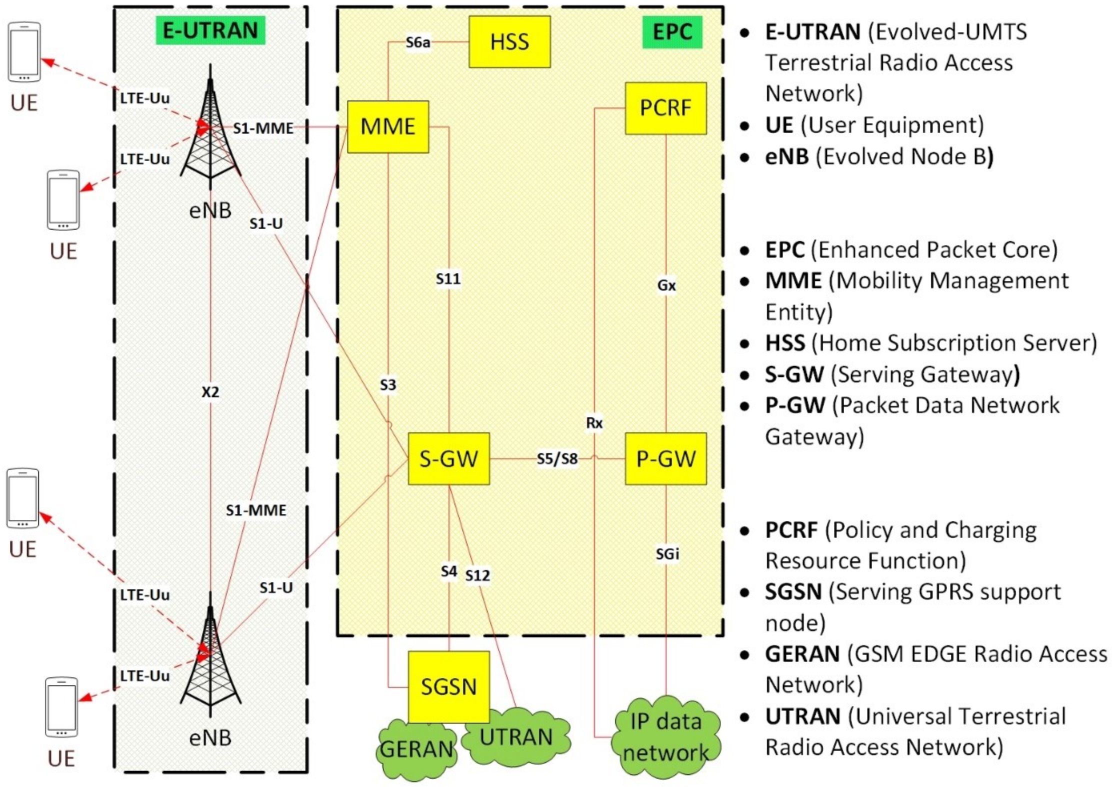

Figure 4. *The architecture of the 4G wireless cellular network. It was redrawn based on [13].*

According to [3GPP] eNB architecture, the evolution of the Control Plane / User plane splitting process had been prioritized on December 2019 TSG meetings to be included in Release 17.

2.5 Fifth Generation New Radio (5G NR) Technology

Despite 4G networks have provided advanced services and increased the data rate (explained briefly in the previous subchapter), there was still a need to have higher performance and capacity. The continuous growth in demands for better mobile broadband experiences is why the industries are inspired to step forward on the 5G road towards continuing the evolution of cellular communications. The first commercial launch of 5G services on smartphones in the world was in South Korea by operators (SK Telecom, Korea Telecom, and LG U+) in April 2019 [14]. Fifth Generation New Radio is prepared for the cellular technology that will handle those requirements. The 5G NR emphasizes the development of existing techniques to improve capacity.

It is expected that the 5G NR technology will extend wireless access widely beyond the human to human communications. It will provide and support higher connectivity so that automated machines and remotely controlled robots will be connected, which will open the door to obtain more benefits. Meeting futuristic societal and industrial needs is one motivator for 5G NR technology by providing high-speed and high-quality wireless broadband. To be able to fulfill this kind of conception, several challenges must be taken into assumption. One crucial challenge is hosting different platforms to work together and interact smoothly as homogenous components to support any pattern usage.

The next step is to integrate those different and separated entities and enable them to be connected. This kind of upgrade needs standardization which will allow building much bigger integrated entities with more functionalities. Upgrading the current wireless communication systems is not enough to handle this kind of high-performance requirements and advanced usage patterns. Instead, new access technologies and protocols are required. The promised high performance, high data rate, low latency, and massive connectivity of 5G NR networks are laid on the benefit of using higher frequencies where a higher spectrum is available.

The operation radio spectrum is wide, starting from 410 MHz to 116 GHz [15,16]. Temporarily, there are two frequency ranges according to [3GPP] in the definition of specifications, where New Radio NR can operate. The first frequency range (FR1) is 410 MHz – 7 125 MHz, the second frequency range (FR2) is 24.25 GHz – 52.6 GHz [15], and the third frequency range 52.6 GHz – 116 GHz is added recently and needs to be further studied [16]. There are two operation modes of 5G NR networks that have been introduced by the 3rd Generation Partnership Project [3GPP]. The first operation mode is Non-Standalone (NSA), and the second operation mode is Standalone (SA).

2.5.1 5G NR Non-Standalone (NSA) operation mode

5G NSA specifications were introduced by [3GPP Release 15 in late 2017] [17]. The 5G NSA utilizes 4G Core Network (CN) and base station eNBs to deploy 5G NR networks. According to [3GPP] [17], next-generation – Node B (gNB) or E-UTRAN New Radio Dual Connectivity – gNB (en-gNB) were added (en-gNB when it is connected to 4G core network, and gNB when It is connected to 5G NR core network). E-UTRAN New Radio Dual Connectivity – next-generation Node B (en-gNB) is a node providing the protocol terminations of NR user plane and control plane towards UE and acting as Secondary Node (SN) in E-UTRAN [63].

The other node is next-generation Node B (gNB). It provides NR user plane and control plane protocol terminations towards UE, gNB is connected via the New Generation (NG) interface to the 5GC [64]). The E-UTRAN New Radio Dual Connectivity – next-generation Node B (en-gNB) operates along with eNB to provide the so-called E-UTRA-NR Dual Connectivity (EN-DC) or "Architecture Option 3", where UE is connected to CN by en-gNB and eNB simultaneously [20]. More details in chapter 4.

Based on the reality that a higher radio spectrum is utilized, the 5G NSA operation mode aims to boost the capacity, increase the delivery efficiency, and enhance the data throughput. Therefore, 5G NSA will open the opportunities to enable video streaming, Augmented Reality and Virtual Reality (AR/VR), and new cases of use, for example, the Internet of Things (IoT) [18].

It is important to know that upgrading eNB and Evolved Packet Core (EPC) is required to insert and operate en-gNB [19]. Figure 5 below shows the architecture of 5G NSA.

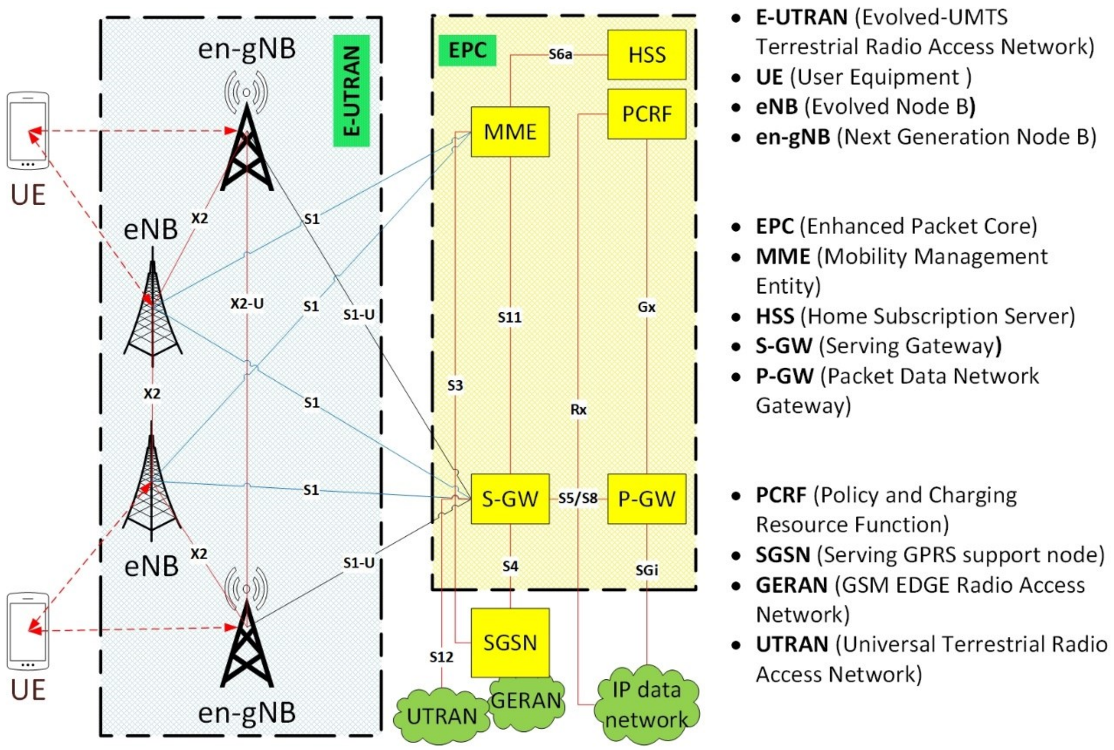

Figure 5. *The architecture of the 5G NSA wireless cellular network. It was redrawn based on [13,20].*

2.5.2 5G NR Standalone (SA) operation mode

Standalone (SA) mode of 5G NR is the deployment of 5GC and gNB, instead of lying on CN as in 5G NSA operation mode. This operation mode is simplified New Generation Radio Access Network (NGRAN) architecture. The NGRAN will bring lower latency because of the more simplified access progress and management (in NSA, en-gNB, and eNB, two nodes must handle the access, connection establishment, maintenance, and management. While in SA, gNB handles all the previous functionalities).

Since the 5G SA mode operates on 5GC, a more comprehensive range of new functionalities and features will be supported [18]. Figure 6 below shows the architecture of the 5G SA network.

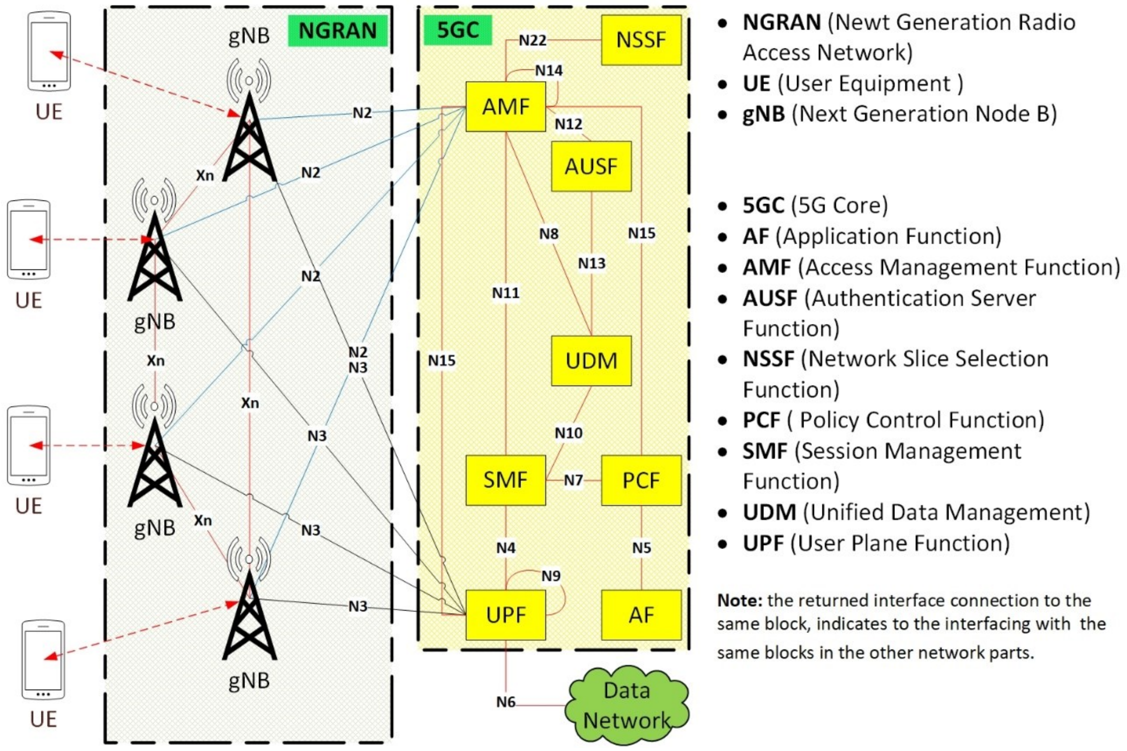

***Figure* 6.** *The architecture of the 5G SA network. It was redrawn based on [20, 21].*

As a brief view of this chapter (Evolution Timeline of Mobile Networks Technologies), the consecutive generations of mobile communications technologies differ from each other in several aspects where utilized technology developments are occurring. These differences can be categorized according to the used technology details in a specific cellular communications generation (hardware technologies generally from the network parts and UE point of view). The categories are the used or utilized frequencies and frequency bands, the frame structure, the frame configuration, the used protocols in communications, and data conveyance management in the wireless communications part, in the different parts, layers, and network interfaces.

As a result, those developments are leading to enhance the performance and enable new services. The service enhancement can be seen through reviewing the 1G, where it was just about performing voice call service, all the way to 5G NR, where the supported services have been taken into an advanced concept and level. In 5G NR, even the machines started communicating M2M and humans to machines communications in addition to the new potential use cases of 5G NR, which were not imaginable or at least to be a reality at the time of 1G.

2.6 Terminology

In the rest of the thesis, the term Fourth Generation and abbreviation (4G) will refer to the Long Term Evolution version of 4G according to [3GPP] definitions of LTE-A. The term Fifth Generation and abbreviation (5G) will be used to refer to Fifth Generation New Radio (5G NR) according to [3GPP] definitions 5G NR versions (regardless of whether it is Non-Standalone or Standalone operation mode of 5G NR). In some parts and paragraphs, 4G refers clearly to the Fourth Generation of wireless cellular technology, where the context indicated that. For instance, chapter 2 introduces the 4G networks history.

2.7 Chapter summary

Several general outlines can be extracted from this chapter:

- The consecutive generations of mobile communications technologies differ from each other in several aspects where the developments are occurring.
- The used technology in a specific generation of cellular communications (hardware technologies generally from the network parts and UE points of view).
- The used or utilized frequencies and frequency bands.
- The frame structure and the frame configuration.
- The protocols used in wireless communications and data conveyance management in the wireless part inside the network and between the network interfaces.

The sorted points up can draw the main headlines of the differences among different wireless cellular technology generations.

As a result, those developments or improvements lead to enhanced performance (higher data rates, lower latency, and better utilization of resources, et cetera) and add new services as shown starting from 1G up to 4G. The 4G has enabled much more services and benefits in comparison with previous generations. The supported data rate in 4G was boosted up to 100 Mbps compared to 3G, which is around 2 Mbps. Furthermore, more enabled services and data rates were increased even in comparing the different versions of a specific generation of wireless cellular technology. For example, IoT service was supported in LTE-A. Another example from a data rate point of view, the supported data rate peak in 4G was 100 Mbps. Then it increased up to 1 Gbps peak data rate in 4G LTE-A. Presently, 5G wireless cellular technology is taking place, 5G is promising to boost the provided services in comparison with 4G. Furthermore, 5G wireless cellular technology produces new concepts and capabilities of wireless communications and related applications.

In a parallel path to that improvement march and performance enhancement, the complexity of wireless cellular network technologies and the accompanying challenges are increasing. That requires more innovations and enablers to providing solutions for the accompanying challenges.

3. THE BASICS OF 4G CELLULAR TECHNOLOGY

Historically, the first 4G commercial service launched was in Oslo, Norway, and Stockholm, Sweden, in 2009 by TeliaSonera and Ericsson [22]. The requirements of 4G were standardized by the International Telecommunications Union-Radiocommunications Sector (ITU-R) named the International Mobile Telecommunications Advanced (IMT-Advanced) specification. According to [IMT-Advanced], several requirements were identified, enhanced peak data rates up 100 Mbps for high mobility and 1 Gbps for low mobility, mobility up to 350 km/h [24], control plane latency less than 100 ms [24], it is in the range of 30 ms to 50 ms [23]. Handover interruption time 27.5 ms for intra frequency, 40 ms within a spectrum band, and 60 ms between spectrum bands, and scalable channel BWs up to 40 MHz shall be supported by the Radio Interface Technology [24].

Fourth Generation wireless cellular technology was designed to utilize frequency bands and increase data throughput by exploiting new coding and modulation techniques and expanding BW. Several techniques were used to support these data rate requirements and support a higher number of connected UEs per cell. Multiplexing is one utilized technique, wherein 4G, the multiple access schemes for the physical layer is based on OFDM with a Cyclic Prefix (CP) in Downlink (DL), and on Single-Carrier Frequency Division Multiple Access (SC-FDMA) with a CP in Uplink (UL). The duplexing technique is another technique that was utilized for similar aims. Frequency Division Duplex (FDD) and Time Division Duplex (TDD) are two supported duplexing modes in 4G, and they enable 4G to have a transmission in the paired and unpaired spectrum [80]. Another utilized technique this time in the antenna side, where MIMO is used.

Fourth Generation wireless cellular technology development was the key to enabling new services like high-definition video streaming (because of increasing the data rate peak) and network games (by reducing the latency and make games interactions and responses of players close to real-time). Another service is the video chat that had become possible on the mobile phone. There is a high similarity between Voice Over Internet Protocol (VOIP), which is in use in many applications, and Voice Over Long Term Evolution (VOLTE). The high clarity of VOLTE and the ability to text simultaneously with a call are leaning on 4G network capabilities. The previously mentioned features were not supported in the previous technology generations.

Despite some insignificant differences between 4G, LTE, LTE-Advanced (LTE-A), and LTE-Advanced Pro (LTE-A Pro) cellular networks, 4G and LTE are almost the same. The differences are limited to the upgrades that have eventually led to LTE, LTE-A, and LTE-A Pro. Those upgrades have enhanced the overall performance of cellular networks, but no essential differences were made so that LTE and the later versions can be considered as a new generation, as what happened with 5G NR. According to [3GPP] [84], the capability requirements of LTE-A are to boost the UL peak data rate to 500 Mbps and DL peak data rate up to 1 Gbps. Overall, the user's average throughput is enhanced up to three times in LTE-A than LTE, while the cell edge user throughput is up to twice.

On the latency side, the targeted latency of the control plane has included in several parts:

- The targeted latency transition time from Idle mode to connected mode should be less than 50 ms (user plane establishment is included in that 50 ms, while S1 transfer delay is not included) [32].
- The targeted latency of transition time from a dormant state in connected mode is less than 10 ms for two ways or 5 ms for one way (Discontinuous reception (DRX) delay is not included in that 10 ms), as compared with 10 ms in for one way [32].

Discontinuous reception is a power-saving mechanism switching off the transceiver of UE to be in the sleeping mode most of the time and switching it on periodically. Therefore, UE will not receive any data during the sleeping mode; thus, the waking up progress has a delay interval [32]. On the user plane latency side, the overall achieved latency should be reduced in Advanced E-UTRA and Advanced E-UTRAN compared with Release 8 E-UTRA and E-UTRAN. More specifically, in situations where UE does not have a valid scheduling assignment, and it needs to sync and obtain a scheduling assignment.

The peak spectrum efficiency is improved where the targeted efficiency is 30 bps/Hz with a configuration assumption of 8×8 MIMO or less in DL. The targeted efficiency is 15 bps/Hz with a configuration assumption of 4×4 MIMO or less in UL. Long Term Evolution Advanced (LTE-A) supports scalable BW and supports Carrier Aggregation (CA) techniques. Those techniques have contributed significantly to increasing the data throughput and the flexibility of utilizing BW and maximizing the utilization of BW from the eNB side. There are more requirements regarding spectrum performance, mobility, deployment, E-UTRAN architecture and migration, et cetera. [84]

Table 1 below shows the variations of different 4G standards in a simplified manner.

Table 1. *The considered standards of 4G. [Releases 8, 10, and 13]*

LTE On 2009 Release 8-9	LTE-A On 2011 Release 10	LTE-A Pro On 2016 Release 13
DL peak data rates of 300 Mbps UL peak data rates of 75 Mbps	DL peak rates of 3 Gbps UL peak rates of 1.5 Gbps	DL peak data rates of 10 Gbps
BW is up to 20 MHz	BW is up to 100 MHz by maximum carrier aggregation of 5, where the carrier BW is 20 MHz	BW is up to 640 MHz by maximum carrier aggregation of 32, where the carrier BW is 20 MHz
Minimum latency of 10 ms	Minimum latency of 10 ms	Minimum latency ~ 2 ms
64QAM	256QAM in DL	256QAM
Multiuser MIMO in DL	MIMO enhancement, 8×8 in DL and 4×4 in UL	Advanced MIMO

As a result of the previous enhancements and technology developments and new spectrum utilization, 4G started to operate in new frequency bands, which have been designed for 4G specifically and operating existing cellular bands at the same time. The frequency bands list of E-UTRAN operating bands is identified in Release 16. The used duplex modes are Frequency Division Duplex (FDD) and Time Division Duplex (TDD). Evolved-UMTS Terrestrial Radio Access Network operating band number 87 is the lowest operating frequency of 410 MHz for the UL operating band, with channel BW of 1.4 MHz, 3 MHz, and 5 MHz, FDD mode. Evolved-UMTS Terrestrial Radio Access Network operating band number 47 is the highest operating frequency of 5 925 MHz for the DL operating band, with channel BW of 10 MHz and 20 MHz (cellular vehicle to everything communication purposes), TDD mode. The wide channels approach was considered to achieve high data rates. The used BWs starting from 1.4 MHz to 20 MHz, while 5 MHz and 10 MHz BWs are the most commonly utilized bands. [25]

There are several utilized techniques in 4G to achieve high data rates; modulation schemes are among them. Fourth Generation technology supports the Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme, which can meet the spectral efficiency requirements to achieve a high data rate and enable multiple users to share the same bandwidth simultaneously. By dividing a given frequency band into smaller orthogonal sub-bands (carriers) in the frequency domain, it has become possible to achieve high throughput by transmitting symbols on each subcarrier simultaneously.

Those subcarriers are received and aggregated on the receiver side; thus, the total throughput at the receiver results from aggregated throughput of each received carrier. This process or transmission scheme is called Carrier Aggregation (CA).

There is a possibility that the adjacent subcarriers would interfere with each other because of the channel impacts on the received signal of multipath, unsystematic fades that the channel applies on the different frequency components, et cetera. The old approach in FDD was to add small gaps or guard bands between the carriers, which causes spectrum wasting and reduces spectral efficiency eventually. In OFDM, a new approach was utilized; the subcarriers were designed orthogonally, enabling better utilization for spectrum. Therefore, those subcarriers can overlap each other in the frequency domain without any mutual influence on the central frequency f_c of the subcarrier where the value of amplitude and phase is considered at UE. Figure 7 shows the OFDM subcarriers structure.

The channel impacts the propagated signal in different ways. Thus, the individual symbol eventually, where the channel impacts amplitude and phase distortion, will appear in the receiver's received signal. As a result of the imposed amplitude and phase distortion by channel, the so-called Inter-symbol Interference (ISI) would occur in the receiver. This means the orthogonality was already disrupted. Usually, ISI happens because of the multipath channel where several copies of the symbol’s transmitted signal are received. Several copies of the symbol's transmitted signal differ in amplitude and arrive at UE at different time instances, which causes phase offset among the several copies of the symbol signal.

To mitigate that ISI and preserve the orthogonality, CP is added to the end of the transmitted symbol and before the next symbol transmission. In short, the Cyclic Prefix is prefixing of the previous symbol with a repetition of the end for a time duration equal to multipath time delay. In turn, User Equipment is designed to ignore or discard the CP by modeling the repeated part of the symbol as circular convolution. After removing repetitions, UE starts receiving the useful part of the next symbol; thus, the ISI is prevented at some acceptable level. [26]

Figure 7 shows the power spectrum mapping in the frequency domain of individual OFDM subcarriers. Figure 8 shows the power spectrum mapping in the time and frequency domain of overlapped OFDM subcarriers.

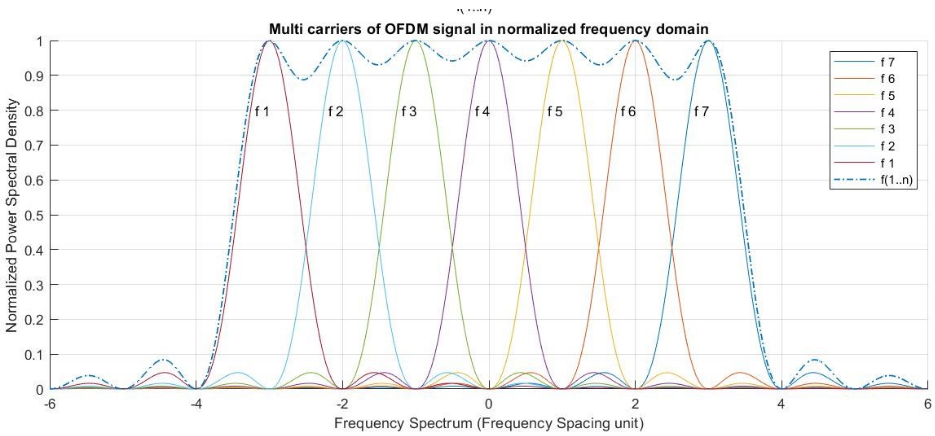

Figure 7. *The normalized power spectrum mapping of OFDM subcarriers in the frequency domain.*

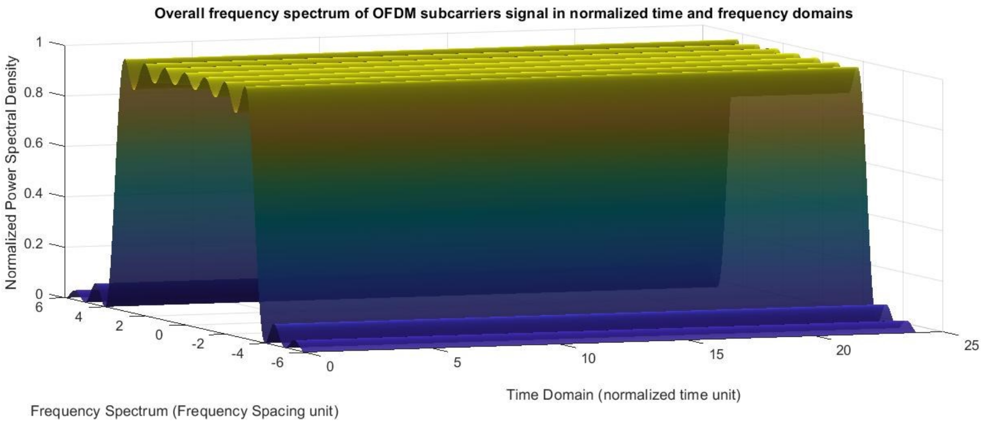

Figure 8. *The power spectrum mapping in the time and frequency domain of overlapped OFDM subcarriers.*

Generally, in wireless communications systems, there are different utilized access technologies. Time Division Multiple Access is one of those technologies. It allocates access in the time domain; therefore, devices can access eNB in different periods. Another access technology is the Orthogonal Frequency Division Multiple Access (OFDMA). It allocates access to various orthogonal frequency bands; therefore, devices can access eNB by utilizing different frequency bands.

Another access technology is CDMA. It allocates access to different codes where the device can be distinguished among other devices by a unique given code. In CDMA access technology, the advantage is the device has access to the whole BW continuously in time. On the other hand, the disadvantage is the complexity of devices to performing this kind of technique is increasing.

In 4G, both TDMA and OFDMA are utilized. In contrast, the Single Carrier Frequency Division Multiple Access (SC-FDMA) scheme is utilized in UL based on the advantage of TDD inclusion, where UEs are separated in the time domain. Therefore, each UE will occupy the whole bandwidth during transmission SC-FDMA [27]. Single Carrier Frequency Division Multiple Access is utilized access scheme on the UL side, where it is multiple carriers that are modulated with the same data symbol. The SC-FDMA scheme is utilized in UL, while the OFDMA scheme is utilized in DL.

In OFDMA, each subcarrier is modulated separately with a different data symbol but lasts for a longer time than the SC-FDMA symbol time duration. The SC-FDMA scheme is used in 4G-UL access modes to reduce the peak to average power ratio and increase the power amplifier's efficiency, which eventually leads to saving the battery life of UE. Orthogonal Frequency Division Multiple Access cannot be used in UL because of the limited capability of UE transmitting Power Amplifier (PA). It would be costly and challenging and to implement a more capable and extended dynamic range of transmitting PA in UE. On the other hand, the OFDMA scheme is workable in DL because of the large dynamic range of transmitting PA. Furthermore, OFDMA is beneficial from different data rate scalability and capability for effective frequency scheduling.

Figure 9 below shows the differences between OFDMA and SC-FDMA modulation schemes in the time and the frequency domain.

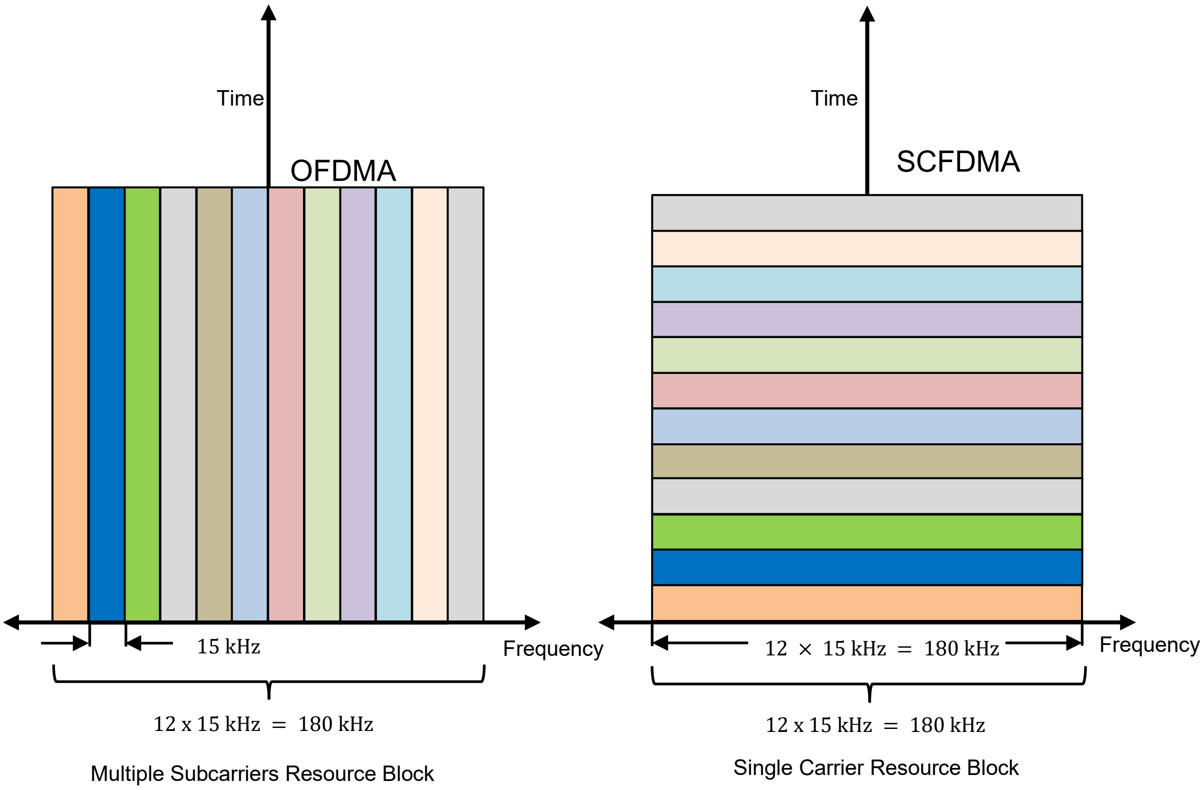

Figure 9. *The Modulation schemes of OFDMA and SC-FDMA. [28]*

3.1 4G frame structures

According to [3GPP] [27], there are three standardized frame structures, type 1, 2, and 3. Frame structure type 1 is applicable in FDD modulation only, frame structure type 2 is applicable in TDD modulation, and frame structure type 3 is applicable in License Assisted Access (LAA) secondary cell operation only.

3.1.1 Frame structure type 1

This frame structure consists of 10 subframes. Each subframe consists of 2 slots; therefore, the total number of slots is 20, starting with sequence 0 (slot number 1 in the first subframe), ending with slot sequence 19 (slot number 20 in subframe number 10). The time duration for one slot is 0.5 ms. Each slot has seven OFDM symbols with normal CP configuration or six OFDM symbols with extended CP (eCP) configuration.

Cyclic Prefix performs as a guard interval to eliminate ISI from the previous symbol. Cyclic Prefix is designed so that a copy of the end part of each OFDM symbol is sent after the OFDM symbol itself, which eventually increases the transmission robustness. On the other hand, the data capacity is reduced because the time resources are partially being wasted by CP [29]. It is essential to mention that CP lengths differ; thus, there are normal and extended CP lengths.

The total time duration of one radio frame is 10 ms, while the considered subcarrier spacing (Δf) is 7.5 kHz and 15 kHz. This frame type suitable for half and full-duplex FDD only. Figure 10 below shows the radio frame structure type 1, FDD. [27]

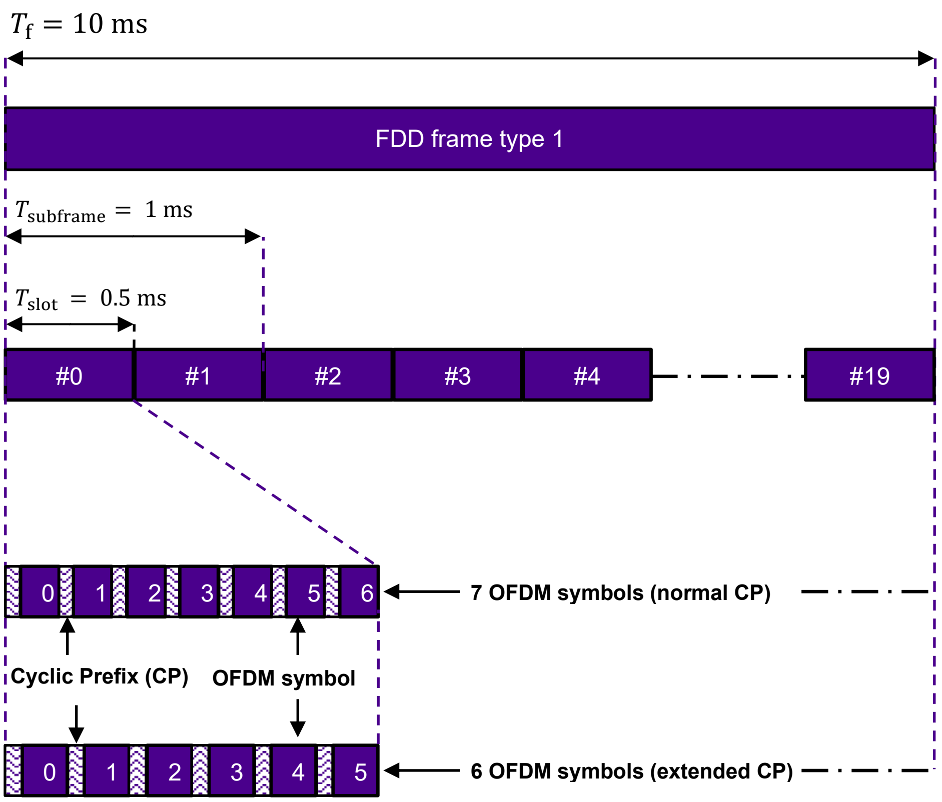

Figure 10. *Frame structure type 1, FDD. [27]*

3.1.2 Frame structure type 2

The frame structure consists of two halves, with a total subframes number of 10, where the first and second half-frame consists of 5 subframes. There are ten individual slots, starting with a sequence subframe of 0 (slot number 1 at the beginning of the first half of the mainframe), ending with a slot sequence subframe of 9 (slot number 5 at the end of the second half of the mainframe). The time duration of one subframe $T_{subframe}$ is 1 ms, the time duration of 1 half-frame is 5 ms; therefore, the total time duration of one radio frame T_f equals to 10 ms.

It is important to mention that every single subframe consists of two slots. Each slot has a time duration T_{slot} of 0.5 ms. Figure 11 shows the radio frame structure type 2, TDD. [27]

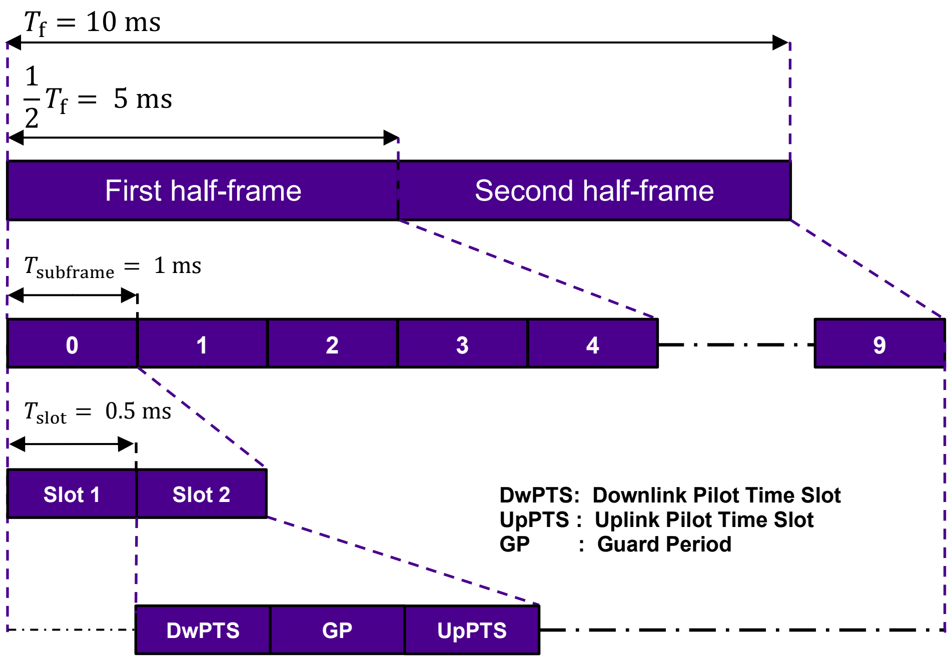

Figure 11. *Frame structure type 2, TDD. [27]*

3.1.3 Frame structure type 3

The third type of frame structure is new, and the main application of the third type is LAA. The total time duration of one frame is 10 ms, and each frame consists of 20 slots, starting with a sequence number of 0 and ending with a sequence number of 19. Every two consecutive slots are forming one subframe. The time duration of one slot is 0.5 ms, where it is 1 ms for one subframe. The details of frame structure type 3 are the same details of frame structure type 1 shown in figure 10. [27]

3.1.4 The frame structure of the Physical Sidelink Channel

The time duration of one frame is T_{f}, each frame consists of 20 slots where the slot's time duration is T_{slot}, each sidelink subframe consists of two consecutive slots, the starting number of the slot is even. [27]

3.1.5 The frame structure of Narrowband Internet of Things NB-IoT

In FDD operation, frame structure type is applicable. In TDD operation, frame structure type 2 is applicable with applying the following restrictions [27]:

- Configurations number 0 and 6 are not supported in UL-DL (frame configurations are shown in Table 1).
- Narrowband Physical Uplink Shared Channel (NPUSCH) or Narrowband Physical Random Access Channel (NPRACH) do not use Uplink Pilot Time Slot (UpPTS).
- In special subframe configuration 10, Downlink Pilot Time Slot (DwPTS) and / Uplink Pilot Time Slot (UpPTS) are not used for transmissions.
- For transmissions of Narrowband Physical Download Control Channel (NPDCCH) and Narrowband Physical Download Shared Channel (NPDSCH), DwPTS in special subframe configurations 0 and 5 for CP is not used.

3.2 Fourth Generation Long Term Evolution 4G Frame Configurations

As shown in the frame structures section, there are several frame structures. In the next three subchapters of frame configurations, there are more coming details about frame configures and the available settings of UL, DL, and special slots and subframes.

3.2.1 Frame Structure Type 1 Configuration

The SC-FDMA/OFDMA symbols are distributed in different sub-slots of subframes; therefore, there are specific UL and DL sub-slot patterns. According to [3GPP], the standardized subcarrier Δf is 7.5 kHz and 15 kHz. At $\Delta f = 15$ kHz, it is easy to calculate the available symbols in one radio frame. One radio frame consists of 10 subframes. Each subframe has two slots; each slot has seven symbols, or $\frac{140 \text{ symbols}}{1 \text{ radio frame}}$ in total. From that number of symbols $\frac{14 \text{ symbols}}{1 \text{ subframe}}$ or $\frac{140 \text{ symbols}}{1 \text{ radio frame}}$ are utilized for UL, and the same number of symbols are utilized for DL. It is necessary to note that the details rate depends on modulation, coding order, the utilized bandwidth in transmission, and number symbols per frame. [27]

3.2.2 Frame Structure Type 2 Configuration

In TDD single radio frame, there are ten subframes. Each subframe has a 1 ms time duration. Until now, the frame and subframe's time durations are still the same as the FDD frame and subframe. The difference starts with the subframe types. In the TDD frame, there are three types of subframes. The first type is for DL denoted by "D", the second type is for UL denoted by "U", and the third type is a Special subframe denoted by “S”. The Special subframe has two fields (or three fields if Guard Period is included), Downlink Pilot Time Slot (DwPTS), Uplink Pilot Time Slot (UpPTS), separated by a transmission gap Guard Period (GP) as shown in figure 11. The time duration of the three fields (GP is included) may vary, but the accumulated time duration of them is 1 ms. In all seven TDD frame configurations, subframes 0 and 5 are D, subframe 1 is S, and subframe 2 is U, while subframes (3, 4, 6, 7, 8, and 9). On the other hand, the periodicity time varies between 5 ms for configurations 0, 1, 2, and 6; and 10 ms for configurations 3, 4, and 5, as shown in Table 2 below. [27]

Table 2. *Uplink Downlink frame configurations [27].*

UL-DL configu-ration	UL-DL Switch-point periodicity (ms)	One Radio Frame (10 Subframes)									
		0	1	2	3	4	5	6	7	8	9
0	5	D	S	U	U	U	D	S	U	U	U
1	5	D	S	U	U	D	D	S	U	U	D
2	5	D	S	U	D	D	D	S	U	D	D
3	10	D	S	U	U	U	D	D	D	D	D
4	10	D	S	U	U	D	D	D	D	D	D
5	10	D	S	U	D	D	D	D	D	D	D
6	5	D	S	U	U	U	D	S	U	U	D

3.2.3 Frame Structure Type 3 Configuration

In frame structure type 3, the configuration is slightly different from both previous types. Uplink is not allowed. On the DL side, the whole ten subframes of frame type 3 can be dedicated to DL. Downlink transmission can start at any subframe where it should occupy one or more consecutive subframes and ends with the last subframe boundary or any one of the DwPTS. Downlink transmission may occupy the subframe fully or one DwPTS duration. It is important to mention that there are eleven available configurations for special frames type. [27]

3.3 Physical Resources of Fourth Generation Long Term Evolution 4G

Resources term in wireless communications is commonly used to indicate the available radio spectrum, that can be utilized for a known time duration mutually between a single access point and terminal/s (eNB and UE in 4G case) to exchange information in one or both directions network operators and infrastructure. On a bigger scale, the network's available infrastructure (the number of access points per area unit) is included in the resources term in addition to the spectrum and time quantities. On the other hand, the infrastructure size becomes crucial to restrict and regulate how that spectrum should be distributed and utilized among the available infrastructure for a known time duration. This section will investigate the resources part from the spectrum and time point of view between eNB and UE. This investigation can be considered as a foundation stone to build a full visualization or concept of the physical resources designing policy for given limitations of radio network planning and key performance indicators.

3.3.1 Resource Element (RE)

Resource Element refers to the smallest time-frequency unit for transmission. In 4G case, RE refers to the transmitted signal in each OFDM symbol, which has $\Delta f = 7.5$ kHz or 15 kHz in the frequency domain, and the duration of one OFDM symbol is $\frac{0.5\ \text{ms}}{7\ \text{symbols}}$ in normal CP and $\frac{5\ \text{ms}}{6\ \text{symbols}}$ in eCP in the time domain. Resource Element is the smallest unit that can carry a recognized information signal. [27]

3.3.2 Resource Block (RB)

Resource Block indicates a grid that can be described in two dimensions. Frequency is the first dimension, where the unit on the frequency axis is one subcarrier (SC) bandwidth, $\Delta f = 15$ kHz in the first case, and as the total wide of RB is 12 subcarriers (SCs), the total BW of RB would equal to $12 \cdot 15$ kHz $= 180$ kHz. The second case is when SC bandwidth, $\Delta f = 7.5$ Hz; therefore, the total width of RB is 24 SCs that give RB BW of 180 kHz again. The second dimension is time, where the smallest unit on the time axis is the time duration of 6 or 7 OFDM symbols in extended or normal CP, respectively. The time duration of one slot is 0.5 ms. Therefore, it is easy to know that the RB is nothing but a group or a grid of REs. The RB dimensions can be identified as the first dimension in the frequency domain (180 kHz in frequency term of either 12 or 24 SCs), and the second dimension in the time domain (7 or 6 OFDM symbols in terms of OFDM symbol or 0.5 ms in terms of the time duration of 7 or 6 OFDM symbols). The RB is the smallest resource that can be allocated to a user. Table 3 shows the Resource Block standards, including DL RB's size in terms of SC and the number of OFDM symbols in the DL slot in 4G.

Resource Block size varies in the UL case. The RB size is 12 SCs of 6 or 7 SC-FDMA symbols in the UL slot, depending on if the CP configuration is normal, respectively (the same configurations are applied Sidelink Resource Block SL-RB). In the DL case, RB size has more options. Table 3 shows the different parameters and configurations of DL RB.

In Narrowband Internet of Thing Downlink (NB-IoT DL), the RB size is the same as Downlink Resource Block (DL RB) configuration, but only 15 kHz of SC is supported. [27]

Table 3. *Physical resource block parameters. [27]*

Cyclic Prefix (CP) Configuration	Δf kHz	DL RB size in term of $\#SC$	OFDM symbols number in DL slot
Normal	15	12	7
Extended	15	12	6
	7.5	24	3
	2.5	72	1
	1.25	144	1
	0.37	486	1

3.3.3 Resource Grid

The resource grid is represented by two dimensions entity (time and frequency). The time dimension is equal to one slot time duration in the UL case (0.5 ms). The frequency dimension is equal to the number of utilized RBs multiplied by the BW of RB in the UL and DL cases. In Physical Sidelink Channels (PSLCH), there are two options of BW. The first option is that the SL BW is equal to UL BW if ($\text{Cell selection RX level Value} > 0\ \text{dB}$, and $\text{Cell selection quality value} > 0\ \text{dB}$), for an equal uplink carrier frequency to the side-link's for that specific serving cell; otherwise a preconfigured value is used [30]. [27]

Table 4 below shows the available channel BWs with and without GP

Table 4. *The available SCs and corresponding BWs in 4G, UL, and DL. [27]*

Δf kHz	$\#\text{SCs}$ per RB	$\text{Physical RB BW} = 12\ (\text{SCs}) \cdot \Delta f$ kHz	$\#\text{RBs}$	$\#\text{SCs}$ in DL	$\#\text{SCs}$ in UL	BW, GP is not included MHz	CH BW and GP MHz
15	12	180	6	73	72	1.08	1.4
15	12	180	15	181	180	2.7	3
15	12	180	25	301	300	4.5	5
15	12	180	50	601	600	9	10
15	12	180	75	901	900	13.5	15
15	12	180	100	1201	1200	18	20

It is important to notice that $10\ \%$ of the BW is dedicated to the guard band. For example, in 5 MHz, there are 25 RBs, multiplied by 180 kHz for each RB, which gives 4.5 MHz or $90\ \%$ of actual BW utilization and left up with 0.5 MHz wasted for guard bands. In 4G, the most commonly used BW is 5 MHz. In Narrowband IoT, the UL resource grid consists of 12 or 48 SCs of 15 kHz or 3.75 kHz, respectively.

3.3.4 Narrowband and Wideband

One Narrowband is defined as six non-overlapped physical RBs aggregated consecutively in the frequency domain. Therefore, the total number of UL narrow bands in UL transmission BW configured in a cell is given by dividing the total number of UL RBs by 6. [27]

One wideband is defined as four non-overlapped physical RBs, aggregated consecutively in the frequency domain. Therefore, the total number of UL wide bands in UL transmission BW configured in a cell is given by dividing the total number of UL RBs by 4. [27]

3.3.5 Guard Period (GP)

In UL case, the first option of setting GP is that UE does not transmit the last SC-FDMA symbol in the first subframe if the number of symbols in a guard period for narrowband or wideband retuning $(N_{\mathrm{symb}}^{\mathrm{retune}}) = 1$ [27]. The second option is that UE does not transmit the first SC-FDMA symbol in the second subframe in addition to the previous SC-FDMA symbol if $N_{\mathrm{symb}}^{\mathrm{retune}} = 2$ [27]. These are examples of the considered configurations by UE when creating and setting the GP. There are slightly different settings and conditions of the GP in the same frame structure type, depending on the transmission cases and higher layers' configurations. Furthermore, the differences are more between GP settings and conditions in the different structures of the frame. [27]

There are two types of GPs, GP for half-duplex FDD operation and GP for TDD operation in the DL case. Guard Period for half-duplex FDD operation has two subtypes of GP in turn. UE creates type A of GPs half-duplex FDD by dropping the last part of the DL subframe and immediately preceding the UL subframe from the same UE. In the first case of type B of GPs, GP is created by UE dropping DL subframe and immediately preceding UL subframe from the same UE. In the second case of type B of GPs, GP is created by UE dropping DL subframe and immediately following UL subframe from the same UE. The second type of GPs is GPs in TDD operation. The GP field in the frame structure type 2 serves as a guard period. In Sidelink (SL), the last SC-FDMA symbol shall not be used for SL transmission; thus, it serves as a GP. Finally, in DL Narrowband Internet of Thing (DL NB-IoT), the GP for half-duplex FDD operation is type B. For DL NB-IoT, TDD operation, the GP is created by dropping the first part of the OFDM symbol of DL subframe and immediately following UL subframe from the same UE for 15 kHz subcarrier spacing. The progress is standardized with frame structure type 2, correspondingly with several conditions that must be considered. [27]

3.4 Physical channels of Fourth Generation Long Term Evolution 4G

It is important to clarify the different layers that the Physical Channels (PHY CHs) connect briefly before going into the details and functionalities of the PHY CHs. After that, it will be easy to understand the different aims and reasons for finding those PHY CHs and their different configurations. In this section of PHY CHs, the details of logical channels and protocol layers will be reviewed before diving into the details of PHY CHs.

According to [Open Systems Interconnection model (OSI)], there are three relevant radio interface layers of 4G out of seven layers in the OSI model.

The physical layer presents at the bottom of the OSI model hierarchy, which includes and corresponds to the physical protocol layer in protocols layers architecture or model. The physical layer is located where the signal that carries data and control information is transmitted and received by the PHY CHS between UE and eNB, vice versa. The physical layer interconnects with a higher protocol layer, the Medium Access Control protocol layer (MAC), through the transport channels. Medium Access Control protocol layer presents in both UE and eNB. [31]

When comparing the UE and eNB side to side, they have different physical channels to transport channels mapping and vice versa. Furthermore, different sets of physical and transport channels in UL and DL progress in each of UE and eNB are used. The physical layer handles the following functions [31,80]:

- Detection of errors on the transport channel and indication to higher layers.
- Forward Error Correction (FEC) encoding/decoding of the transport channel.
- Hybrid Automatic repeat ReQuest (HARQ) soft-combining.
- Matching the rate of the coded transport channel to physical channels.
- The coded transport channel mapping onto the physical channels.
- Power weighting of physical channels.
- Modulation and demodulation of physical channels.
- Frequency and time synchronization.
- Measurements of radio characteristics and indication to higher layers.
- MIMO antenna processing.
- Transmit Diversity (TX diversity).
- Beamforming.
- Radio Frequency (RF) processing.

The OSI model's Data Link layer is the second layer, which includes or corresponds to three protocol layers. Medium Access Control protocol layer, Radio Link Control layer (RLC), and Packet Data Convergence Protocol layer (PDCP).

Medium Access Control protocol layer is the first in the Data Link layer. The MAC layer presents on top of the PHY layer and interconnects with it through the transport channels

[31]. Medium Access Control protocol layer presents in UE and eNB. The MAC layer handles the following functions [32]:

- Multiplexing of MAC Service Data Units (MAC SDUs) from one or different logical channels onto transport blocks (TB) to be delivered to the PHY layer on transport channels.
- Demultiplexing of MAC SDUs from one or different logical channels from TB delivered from the physical layer on transport channels.
- Scheduling information reporting.
- Error correction through HARQ.
- Priority handling between UEs utilizing dynamic scheduling.
- Priority handling between logical channels of one MAC entity.
- Logical Channel prioritization.
- Transport format selection.
- Radio resource selection for SL.

There are differences of logical channels to transport channels mapping vice versa, and the sets of the logical and transport channels in UL and DL.

Radio Link Control layer is the second protocol layer in the Data Link layer. The RLC presents on top of the MAC layer and beneath the PDCP layer. The Radio Link Control layer interconnects with the MAC layer through the logical channels. The RLC layer handles the following functions [78]:

- Transfer of upper layer Protocol Data Unit is (PDUs).
- Error correction through Automatic repeat ReQuest (ARQ) (only for Acknowledged Mode AM data transfer).
- Concatenation, segmentation, and reassembly of RLC SDUs (only for Unacknowledged Mode UM and AM data transfer).
- Re-segmentation of RLC data PDUs (only for AM data transfer).
- Reordering of RLC data PDUs (only for UM and AM data transfer).
- Duplicate detection (only for UM and AM data transfer).
- RLC SDU discards (only for UM and AM data transfer).
- RLC re-establishment.
- Protocol error detection (only for AM data transfer).

Packet Data Convergence Protocol layer is the third protocol layer in the Data Link layer. The PDCP presents on top of the RLC layer and beneath the Radio Resource Controller (RRC) layer. The PDCP layer interconnects with the RLC layer through the Radio Bearers. The PDCP layer handles the following functions [79]:

- Header compression and decompression of IP data flow using the RObust Header Compression (ROHC) protocol.
- Header compression and decompression of Ethernet data flow using the Ethernet Header Compression (EHC) protocol.
- Compression and decompression of UL PDCP SDU.
- Transfer of data (user or control planes).
- Maintenance of PDCP Sequence Numbers (SNs).
- In-sequence delivery of upper layer PDUs at re-establishment of lower layers.
- Eliminate duplication of lower layer SDUs at re-establishment of lower layers for radio bearers mapped on RLC AM.

- Ciphering and deciphering the data of the user plane and control plane.
- Protection and verification of the integrity of control plane data.
- Integrity protection and integrity verification of SL one-to-one communication data.
- For Relay Nodes (RNs), integrity protection and integrity verification of user plane data.
- Timer-based discard.
- Duplicate transmission and duplicate discarding.
- For split and -WLAN Aggregation (LWA bearers), routing, and reordering.
- For Dual Active Protocol Stack (DAPS) bearers, routing, and reordering.

There are three types of channels in 4G communications technology classified hierarchically among the previously mentioned layers, logical channels, transport channels, and PHY channels. The function of different sets of channels is to connect the different previous layers. The connection between the different layers is made by assigning each channel to a Service Access Point (SAP) between different layers and provide various services between the different layers. Generally, the function of logical channels is to provide services at SAP between RLC and MAC layers. The MAC layer's expected services to the upper layers are data transfer and radio resources allocation, while the transport channels provide services at SAP between MAC and PHY layers. The expected services to be provided by the PHY layer to the MAC layer are data transfer, signaling of HARQ feedback, signaling of Scheduling Request (SR), and measurements.

As a result, there are different sets of channels that interconnecting the different layers. Those channels, in turn, are enabling the segregation of data orderly. Those different sets of channels between the different layers require the so-called “channel mapping” process or function to interface the different layers within the protocol stack. Medium Access Control protocol layer supports channel mapping between logical channels and transport channels. In transmitting data, the MAC layer multiplexes MAC Service Data Units (MAC SDUs) from one or different logical channels onto transport blocks to deliver the transport blocks to the PHY layer on the transport channels. Finally, in receiving data, the MAC layer demultiplexes transport blocks from one or different transport channels onto MAC SDUs to deliver the MAC SDUs to the RLC layer on the logical channels. [32]

Physical channels can be defined as transmission channels that carry user data and control messages originated and oriented from higher layers by a dedicated set of resource elements [27]. There are different requirements and functions for UL, DL, SL, and Narrowband IoT (NB-IoT) physical channels depending on the assigned function/s to that physical channel and several other parameters.

The uplink physical channel is where UE transmits information by the utilized resource elements of the 4G frame to eNB (explained in an earlier section). The same definition applies to SL, UL, and NB-IoT UL physical channels. Downlink Physical Channel is where eNB transmits information signals to UE. The exact definition applies to SL, DL, and NB-IoT DL channels. Physical Channels continuously vary in time and accordingly with the UE distance from the eNB transmitter antenna. The channel's continuous variation impacts the signal power level generally, signal to noise ratio, multipath (phase offset at the receiver), and distorts the signal, et cetera. Therefore, UE and eNB would have to equalize the received signal at some level, trying to remove the channel impacts on the received signal and recover the original shape of the transmitted signal. There are several physical channels according to [3GPP] standards of 4G as defined below.

3.4.1 4G Uplink Physical Channels

The Uplink Physical Channels correspond to sets of time-frequency resources that carry transport channel data and control information from higher UE layers to eNB. Uplink Physical Channels in 4G are divided into [27]:

- Physical Uplink Shared Channel (PUSCH).
- Physical Random Access Channel (PRACH).
- Short Physical Uplink Channel (SPUCCH).
- Physical Uplink Control Channel (PUCCH).

The 4G uplink physical channels' importance is represented in the data and the control information that channels carry from UE to eNB.

Physical Uplink Shared Channel (PUSCH)

This channel carries RRC signaling messages, Uplink Control Information (UCI), application data, user information data [27]. Furthermore, it carries Uplink Synchronization Channel (UL-SCH) [33]. The supported modulation schemes for PUSCH are π/2 Binary Phase Shift Key (π/2 BPSK), Quadrature Phase Shift Key (QPSK), 16 Quadrature Amplitude Modulation (16QAM), 64QAM, and 256QAM (the last modulation is not in use that much until now). [27]

Physical Uplink Control Channel (PUCCH)

This channel carries HARQ ACK/NAKs in response to DL transmissions, Scheduling Request (SR), and Channel State Information (CSI) [33]. User Equipment supports PUCCH and PUSCH transmission simultaneously by enabling it from higher layers [28]. Physical Uplink Control Channel supports nine formats with different numbers of bits per subframe. The PUCCH is not transmitted in the UpPTS field for the frame structure type 2 (Figure 11 shows the frame structure type 2).

The supported modulation schemes for PUCCH are BPSK or QPSK or both in the same PUCCH format. The number of bits per subframe varies according to the PUCCH format and modulation scheme [27]. Physical Uplink Control Channel signal consists of:

- HARQ.
- ACK/NACK.
- Channel Quality Indicators (CQI).
- MIMO feedback, Precoding Matrix Indicator (PMI), and Rank Indicator (RI).
- SR for UL transmission.

The supported modulations for PUSCH are BPSK and QPSK [27].

Short Physical Uplink Channel (SPUCCH)

This channel carries HARQ ACK/NAKs in response to DL transmissions and carriers SR [33]. User Equipment transmits SPUCCH and PUSCH simultaneously from the same UE using the slot, or sub-slot transmission is supported if higher layers enabled it. The transmission of SPUCCH is not supported in frame structure type 2 and in UpPTS (frame structure type 2 is clarified in figure 11) [27].

SPUCCH supports five formats for slot transmission 1,1a,1b,3, and 4 with modulation schemes BPSK and QPSK. There are four supported formats of sub-slot transmission, 1, 1a, 1b, and 4. Only the QPSK modulation scheme is supported for the fourth SPUCCH format and N/A for the rest of the SPUCCH formats. The number of bits per slot varies according to the SPUCCH format and modulation scheme. The supported modulations for SPUCCH are BPSK and QPSK. [27]

Physical Random Access Channel (PRACH)

This channel is shared among terminals to access the mobile network by the different access technologies mentioned earlier. This channel carries random access preambles, enabling UEs to access and establish a network connection [33].

In 4G, PRACH is a reserved RB by eNB. The number of PRACH resources per one radio frame (10 ms of time duration) depends on the configuration index of PRACH. For frame structure type 1, FDD (Figure 10 shows the frame structure type 1), there are four preamble configurations, starting with preamble format 0 and ending with 3. The PRACH configuration index starts from 0 at preamble format 0 and ends with configuration index 63 at preamble format 3. For frame structure type 2, TDD (Figure 11 shows the frame structure type 2), five preamble configurations start with preamble format 0 and end with 4. The PRACH configuration index starts from 0 at preamble format 0 and ends with configuration index 57 at preamble format 3. [27]

3.4.2 4G Downlink Physical Channels

The Downlink Physical Channels correspond to sets of time-frequency resources that carry transport channel data and control information from higher layers in eNB to UEs. Downlink Physical Channels in 4G are divided into [33]:

- Physical Downlink Shared Channel (PDSCH).
- Physical Broadcast Channel (PBCH).
- Physical Multicast Channel (PMCH).
- Physical Control Format Indicator Channel (PCFICH).
- Physical Downlink Control Channel (PDCCH).
- Physical Hybrid ARQ Indicator Channel (PHICH).
- Enhanced Physical Downlink Control Channel (EPDCCH).
- MTC Physical Downlink Control Channel (MPDCCH).
- Short Physical Downlink Control Channel (SPDCCH).
- Relay Physical Downlink Control Channel (R-PDCCH).

The 4G physical downlink channels' importance is represented in the data and the control information that channels carry from the enhanced base station eNB to the UE.

Physical Downlink Shared Channel (PDSCH)

This channel represents the primary data bearer. It carries Downlink Synchronization Channel (DL-SCH) and Paging Channel (PCH) so that UE can monitor the network in idle mode [33]. The supported modulations are QPSK, 16QAM, 64QAM, and 256QAM. The modulation selecting process is handled by eNB based on several parameters like channel condition [27].

Physical Broadcast Channel (PBCH)

This channel carries system information for UEs that are necessary to initiate cell access [33]. The supported modulation is QPSK [27].

Physical Multicast Channel (PMCH)

This channel carries Multimedia Broadcast and Multicast Services (MBMS), briefly it carries the Multicast Channel (MCH) [27,33]. The supported modulations are QPSK, 16QAM, 64QAM, and 256QAM [27].

Physical Control Format Indicator Channel (PCFICH)

This channel provides information, including the number of symbols per subframe for Physical Downlink Control Channel (PDCCH) transmission. In other words, PCFICH informs the UE and Radio Network (RN) number of utilized OFDM symbols in PDCCHs transmissions. The periodicity of PCFICH transmissions is in every DL or special subframe [33]. The supported modulation is QPSK [27].

Physical Downlink Control Channel (PDCCH)

This channel carries Downlink Control Information (DCI), scheduling priority decisions, and power adaption control signals. This channel informs the UE and Radio network about resources' allocation of Physical Channel and PDSCH. Physical Downlink Control Channel informs UE about HARQ of DL-SCH and carries UL and DL scheduling grants [33]. The supported modulation is QPSK [27].

Physical Hybrid ARQ Indicator Channel (PHICH)

This channel carries Hybrid ARQ ACK/NAKs in response to UL data transmissions on PUSCH (positive and negative acknowledgments) [33]. The supported modulation is BPSK [27].

Enhanced Physical Downlink Control Channel (EPDCCH)

This channel was introduced as a complementary control channel. It is differing from PDCCH from precoding and mapping to physical resources point of view. This channel carries the scheduling assignments. In more detail, this channel informs UE about the allocation of resources and HARQ information related to DL-SCH, UL, and SL scheduling grants [33]. The supported modulation is QPSK [27,33].

Machine Type Communication (MTC) Physical Downlink Control Channel (MTCPDCCH)

This channel is very similar to EPDCCH. The MTCPDCCH informs UE about DL-SCH resources allocation and HARQ information related to DL-SCH in response to UL transmission, UL and SL scheduling grant, and direct indication information. In short, this channel carries DCI [33]. The supported modulation is QPSK [27].

Short Physical Downlink Control Channel (SPDCCH)

This channel carries information about the allocation of resources of the DL-SCH to UE, HARQ information related to DL-SCH, and UL scheduling grant [33]. The supported modulation is QPSK. [27]

Relay Physical Downlink Control Channel (R-PDCCH)

This channel carries information about the allocation of resources of the DL-SCH to UE, HARQ information related to DL-SCH, and the UL scheduling grant. The supported modulation is QPSK. [33]

3.4.3 4G Sidelink (SL) Physical Channels

The Sidelink Physical Channels are an addition to the standards, allowing direct communication between two UEs without eNB involvement. The Sidelink Physical Channels correspond to sets of time-frequency resources that carry information originated and oriented from higher layers in UE to another UE. Sidelink Physical Channels in 4G are divided into [27]:

- Physical Sidelink Shared Channel (PSSCH)
- Physical Sidelink Control Channel (PSCCH).
- Physical Sidelink Discovery Channel (PSDCH).
- Physical Sidelink Broadcast Channel (PSBCH).

The importance of 4G physical sidelink channels is represented in data and control information that channels carry from one UE to another UE and vice versa.

Physical Sidelink Shared Channel (PSSCH)

This channel carries data information from UE for SL and vehicle to everything (V2X) SL communications [33]. The supported modulations are QPSK, 16QAM, and 64QAM [27].

Physical Sidelink Control Channel (PSCCH)

This channel carries control information from UE for SL and vehicle to everything (V2X) SL communications [33]. The supported modulation is QPSK [27].

Physical Sidelink Discovery Channel (PSDCH)

This channel carries a sidelink discovery message from UE [33]. The supported modulation is QPSK [27].

Physical Sidelink Broadcast Channel (PSBCH)

This channel carries system and synchronization-related information from UE [33]. The supported modulation is QPSK [27].

3.4.4 4G Narrowband Uplink Physical Channels

The Narrowband Uplink Physical Channels correspond to sets of time-frequency resources that carry transport channel data and control information from higher layers in Narrowband IoT UE (NB-IoT UE) to eNB. Narrowband Uplink Physical Channels in 4G are divided into [27]:

- Narrowband Physical Uplink Shared Channel (NPUSCH).
- Narrowband Physical Random Access Channel (NPRACH).

The importance of 4G NB physical UL CH is represented in data and control information that the channels carry from NB-IoT UE to eNB.

Narrowband Physical Uplink Shared Channel (NPUSCH)

This channel carries UL-SCH, HARQ ACK/NAKs in response to DL transmission, and SR for NB-IoT UE [33]. The supported modulations are BPSK, QPSK [27].

Narrowband Physical Random Access Channel (NPRACH)

This channel carries random access preambles which enable NB-IoT UE to access and establish a connection with the network and carry SR for NB-IoT UE [33]. Each symbol is fixed with value one and modulated on a 3.75 kHz tone with a variable tone frequency index for different symbol groups. [27]

3.4.5 4G Narrowband Downlink Physical Channels

The Narrowband Downlink Physical Channels correspond to sets of time-frequency resources that carry originated and oriented information from higher layers in eNB to NB-IoT UE. Narrowband Downlink Physical Channels in 4G are divided into [27]:

- Narrowband Physical Downlink Shared Channel (NPDSCH).
- Narrowband Physical Broadcast Channel (NPBCH).
- Narrowband Physical Downlink Control Channel (NPDCCH).

The importance of 4G Narrowband physical downlink channels is represented in data and control information that the channels carry from eNB to NB-IoT UE.

Narrowband Physical Downlink Shared Channel (NPDSCH)

This channel carries DL-SCH and PCH for NB-IoT UEs [33]. The supported modulation is QPSK [27].

Narrowband Physical Broadcast Channel (NPBCH)

This channel carries system information for NB-IoT UEs necessary for initiating cell access [33]. The supported modulation is QPSK [27].

Narrowband Physical Downlink Control Channel (NPDCCH)

This channel carries information about the allocation of the PCH resources and the DL-SCH to NB-IoT UE, the UL scheduling grant for NB-IoT UE, and the direct indication information [33]. The supported modulation is QPSK [27].

3.5 Multiple Input – Multiple Output in 4G (MIMO)

Multiple Input Multiple Output (MIMO) is a wireless communications technique that utilized simultaneous transmission and reception performed by several antennas on both transmitter and receiver sides, respectively. This technique exploits the phenomenon of multipath scattering between the receiver and the transmitter. Multiple Input Multiple Output technique is dividing serial data stream into parallel streams. Each of those streams is transmitted as a signal on a separated antenna. These streams are transmitted simultaneously by taking advantage of different propagation paths towards the receiver. Another advantage is presented on the receiver side, where the receiver is distinguishing and processing the streams eventually. [34]

The MIMO offers several advantages that can be obtained without increase the transmitting power or the utilized BW. The advantages can be summarized by increasing the data rate since more antennas are utilized, resulting in more simultaneous transmissions. The second advantage is increasing the reliability since the diversity technique is being used in transmission and/or reception; thus, a higher probability of delivering error-free packets is accomplished. Furthermore, more advantages still to come, like spatial signal orientation and isolation. In the spatial signal orientation and isolation, beams with the same frequency can be separated spatially (especially in high frequencies, mmWaves). The spatial allocation of beams increases the efficiency of using resources (frequency in this case).

On the other hand, there are also disadvantages, which can be summarized by, more complexity of UEs hardware because of the small size of UE in addition to the other existed antennas of Bluetooth, different bands of Wi-Fi, Near Field Communications (NFC), and Global Positioning System (GPS). Therefore, more required computational power and higher costs of MIMO systems. [34]

In 4G, the MIMO application is manifested by the several ports of the antenna. The different physical channels of UL and DL are distributed on different antenna ports after mapping them to the resource elements of the 4G frame. In the 4G UL case, the supported MIMO is 4×4, while in the DL case, the supported MIMO is 8×8 $(\text{The formula of MIMO order } = \#\text{transmitting antennas } \times \#\text{receiving antennas})$. [35]

3.6 Coding Rate and Modulation Order in 4G

Channels in wireless communications are unstable. This means the characteristics of channels vary continuously. The channel characteristics vary continuously because of the multiple sources of noise and interferences from neighbor cells and/or other UEs, Doppler effect and multipath propagation, et cetera. In addition to the power attenuation of the received signal at UE because of the path losses, the wireless channel's instability impacts the received signal's power and phase and distorts it. Eventually, at UE, the received signal power is significantly attenuated and distorted; thus, the received signal needs to be fixed first, decoded, and mapped back to bits to recover the transmitted information.

Fortunately, UEs in 4G wireless communications systems use the so-called Channel Quality Indicator (CQI). Channel Quality Indicator is defined as reported information from UE based on an observation interval in time and frequency domains. In general, the UE shall derive for each CQI value reported in UL, the highest CQI index, so that a received TB error probability does not exceed a given threshold. Transport Blocks are reserved RBs termed the CSI. Each RB is set with a combination of modulation schemes and TB block size corresponding to the CQI index. According to [3GPP] [36], PDSCH has ten transmission modes for each CSI reference resource.

The transmission modes differ in configurations of antenna ports number of UE, enabling or disabling the transmission diversity, in close loop special multiplexing with and without a single transmission layer, and other different configurations for activated and dormant serving cells cases and multi-user MIMO. The CQI index, in turn, specifies the modulation order and coding rate. The Channel Quality Indicator value is upgraded continuously to guarantee that the probability of error occurrence will not exceed the given threshold and maximize efficiency at the same time. [36]

3.7 Chapter Summary

Several general outlines can be extracted from this chapter:

- The Fourth Generation (4G) of wireless cellular technology has boosted data rates tremendously compared to the previous generations.
- New and more efficient multiple access technologies were used in 4G, like OFDMA, TDMA, and SC-FDMA.
- Several upgrades were performed on 4G, which have led to boost data throughput, reduce latency, and increase mobility.
- Multi-Input Multi-Output (MIMO) technology is boosted data rate and increase signal robustness against channel impacts
- Carrier Aggregation technology is an essential upgrade in 4G, contributing strongly to boost data rates.

Internet of Things (IoT) and Device-to-Device (D2D) communications are started with 4G networks technology. The Fourth Generation of wireless cellular technology has enabled wireless communications for industrial use cases and applications. Simultaneously, the complexity, deployment, operations, and maintenance costs have increased parallelly, with 4G wireless cellular networks' growing abilities.

4. THE BASICS OF 5G CELLULAR TECHNOLOGY

Fifth Generation (5G) of wireless cellular network technology officially, the first commercial launch of 5G services on smartphones in the world was in South Korea by operators (SK Telecom, Korea Telecom, and LG U+) in April 2019 [14]. The key feature of 5G is the newly utilized radio spectrum, which was divided into three ranges. Frequency Range 1 (FR1) is 410 MHz – 7 125 MHz [15], Frequency Range 2 (FR2) is 24.25 GHz – 52.6 GHz [15], and Frequency Range 3 (FR3), which was proposed in radio regulations for NR requirements beyond 52.6 GHz is 52.6 GHz – 116 GHz [16]. Based on the comparison between 4G and 5G, from the point of view of utilized frequencies and radio spectrum of each, 5G targets to provide 100 times higher data rate. Therefore, the UL peak data rate of 10 Gbps and DL peak data rate of 20 Gbps/user. Furthermore, 100 times higher density connected devices (per km^2), 1.5 higher mobility 500 km/h, and 1/30 to 1/50 times less latency. The latency in 4G is between 50 ms and 30 ms, and it will drop in 5G to 4 ms in eMBB and 1 ms in URLLC. The spectral efficiency will be three times more in 5G, and it will be 15 bps/Hz in UL and 30 bps/Hz in DL. The energy efficiency of the network will be 100 times. The area traffic capacity will increase ten times, and it will be 10 $Mbps/m^2$. The BW will be at least 1 GHz and a contiguous wideband spectrum up to 6 GHz. Programmability capabilities will be added to 5G wireless cellular networks like Network Function Virtualization (NFV) and Software Defined Network (SDN) [23,37].

The identified major classes of 5G use cases are as below:

Enhanced Mobile Broadband (eMBB)

This use case targets the communications that require high data rates and high traffic volumes [23,37].

Ultra-Reliable and Low Latency Communications (URLLC)

This use case targets very low latency, very high reliability, and communication availability [23,37].

massive Machine Type Communications (mMTC)

This use case targets a massive number of connected devices [23,37].

4.1 5G Use Cases

The newly supported and handled use cases by 5G are preparing the industry to be revolutionized and get more industrial advances. That revolutionization will be performed by utilizing and creating new concepts and complexity of the used applications by enabling rapid and more effective inspections through predictive intelligence and the mmWaves spectrum, which will rapidly boost data rate and capacity. On the other hand, the mmWaves spectrum will minimize the latency because of the unoccupied spectrum (BW availability). The 3rd Generation Partnership Project has provided some expected and possible use cases and applications in detailed descriptions, which will be reviewed as below [16].

4.1.1 High data rate eMBB

This use case will be utilized for delivering ultra-high-definition multimedia services, augmented and mixed reality. Furthermore, it will serve high user density areas by cellular networks to individuals and groups. The wide range of the 5G spectrum enables the possibility of utilizing the optimum frequency band/s for each use case scenario. The high frequencies, 52.6 GHz to 114.25 GHz, are interesting for this kind of use cases of high data rate demand because of the wide available spectrum. [16]

4.1.2 Mobile data offloading

The continuous increase of applications and connected devices and mobile communication technologies' rapid development cause rapid growth of data traffic loads. The matter of eMBB data traffic congestion becomes more problematic and crucial so that QoS level or network performance degrades increasingly, which needs a radical solution/s eventually. One of the solutions for this issue and use cases of 5G technology is mobile data offloading. The mobile data offloading solution is an option that network operators can utilize to offload data in hot spots from macrocells. Mobile data offloading can be done by dual connectivity with the high band or CA, with the low band techniques, where the coverage is not a priority in this scenario or use case. The frequencies above 52.6 GHz with more than 10 GHz of BW availability are interesting for this kind of use case. [16]

4.1.3 Short-range high data rate D2D communications

This use case mainly targets wireless docking in offices for varied applications of large screens projecting 8K Ultra High-Definition (UHD), AR/VR. The new D2D high-speed connection will enable new applications of smart home, office, and factory applications. The frequencies below and above 52.6 GHz are interesting for this kind of use case. [16]

4.1.4 Vertical distribution factory application

Vertical industry factory applications have different services. Different services need various end-to-end latency requirements, service availability, high data transmission, high reliability, safety, and security or privacy to be supported. There are diverse applications for this use case like motor control, mobile control, motor robot, AR, et cetera. The applications of this use case need a highly adaptable and scalable system/s. The frequencies above 30 GHz (mmWaves) are interesting for this kind of use case. [16]

4.1.5 Broadband distribution network

This use case serves public or non-public networks with a 200 m to 500 m range of wireless communications. In this range of wireless communications, a single node can provide a data rate peak of 20 Gbps for few fixed devices. In this case, point to multi-point transmission and high data rates of backhauling of wireless to distribution networks in both UL and DL should be supported. The frequencies above 52.6 GHz are interesting for this use case. [16]

4.1.6 Integrated Access Backhauls (IAB)

This use case is applied for backhauling deployment in case of the unavailability or inconveniently optical or dedicated wireless backhaul. The approximate expected range of gNB coverage in this use case is from 300 m to 500 m. The frequencies above 52.6 GHz are interesting for this use case. [16]

4.1.7 Factory automation/Industrial IoT (IIoT)

This use case targets indoor industrial automation applications, with wireless communications ranging from 50 m to 100 m and with mobility of less than 5 km/h. [16]

4.1.8 Augmented Reality / Virtual Reality headsets and other high-end wearables

Those applications require high data rates because of the high-resolution uncompressed videos and low transmission power to maintain the battery power consumption. The technique of preserving battery power consumption is essential to avoid the larger size of the battery, which will increase the size and the weight of the wearable. [16]

4.1.9 Intelligent Transport Systems (IT IS) and V2X

This use case supports transportation means to be safer, more efficient, and improving the efficiency and safety of using the transport infrastructure. The operation ranges of utilized frequencies in this use case are short, which will increase the reuse factor of frequency resources and increase the flexibility of wideband communications. The frequencies above 52.6 GHz are interesting for this use case. [16]

4.1.10 Data Center Inter-Rack Connectivity

It is known that fiber optic cables are in use in interface links between racks in data centers. Because of the extremely high bit rates that NR BWs (higher frequencies mean higher available BW). It became possible to use wireless connectivity as secondary interface links of racks in data centers, which will help in fiber optics' failure cases. Furthermore, some inter-rack links can be replaced with high BW and high reliable NR communications as main interface links (no fiber optic cable). This new use case will reduce the cabling complexity and allow flexible reorganizing of equipment in the facility. [16]

4.1.11 Smart grid automation

Since the path losses are directly proportional to the second power of propagation distance and the propagated wave frequency, short-distance wireless communications are more practical and beneficial to be performed by high frequencies (mmWaves). The NR spectrum is an impressive spectrum for this use case. [16]

4.1.12 Radar/Positioning

Automated factories are requiring positioning methods with high accuracy. The MmWaves can perform this kind of positioning method since mmWaves are offering higher accuracy of positioning. The mmWaves are sensitive against the blockage phenomenon. Therefore, using mmWaves in this kind of application, where the terminals connected are mobile, the assumption of signal blockage avoidance must be considered (e.g., automated robots require high accuracy positioning and fast responses in some factories). [16]

4.1.13 Private Networks

Enable deployment of easy and economical industrials private networks (semi-closed group access or closed group access). [16]

4.1.14 Critical medical communications

There are different requirements (latency, data rate, and reliability) of applications in this use case. The offered BWs by 5G NR above 52.6 GHz can meet the required Key Performance Indicators (KPIs) of those applications. [16]

4.2 5G technology challenges

The fifth generation of wireless cellular technology promises to take the concept of communications to a new level. The concept of wireless communication capabilities in 5G is unique compared to the traditional wireless communication technologies in the 4G era and before. An example of the new concepts that 5G will offer is mMTC. Massive Machine Type Communication requires very high capacity and spectrum availability to host the enormous number of devices with widely diverse connection requirements that 4G networks cannot meet. Therefore, several risen challenges must be handled and solved to enable this kind of capabilities and features in 5G [38].

4.2.1 Capacity

This challenge stems from the fact that the number of devices demanding connection to the gate node (including UEs, M2M, and IoT) is enormous compared to 4G. [38]

4.2.2 Data rates for individual devices, the whole cell, and the backhaul

This challenge stems from the fact that having an enormous number of connected devices to a single gate node will apply an enormous data rate demand on that gate. Furthermore, the individual data rate demand of the individual connected devices will increase enormously (DL peak data rate of 20 Gbps/user, UL peak data rate of 10 Gbps/user) compared to the data rates' demands of 4G. [23,38]

4.2.3 End to End Latency

Real-time remote control applications are targeted applications of 5G. Real-time remote control applications are requiring real-time responses. By considering that, 5G wireless cellular technology is more complicated than 4G wireless cellular technology. Furthermore, 5G applications require more data to be handled, processed, oriented, delivered efficiently and simultaneously by 5G network or the supportive networks out of 5G (e.g., internet or/and other network/s). That high data traffic will cause congestions (bottleneck problem) in some parts of the network. Therefore, the probability of error occurrence in the exchanged data will increase, thus more required time to fix errors (if that option is allowed), increasing latency. The reliability of connection in this kind of real-time control application is significantly important (e.g., remotely controlled robot to execute a surgery). Therefore, the reliability must be kept too high. [38]

4.2.4 The massive number of connections

Since the number of connected devices is massive (including humans, M2M, and IoT), the required number of initiated connections will be massive as well. The challenge here is to allocate the devices or terminals in the frequency, time, and spatial (by mMIMO) dimensions. Furthermore, every single instrument must be addressed, distinguished, and synchronized. [38]

4.2.5 Cost of 5G networks deployment, operation, and maintenance

Fifth Generation wireless cellular networks are much complicated than 4G from technology, deployment, and maintenance points of view. As the utilized frequencies in 5G are significantly high, the coverage ranges are considerably shorter. Furthermore, the transmission ranges of devices are much shorter because of the limited power resources of devices. Therefore, network deployment of 5G needs to be much denser to provide the required coverage. The approach of denser deployment of 5G will increase the cost and power consumption eventually. When the network deployment is denser, the probability of system failures partly or completely increases significantly. Therefore, it requires more maintenance services and thus more maintenance expenses. [38]

4.2.6 Quality of Experience (QoE)

According to [ITU-T Recommendations (P.10/G.100)], QoE can be defined as “the overall acceptance or rejection of user to an application or service”. The QoS in 5G can be represented in terms of network data throughput, capacity, and the end to end latency [39]. [38]

4.3 5G potential enablers and solutions

Several potential enablers will help to solve the previously reviewed challenges. Those enablers can be used separately and/or combined to solve one challenge or more [38].

4.3.1 Spectrum

By utilizing higher frequencies, more spectrum becomes available; thus, more channels in the frequency domain can be standardized and used. Therefore, increase the spectrum availability, which leads to initiate more wireless connections. Those advantages of the newly utilized spectrum offer solutions for the challenges of capacity, data rate, and the massive number of connections. [38]

4.3.2 MIMO with limited antenna elements and 3D-MIMO or FD-MIMO with massive antenna elements

With MIMO technology, it became possible to transmit and receive several streams simultaneously, as in 4G. In 5G, the case is advanced by using massive MIMO (mMIMO). In mMIMO, it became possible to form narrow beam patterns by shifting each signal on each antenna port differently in phase. As a result, constructive interference will occur in the desired transmitting angle or direction. Therefore, farther ranges of transmission are achieved. Simultaneously, destructive interferences will occur in the angular range where transmission is not desired (this process is called Beamforming or Spatial firing). One essential advantage of mMIMO is eliminating interference occurring with the neighbor transmissions since the mMIMO transmission pattern is mostly a narrow directive beam. [40]

By controlling the phase of each transmitted signal individually and continuously on each antenna port, it became possible to drive the formed beam spatially in 3D space (this process is called Beamsteering or Beam steering). Furthermore, it became possible to reform the transmitted beam in narrower angles, thus approach farther distances. Another possibility is to reform the transmitted beam in wider angles to cover closer transmission ranges but wider areas [40]. This technology improves the multiple access schemes. It became possible to separate users spatially and increase the frequency reuse factor by reducing the interference through beamforming and beam-steering techniques.

This improvement of multiple access schemes enhances the capacity and the utilization of frequency resources. Multiple Input Multiple Output and mMIMO increase the reliability of transmission by creating several transmitted beams of signal to deliver data parallelly at the same time. That approach increases the probability of delivering data in several paths to UE, which reduces the likelihood of errors occurring at UE since several copies of the same transmitted signal are received. Therefore, low latency is guaranteed. [38]

4.3.3 New air interface

Designing a new air interface for 5G has enabled a great variety of services, devices, and deployments. Developing a new air interface offers solutions for the challenges of capacity, data rate, latency, and a massive number of connections [38].

4.3.4 All optical networks

Fiber optic communications have many advantages, like higher BW, higher throughput, longer transmission distances, flexibility, and security. Furthermore, the tiny diameter of fibers has enabled the packing of many fibers beside each other. Therefore, reducing the occupied space by fiber optic cables. Those features made the fiber optic cables a promising candidate to play a role in 5G networks enabling.

Optical transceivers can offer high capacity communications that will meet the explosive increase in data traffic demand (because of the data orientation and concentration that will be forwarded from gNBs towards 5GC, and the other parts of the network vice versa). Those features of optical networks offer solutions for the challenges of capacity, data rate, and latency. [38,41]

4.3.5 Small cells

Generally, there are several advantages of smaller cellular cells [42]:

- The maximizing of capacity, because the frequency reuse-factor increases, thus hosting more users per cell.
- The minimizing of transmission power, because of the smaller area of cells and smaller ranges of transmission.
- The minimizing of interference, because of the lower transmission power. Therefore, the interference will occur locally.
- The increase of the wireless cellular system's performance robustness

There are other advantages of small cells when it comes to utilizing higher frequencies in 5G. Small cells provide wide local and close coverage for UEs and machines that are operating on higher frequencies. Therefore, the base station must be capable of operating with short communications ranges [42]. Small cells' advantages are offering solutions for the challenges of capacity and data rate [38].

4.3.6 Local offload

Device-to-Device communications term refers to the technology where devices can communicate directly instead of requiring access point/s or base station/s (generally network infrastructure) involvement. Device-to-Device communication is offloading the data transfer load from the access points and core networks to the devices. This kind of communication requires short distances between/among devices. There are several advantages of D2D communications includes the ultra-low latency because of the less involved network component or parts and the shorter Round Trip Time (RTT) of the signal. Furthermore, more reliability because of the less complexity of data transporting algorithms, less time of error fixing, and finally, the flexibility of boosting data rates. In this kind of communication technology, it is not necessary to have network infrastructure. [43]

Those advantages offer solutions for challenges of capacity, data rate, latency, the massive number of connections, and cost [38].

4.3.7 Caching / Prefetching / Content Delivery Network (CDN)

Caching and prefetching techniques mean allocating more computational centers and content storage units at the network edge and bringing communicating endpoints (UEs, connected devices, et cetera) closer. Those techniques will make base stations smarter, thus performing some processes and decisions locally without moving them to CN or farther. One utilization example of this technology, in critical latency requirements of MTC services, the related processing units of control plane protocols may be reallocated at the network edge. [38,44,45,46]

Content Delivery Network (CDN) is a mechanism that aims to allocate the content close to the end-user by deploying cache servers at the network edge. Usually, the video contents (high resolution) are distributed close to the end-user. Downloading videos apply massive data traffic to the network data algorithms, which causes congestions and a bottleneck problem. Furthermore, the longer required time of downloading content because of the algorithm length in the network/s between the end-user and the cloud, instead of the local caching servers (closer to the end-user). Allocating caching servers closer to the end-user will offload unnecessary traffic from several parts of the network. Furthermore, it will increase the throughput since the involved network nodes between the cloud and end-user are reduced and reduce the latency. [46]

The advantages of those techniques are offering solutions for challenges of latency and QoS [38].

4.3.8 Control Plane and User Plane split

The separation between control and user plane will enable flexible scaling of resources based on connection requirements of BW and latency and independent deployment of each plane based on connection requirements as well. This plane separation will allow an independent dynamic allocating of functions and decision-making, closer or farther from the user based on needs (an example of control plane allocating in Caching / Prefetching / CDN section). Those features are offering solutions for the challenges of capacity, data rate, and cost. [38,46]

4.3.9 Network Functions Virtualization and Software Defined Networking Cloud (NFV/SDN)

Network Function Virtualization (NFV) is a new designing approach to implement the required functions as software applications on virtual machines, instead of deploying dedicated and customized discrete programmed hardware to implement specific functions [47].

Software-Defined Networking (SDN) is a new design of architecture that enables dynamic reconfiguration of the network. The network's dynamic reconfiguration is done by implementing a software management-based virtual network to provide separated control and data planes. The control planes are centrally administered by the network (global decisions across small cells). Software-Defined Network approach of separating between control and user plane will minimize the hardware of the network and flexibility-centrality of control planes management [45,48,49]. The newly considered features offer solutions for the challenges of the massive number of connections and costs [38].

4.3.10 Third-party and user deployment scenarios

The 5G network trend enables third parties to provide different services by an entry point in the 5G network called Network Exposure Function (NEF). Network Exposure Function authorizes third parties to access and offer various services to 5G networks like, Multiple access Edge Computing (MEC). Therefore, the user can access resources that have been supplied from out of 5G networks, like cloud computing services and edge computing services. [50]

Deployment scenarios revolve around 5G wireless cellular networks' deployment strategy for use cases of eMBB, mMTC, URLLC, UE-based service requirements, and the utilized frequencies, BW gNB/UE antenna elements, and gNB/UE transmission power, et cetera. Several deployment scenarios have been proposed based on the previous factors. Furthermore, there are future studies related to the proposed deployment scenarios [51,52]:

- Indoor hotspot: Small coverage area per site.
- Dense Urban: Macro cells with micro cells and high user densities and high traffic loads in city centers and dense Urban areas.

- Rural: Larger and continuous coverage.
- Urban macro: Large cells and continuous coverage.
- High speed: Continuous coverage along the track in high-speed trains.
- Extreme long-distance coverage in low-density areas: Very wide or large areas with a low density of users.
- Urban coverage for massive connection: Large cells and continuous coverage to provide massive Machine Type Communications.
- Highway Scenario: High speeds vehicles on highways.
- Urban grid for connected car: Highly dense deployed vehicles in Urban area.
- Commercial Air to Ground scenario: UE and machines allocated on commercial aircraft to initiate and receive mobile services.
- Light aircraft scenario: UE and machines allocated on helicopters and air plans to initiate and receive mobile services.
- Satellite extension Terrestrial: Provides services to those areas where the terrestrial service is not available and provides services that are more efficiently supported by satellite systems than terrestrial systems.

The third partner and deployment scenarios enablers offer solutions for capacity and cost challenges [38].

4.3.11 Simple access points

The sample access point is a new concept of deploying access points or radio access nodes to maintain the traffic load and connectivity of 5G networks. The simple access points can be represented by temporally constructed fixed access points based on the demands of coverage or traffic loads, or mobile access points. In advanced cases, the access points can be placed dynamically in real-time (Unnamed Arial Vehicles (UAV)). UAVs' dynamic placement will offer a dynamic and adaptive coverage to meet the network's real-time requirements in a specific spot. This way, simple access points will give a new concept of network architectures or deployment (dynamic deployment of architecture). [53,54]

This new concept of the network will offer a temporal service in the desired area/s and high network reconfiguration flexibility. Thus, it will help to have a higher chance of Line of Sight (LoS) propagation, especially in high-frequency bands. [53,54]

This enabler is offering a solution for cost challenges [38].

4.3.12 Energy Efficient Hardware and energy management techniques

There are several studied schemes of power-saving that can be utilized in UE of 5G networks based on the fact that the power resources and hardware capabilities of UE are limited. In the first power-saving scheme, several parameters can be adapted based on UE data traffic demands to save the power of UE. Those parameters can be listed as below [55]:

- The signal strength and relevant factors.
- The utilized frequency.
- The duration of connection and micro sleep periods in slot/s level.
- The order of utilized MIMO during transmission.
- The periodicity or intensity of monitoring and decoding of PDCCH.
- Discontinuous reception power (DRX) saving scheme.
- UE assistance information.

The DRX power saving scheme is a technology that allows UE to turn the receiver on only when there is DL data arrival and turn the receiver off (use sleep signaling) for the rest of the time. UE assistance information power-saving scheme depends on UE to aid information related to UE adaptions to the network. There are other power-saving schemes related to signal/channel/procedure for triggering UE power consumption adaptation and higher layers-related UE power-saving procedures. [55]

Those different power-saving techniques offer solutions for the challenges of a massive number of communications and costs [38].

4.3.13 Self-Organized Network (SON)

Self-Organized Networks (SON) was first introduced in wireless networks in Release 8 [56]. Self-Organized Networks is a new solution represented by sets of new automation techniques, aiming to make networks automated by enabling automatic network configuration, optimization, self-healed, and self-protected [57,58]. Those new techniques are offering solutions for the challenges of cost and QoS [38].

4.3.14 Traffic management

Traffic Management Solution (TMS) contains several parts that must function and perfume simultaneously to enhance and manage the traffic in 5G networks. NEC Corporation announced on the 1st of August 2018, in Tokyo, the launch of an improved TMS for 5G. This solution aims to improve the data throughput of networks that support data transfer rates of more than 5 Gbps, increasing the QoE for end-users. Furthermore, this solution aims to enhance network operations efficiency for communications service providers by controlling the communications traffic sophisticatedly. [59]

The features of TMS are offering solutions for the challenges of cost and QoE [38].

4.3.15 Big data driven network intelligence

The number of connected devices to 5G networks will be enormous compared to the 4G network. That additional number of connected devices in 5G network is because of Machine Type Communications (MTC) (automated machines, sensors, monitors et cetera), human to machine type communications (remotely controlled robot), and finally, IoT, which will add more connected devices. [60, 61]

These connected devices will increase enormously the amount of exchanged data that needs to be conveyed and processed. Because of 4 G's inability of technologies and software tools to meet the computational and other different requirements of 5G, there was a need to find new solutions to overcome this inability. Machine learning and Artificial Intelligence (AI) techniques promise to play a big role in solving the different challenges through big data analytic. Big data analytic predicts the variation of the needed resources in different system locations versus time and predicts the network's behavior. [60,61]

Those new technologies are offering solutions for the challenges of cost and QoE [38]. Several approved technologies have been used in previous generations of wireless cellular networks. Those technologies will be reused in 5G and newly proposed technologies to support 5G requirements. Multiple access schemes technique is one of those techniques. There are new multiple access schemes that have been proposed newly to be utilized in 5G, in addition to multiple access schemes of OFDMA, TDMA, and SC-FDMA that are already in use in 4G. The proposed access schemes in 5G are Non-Orthogonal Multiple Access (NOMA) schemes, Fired Orthogonal Frequency Division Multiple Access (FOFDMA), Sparse Code Multiple Access (SCMA), Generalized Frequency Division Multiple Access (GFDMA) [38], and power domain Non-Orthogonal Multiple Access [58]. Furthermore, scrambling-based and spreading-based NOMA schemes [58].

Orthogonal Frequency Division Multiple Access in 5G is the same access scheme that is in use in 4G. The only difference is in Δf available bandwidths (will be explained in the frame structure section of 5G). Dynamic-Time Division Multiple Access scheme (D-TDMA) is similar to the TDMA scheme used in 4G. [58]

The difference between D-TDMA and TDMA is that D-TDMA is “Dynamic” now because of the ability of time duration varying of the frame based on bit rate and traffic demand (will be explained in the frame structure section of 5G). Another access scheme in 5G is SC-FDMA. Non-Orthogonal Multiple Access-based schemes are proposed in 5G. The NOMA schemes have different basics than OMA schemes that are in use in 4G. Non Orthogonal Multiple Access schemes allow interference among UEs so that UEs can utilize the same frequency simultaneously to access the base station. Therefore, users can overlap in frequency and time domains practically. However, they can be separated by their different power levels (power domain localization) or different signatures (codes) at the base station. The base station can separate users by successive interference cancelation and superposition coding beforehand. [58]

Other improvements have been approved in the physical layer of the 5G network to improve the capacity. The higher order of modulation schemes is one of those improvements, and the modulation orders that are already in use, π/2-BPSK, BPSK, QPSK, 16QAM, 64QAM, and 256QAM modulation scheme [62].

Based on the previous overview, 5G is unique compared to the earlier generations, more capable air interface technology, and promises much more capabilities, features, and new use cases. Briefly, it is not an upgraded or an enhanced generation. Therefore, to have this kind of entirely new advanced functional system, some compulsory considered and performed stages of preparation must be done beforehand. Fifth Generation Non-Standalone operation mode is the primer operation mode, before 5G SA, representing the fully standardized operation mode of 5G.

4.4 5G NSA versus 5G SA network concepts overview

The fifth Generation Non-Standalone operation mode is described in 3GPP Release 15 [20]. As shown in figure 5, 5G NSA is a 4G CN-based 5G cellular network implementation. In 5G NSA operations mode, the connected base stations to 4G CN are eNB (node provides control plane to UE and acts as Master Node (MN)), and en-gNB (node provides NR user plane to UE and acts as Secondary Node (SN)) [20].

It is essential to notice that en-gNB is added as an upgrade to E-UTRAN to operate together with eNB. From the radio protocol architecture point of view, MN handles control plane connection towards EPC, while SN regulates data plane connection towards EPC, this is the so-called EN-DC [63]. User Equipment is connected to eNB and en-gNB simultaneously, where each of eNB and en-gNB has it is own Radio Resources Entity (RRE) and RRC. Regarding Control Plane management, Protocol Data Units (PDUs) are generated by SN typically and sent to UE by MN. [63]

On the User Plane management side, the scenario is a little more complicated. There are three existed types of bearers, Master Cell Group (MSG), Secondary Cell Groups (SCG), and split bearer. Regardless of the configuration of EN-DC, the network can configure in either option. The E-UTRA Packet Data Convergence Protocol (E-UTRA PDCP) or NR PDCP for MCG bearers in MN termination, while the NR PDCP option is considered for other bearers in both MN and SN. The MN sends MCG bearers to UE, and SN sends SCG bearers to UE, while both MN and SN send split bearers to UE. In this brief manner, the User Plane is managed [63]

The fifth Generation Standalone operation mode is described in 3GPP Release 15. From figure 6, 5G SA operation mode is implemented as a full 5G network deployment without any involvement of 4G parts. The NGRAN is represented by gNB only, where gNB is connected to 5GC in 5G SA mode. Thus, 5G SA is an entirely dependent architecture and deployment from 4G. [20]

The gNB will be responsible for both control and user plane management in 5G SA. Therefore, gNB would provide NR control plane protocol terminations towards UE by NG-RAT interface and through NG interface to Access and Mobility Management Function (AMF) logical entity where the control plane is handled in 5GC. In the same way, user plane data is conveyed by NG-RAT interface from UE to gNB, then through NG interface to User Plane Function (UPF) logical entity in 5GC. User Plane Function logical entity is interfaced logically to the data network (internet), where the data is forwarded eventually [20, 63].

4.5 5G Frame Structure

One of the essential changes in the 5G frame structure compared to the 4G frame structure is the 5G frame structure. The frame structure in 5G is flexible. In other words, there are more different options of Δf bandwidths, thus more variant options of channel BWs in 5G in comparison with 4G. For FR1 (410 MHz – 7 125 MHz) the supported channel BWs are (5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, and 100) MHz. For FR2 (24.25 – 52.6) GHz, the supported channels are (50, 100, 200, and 400) MHz. Numerology term (μ) is an indication of Δf BW, where μ is varying from 0 to 4, thus the available options of $\Delta f = 2\mu.15$ kHz. [20]

It is important to know that the latency is getting reduced as higher Δf is utilized, thus the required time per slot T_{slot} is shortened. Table 5 below shows detailed information about frame structure options.

Table 5. *Numerology of Δf with frame related parameters in 5G. [20]*

μ	SC BW or $\Delta f = 2\mu \cdot 15$	PR size $= 12\,(SC) \cdot \Delta f$	T_{slot}	CP	#symbols per slot	#slots per one radio frame	#slots per sub-frame
	kHz	kHz	ms				
0	15	180	1	Normal	14	10	1
1	30	360	0.5	Normal	14	20	2
2	60	720	0.25	Normal, Extended	12 or 14	40	4
3	120	1440	0.125	Normal	14	80	8
4	240	2880	0.0625	Normal	14	160	16

One of the significant advantages of the 5G design is that the same frame structure is used in TDD and FDD operations. Furthermore, each OFDM symbol in the TDD frame slot can be classified as UL, DL, or flexible (either DL or UL). Therefore, all symbols in the slot can be configured DL, UL, or mixed. Thus, three allowed flexible traffic adaptation options, Static, Semi-static, or Dynamic, as part of the scheduling decision. Transmissions are performed with one slot or more usually.

In 5G, transmission can be done in slot fraction/s (one or two symbols) for specific use cases, like URLLC services. In 5G, one radio frame's time duration is 10 ms, one radio frame contains ten subframes, and lastly, one subframe’s time duration is 1 ms. Up to this point, the time duration of frame and subframe is the same as 4G. The 5G frame structure differences start in the total number of slots contained in one subframe. The total number of slots included in one subframe varies according to the considered Δf, as shown in figure 12. The total number of slots starts with 1 per subframe at $\Delta f = 15$ kHz and ends with 16 subframes per subframe at $\Delta f = 240$ kHz.

The number of OFDM symbols contained in a single slot is fixed $\frac{14 \text{ OFDM symbols}}{1 \text{ slot}}$, except at $\Delta f = 60$ kHz, there are either $\frac{12 \text{ OFDM symbols}}{1 \text{ slot}}$ or $\frac{14 \text{ OFDM symbols}}{1 \text{ slot}}$ Depending on CP type. There are two CPs options, as it is shown in Table 5. The first type is normal CP (in case of using beamforming antenna), the second type is extended CP (in case of using wide beam antenna). Furthermore, there are two types of slots. The first type is the normal slot, which consists of $\frac{14 \text{ OFDM symbols}}{1 \text{ slot}}$ (slot based scheduling), where one possible scheduling unit is allowed. The second type is the mini-slot, which consists of 2, 4, or 7 OFDM symbols. [20, 62,64]

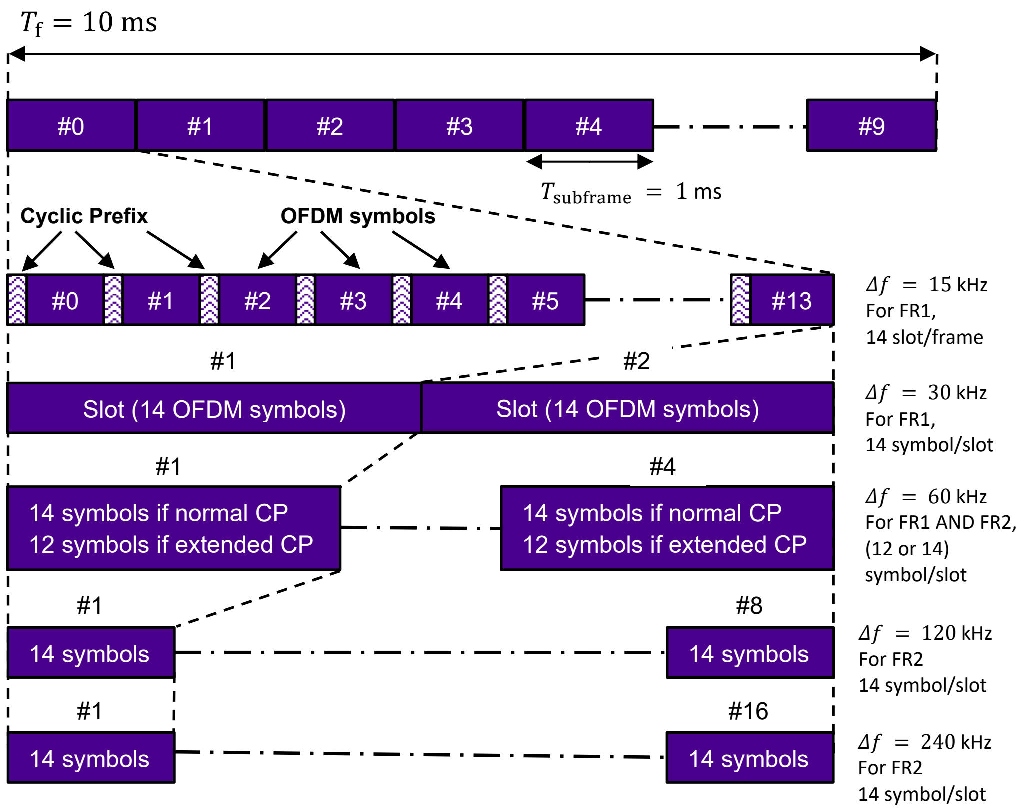

Figure 12. *5G Frame structure, redrawn based on 3GPP Release 15. [20]*

4.6 5G Frame Configurations

Fifth Generation frame configuration can be done at several levels. Numerology (μ) is the first level, where μ varies from 0 to 4. Each μ has corresponding Δf, CP (normal or extended CP), OFDM symbol duration, slot length, and channels. Regarding Δf, Table 5 shows the corresponding Δf options of μ.

As μ increases, the number of slots contained in one subframe, while T_{slot} decreases. Table 5 shows the corresponding number of OFDMA symbols/slot, number of slots/subframe, and T_{slot} options of μ. The same previous concept is applied in T_{slot} and CP duration.

The second level of configuration is the slot format. Slot formatting indicates and tells how each OFDM symbol in a single slot can be configured and used. Orthogonal Frequency Division Multiplexing symbol may be used for UL or DL. In 5G, the symbols within one slot can be configured in different ways:

- There is no need to use every symbol of a slot (a similar concept to LAA's concept, more details in 4G frame structure and frame configuration type 3).
- One slot can be divided into several segments, where each segment contains several consecutive symbols that can be utilized for UL, DL, or flexibly.

In one slot, there are 14 OFDM symbols (in the case of normal CP). Each OFDM symbol can be configured individually in three different ways. Mathematically, there are $14^3 = 2744$ possible different configurations or combinations of symbols for every single slot. The 3rd Generation Partnership Project standardized only a group of them. Table 12 in Appendix A shows the different slot formats that [3GPP] had standardized. [65]

As shown in Table 12 in Appendix A, slot formats 0, 1, and 2, there are heavy transmissions with DL, UL, and F symbols, respectively. Furthermore, there are different sharing percentages among DL, UL, and F symbols in the other slot formats. The 5G scheduling will be flexible so that the most suitable schedule type/s is/are picked based on need or communication requirements. The 5G flexible schedule feature is because of having a wide range of various slot formats and a possibility of using one slot format or combining several slot formats in a row. [66]

4.7 Physical Resources of 5G

Defined as in subchapter 3.3 with the following editions:

- Replace "eNB" with "gNB".
- Replace "4G" with "5G".

4.7.1 Antenna port

According to [3GPP], the antenna port is defined as follows "An antenna port is defined in which the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed". [62]

4.7.2 Resource Element

According to [3GPP], the RE is “Each element in the resource grid for antenna port (p) and Δf configuration μ” [62].

4.7.3 Resource Blocks

Generally, RB can be defined as 12 consecutive SCs. [62]

4.7.4 Resource grid

The resource grid is an entity defined by two dimensions. The first dimension is the time domain, where one resource grid's time duration is equal to the time duration of one subframe (1 ms), or in terms of OFDM symbols, it equals 14.2μ OFDM symbols, ($\mu = \{0:4\}$). The second dimension is frequency domain, where the bandwidth of one resource grid is equal to the carrier BW, or the index in the frequency domain in kHz (15,30,60 120 and 240 for $\mu = \{0:4\}$) respectively. [62]

4.7.5 Bandwidth Part

The bandwidth part is a set of adjacent physical RBs on a given carrier. Physical RBs are selected from an adjoining subset of common RBs for a given numerology μ. Each defined BW part of corresponding μ can have three different parameters, Δf, CP length, and T_{slot}. Table 6 below shows the minimum and maximum corresponding frequency bands for minimum and maximum allowed numbers of RBs for each Δf in UL and DL. [62]

Table 6. *Minimum and maximum corresponding frequency bands for minimum and maximum allowed numbers of RBs for each Δf in UL and DL based on [62].*

μ	Minimum #RBs	Maximum #RBs	Δf	#SCs in one RB	Minimum BW	Maximum BW
			kHz		MHz	MHz
0	24	275	15	12	4.32	49.5
1	24	275	30	12	8.64	99
2	24	275	60	12	17.28	198
3	24	275	120	12	34.56	396
4	24	138	240	12	69.12	397.44

4.7.6 Carrier Aggregation (CA)

Carrier Aggregation refers to multiple carriers' concatenation, which eventually leads to increase BW and data rate. The fifth Generation supports CA of 16 contagious and non-contiguous carrier components, aggregating up to 1 GHz of spectrum BW. [65]

4.7.7 Guard Period (GP)

In the SL case, GP is an OFDM symbol that immediately should follow the last used symbol for Physical Sidelink Shared Channel (PSSCH), Physical Sidelink Feedback Channel (PSFCH), or Sidelink-Synchronization Signal Block (S-SSB).

4.8 Physical Channels of 5G

Physical Channels of 5G are defined as in subchapter 3.4. The services and functionalities of the 5G physical layer are the same as 4G. [81]

In the MAC layer, there are some differences. The differences are shown below [67]:

- Logical channels mapping to transport channels vice versa.
- Multiplexing of MAC SDUs from one or different logical channels onto TB to be delivered to the physical layer on transport channels.
- Demultiplexing of MAC SDUs to one or different logical channels from TB delivered from the physical layer on transport channels.
- The scheduling of information reporting.
- Error correction through HARQ.
- Logical channel prioritization.
- Priority handling between overlapping resources of one UE.
- Radio resource selection.

The RLC layer functions in 5G are the same as the RLC layer in 4G [82], while there are some differences in the PDCP layer as shown below [83]:

- Transfer of data (user plane or control plane).
- Maintenance of PDCP SNs.
- The compressing and decompressing of headers using the ROHC protocol.
- Header compression and decompression using the EHC protocol.
- Ciphering and deciphering.
- Integrity protection and integrity verification.
- Timer-based SDU discard.
- For split bearers and DAPS bearers, routing.
- Duplication.
- Reordering and in-order delivery.
- Out-of-order delivery.
- Duplicate discarding.

Additional following editions:

- Remove “Narrowband IoT Uplink” and “Downlink Physical Channels”.
- Replace “4G ” with “5G ”.
- Replace “eNB” with “gNB”.
- Add “[62]” instead of “[27]”.
- Add “[67]”

4.8.1 5G Uplink Physical Channels

Defined as in subchapter 3.4.1 with the following editions:

- Add “5G” instead of “4G”.
- Add “en-gNB for user information, and eNB for control information (in NSA operation mode) and gNB, both of user and control information (in SA operation mode)” instead of “eNB”.
- Remove “Uplink physical control channels (Short Physical Uplink Channel (SPUCCH)”.
- Add “[62]” instead of “[27]”.

User equipment's frame structure and physical resources that will be used in UL transmissions are defined in subchapter 4.5 and subchapter 4.7, respectively.

Physical Uplink Shared Channel (PUSCH)

This channel carries control information and user application data in a multiplexed manner. The supported modulation schemes for this channel are QPSK, 16QAM, 64QAM, and 256QAM. [62]

Physical Uplink Control Channel (PUCCH)

This channel carries Uplink Control Information (UCI) [67]. Uplink Control Information includes [67]:

- HARQ-ACK as feedback to DL data transmission.
- CSI report for link adaptation and DL data scheduling.
- SR to request resources for UL data transmission.

Physical Uplink Control Channel (PUCCH) has five different formats, 0 to 4. The difference among the five different formats is the number of OFDM symbols. The number of OFDM symbols in PUCCH formats 0 and 2 is 1 - 2 OFDM symbols, while it is 4 - 14 OFDM symbols for the rest of PUCCH formats [64]. The supported modulation schemes for this channel are π/2–BPSK, BPSK, and QPSK, depending on the PUCCH format and number of information bits [20, 62].

Physical Random Access Channel (PRACH)

This channel transmits a random access preamble from UE to indicate a random access attempt to gNB and help gNB adjust UE UL timing [67]. The supported modulation scheme for this channel is N/A [20].

Note: Some details of NR Uplink Physical Channels are missing because of 5G standardization process is still ongoing, and Release 17 is still in progress. According to [3GPP], NR Sidelink enhancement and NR Sidelink relay have been prioritized in December 2019 TSG meetings to be included in Release 17.

4.8.2 5G Downlink Physical Channels

Defined as in subchapter 3.4.2 with the following editions:

- Add “5G” instead of “4G”.
- Add “en-gNB for user information” and “eNB for control information” (in NSA operation mode)
- Add “gNB” both of user and control information (for SA operation mode)” instead of “eNB”.
- Remove “Physical Multicast Channel (PMCH)”, “Physical Control Format Indicator Channel (PCFICH)”, “Physical Hybrid ARQ Indicator Channel (PHICH)”, “Enhanced Physical Downlink Control Channel (EPDCCH)”, “MTC Physical Downlink Control Channel (MPDCCH)”, “Short Physical Downlink Control Channel (SPDCCH)” and “Relay physical downlink control channel (R-PDCCH)”.
- Add “[62]” instead of “[33]”.

User Equipment's frame structures and physical resources that will be used in UL transmission are defined in subchapter 4.5 and subchapter 4.7, respectively.

Physical Downlink Shared Channel (PDSCH)

This channel transmits DL user data, specific higher layer information, paging information, and system information [20,67,68]. This channel's supported modulation schemes are QPSK, 16QAM, 64QAM, and 256QAM [62].

Physical Downlink Control Channel (PDCCH)

This channel carries DCI, and it plays a central role in DL scheduling assignments, UL scheduling grants, slot format indication, preemption indication, and power control [20,62,67,68]. The supported modulation scheme for this channel is QPSK [62].

Physical Broadcast Channel (PBCH)

This channel carries the minimum required system information for access initiating, like System Frame Number (SFN), initial configuration for PDCCH, PDSCH, and Demodulation Reference Signal (DM-RS). It also carries information required to determine the frame timing SS/PBCH block index and half-frame index. [20]

The supported modulation scheme for this channel is QPSK [62].

4.8.3 5G Physical Sidelink Channels

Defined as in subchapter 3.4.3 with the following editions:

- Add “5G instead of “4G.
- Add “Physical Sidelink Discovery Channel (PSDCH)” by “Physical Sidelink Feedback Channel (PSFCH)”
- Add “[62,64]” instead of “[27]”.
- This channel supports direct communication between UEs [64].

The frame structure and Physical Resources which will be considered and used by UE to receive DL transmission are defined in subchapter 4.5 and subchapter 4.7, respectively.

Physical Sidelink Shared Channel (PSSCH)

Physical Sidelink Shared Channel (PSSCH) carries the TBs of data and control information for HARQ and CSI feedback triggers, et cetera. Five or more OFDM symbols are used for PSSCH transmissions. [64]

This channel's supported modulation schemes are QPSK, 16QAM, 64QAM, and 256QAM [62].

Physical Sidelink Control Channel (PSCCH)

Physical Sidelink Control Channel (PSCCH) indicates resource and other transmission parameters by UE for PSSCH [64].

The supported modulation scheme for this channel is QPSK [62].

Physical Sidelink Broadcast Channel (PSBCH)

This channel carries system and synchronization-related information from UE. The supported modulation scheme for this channel is QPSK [62].

Physical Sidelink Feedback Channel (PSFCH)

This channel carries HARQ feedback from UE. The sequence of PSFCH is transmitted by using one Physical Resource Block (PRB). The sequence of PSFCH is repeated over two OFDM symbols by the end of the sidelink resource in a slot [64]. The supported modulation for this channel is N/A.

Note: Some details of 5G Sidelink Physical Channels are missing because of 5G standardization process is still ongoing, and Release 17 is still in progress. According to [3GPP], NR SL enhancement and NR SL relay have been prioritized in December 2019 TSG meetings to be included in Release 17.

4.9 Limited Multiple Input – Multiple Output and 3D massive MIMO in 5G

Given that 5G technology utilizes high frequencies, increasing capacity, increasing data rate, improving coverage, and having massive connectivity or a massive number of connections [38]. Limited MIMO and 3D massive MIMO are essential enablers to overcome the accompanying challenges of the previous sorted improvements and new features of 5G technology. According to [3GPP], the NR MIMO has been prioritized in December 2019 TSG meetings to be included in Release 17.

4.10 Coding rate and Modulation Order in 5G

Explained as in subchapter 3.6 with the following editions:

- Add “5G” instead of “4G”.
- Add “[68]” instead of “[36]”.

4.11 Chapter summary

Several general outlines can be extracted from this chapter:

- The new features, abilities, and use cases will be enabled by 5G.
- The different challenges of 5G technology and potential enablers and solutions.
- The new, used technologies in addition to some of the reused technologies from the previous generations of wireless cellular technologies.
- The new design of frame structures and configurations.
- The two concepts of NSA and SA of 5G cellular networks.

- In 5G NSA operation mode, there will not be a large enhancement in latency in comparison with 4G because both 4G and 5G NSA are operating with CN or EPC. Instead, the improvement in latency will be because of the new features, new used frame structures and configurations of 5G's, and processing capabilities of en-gNB in comparison with eNB in 4G. in other words, the latency enhancement is basically because of en-gNB capabilities versus eNB.
- In 5G NSA operation mode, there will be an enhancement in data throughput because of the utilization of higher frequencies, wider bandwidths, higher MIMO orders, higher modulation scheme orders, and higher CA orders, et cetera, in en-gNB in comparison to eNB.
  Since 4G and 5G NSA are using the same CN, the throughput enhancement will be basically because of the en-gNB capabilities compared with eNB.
- The control plane in 5G NSA on (UE ↔ eNB ↔ MME and backward) is maintained at a frequent signaling pace. The route of user plane connection in 5G NSA is (UE ↔ en-gNB ↔ S-GW).
- There will be a large enhancement in latency in the 5G SA operation mode side compared to 4G and 5G NSA on the other side. That enhancement is because of the different CN in 5G SA operation mode where 5GC will operate, versus EPC in both 4G and 5G NSA.
- In 5G NA operation mode, there will be a considerable enhancement in data throughput because of the higher utilized frequencies, wider bandwidths, higher MIMO orders, higher modulation orders, and higher CA orders, et cetera. As well as, the 5GC on the 5G side in comparison with eNB and UE, plus EPC on the 4G side.
- The control plane in 5G SA on (UE ↔ gNB ↔ AMF) is maintained at a frequent signaling pace. The route of user plane connection in 5G SA is (UE ↔ gNB ↔ UPF).

As a result, the developments and additions in 5G lead to enhanced performance (higher data rates, lower latency, and better utilization of resources, et cetera) and add new services and use cases compared with 4G. In 5G, the supported services are taken to an advanced level (real-time applications, virtual reality applications, remote-controlled, and automated machines). As well, higher data rates are supported. The peak data rate will be up to 20 Gbps in 5G.

In a parallel path to that improvement and performance enhancement, the complexity of wireless cellular communications technologies and the accompanying challenges of new technologies are increasing, as shown in subchapter 4.2. Those challenges require more technology inventions to enable solutions for the present and future challenges. Some of those enablers and solutions are demonstrated in subchapter 4.3.

5. MOTIVATIONS OF MOVING FROM 4G TO 5G

Based on [3GPP TS 36.300, EUTRA and EUTRAN, Overall Description] [33], and [3GPP TS 38.300, NR and NG-RAN, Overall Description] [64], from a comparative perspective between 4G and 5G, the differences can be categorized in several headlines:

- The architecture differences and the composed entities naming.
- Features differences.
- Use cases and network abilities.
- The utilized spectrum for each technology.

The added en-gNB represents the architecture differences between 4G and 5G NSA to the E-UTRAN part of the cellular network. The en-gNB is interconnected with eNB and EPC by new interfaces. Eventually, E-UTRAN is ended up with eNB and en-gNB, which led to the so-called DC feature or “Architecture Option 3” in 5G. In 5G NSA, the DC enables UE to connect EPC via two links. The first link is with eNB (acts as a MN, which provides signaling and represents an anchor point for connected mode mobility). The second link is with en-gNB (acts as a SN, which boosts the capacity and increases data rates). From the CN point of view, both 4G and 5G NSA operate on (EPC), the differences are miners, they are represented by the applied upgrades on 4G CN to enable 5G NSA operation mode. The differences are reviewed in chapter 6.

On the other hand, from 4G versus 5G SA differences between E-UTRAN and NGRAN perspective, NGRAN contains gNB, with new interfaces, names, and functionalities, as an alternative node to eNB in E-UTRAN. Another perspective of comparison between 4G and 5G SA is the Core Network part. The 5G SA has a different core network, 5GC. The 5GC represents an alternative CN, with new entities, interfaces, names, configurations, and functionalities in 5G to EPC in 4G. One very noticed difference between 4G and 5G SA is the data flow path towards the IP Data Network. In 4G, data takes a longer path (UE ↔ eNB ↔ S-GW ↔ P-GW ↔ IP Data Network), while in 5G SA the data takes a shorter path (UE ↔ gNB ↔ UPF ↔ IP Data Network). It is important to notice that the network's complexity level increases as moving from 4G towards 5G NSA and 5G SA.

The differences in features between 4G and 5G NSA are limited to the radio access part majorly (capacity boosting and data rates increasing). On the other hand, from features differences of 4G versus 5G SA perspective, the abilities of 4G are limited to meet the high requirements of the new use cases that 5G should meet (the different use cases and their descriptions and discussions are demonstrated in chapter 4). The 5G offers the ability to meet Key Performance Indicators' requirements (KPIs) by taking advantage of the wider radio spectrum utilization in 5G versus 4G and the other advantages of new technology utilization in 5G versus 4G.

The differences list between 5G and 4G increases as the improvements of the different service aspects of 5G grows. The improvements can be listed as below:

- Peak data rate.
- User experienced data rate.
- User experienced latency.
- Area traffic capacity.
- Mobility.
- Connection density.
- Spectral efficiency.
- Network energy efficiency.
- Connection density.

More details about the previously sorted list are in the introduction of chapter 4. The 4G and 5G's utilized radio spectrum is another and major aspect of differences between the two technologies. The 5G utilizes high-frequency bands, millimeters wavebands (mmWaves), and lower radio spectrum bands. The 5G shares wavebands with 4G, the spectrum key will help overcome traffic congestion in 5G by utilizing more BWs. [69]

Furthermore, there is another main advantage of 5G versus 4G. one key difference or enabler is the wide radio spectrum that 5G utilizes. More precisely, the frequencies higher than 52.6 GHz, where the case in 4G is no utilized frequencies higher than 5.925 GHz. The radio spectrum details are shown in chapter 4.

After this review, it becomes obvious that the motivations and the advantages of the 4G to 5G transition are fascinating. That transition will lead to a full spreading and dominancy of 5G technology upon the previous cellular technologies in the end. Furthermore, the beyond 5G technology (6G and on) will have surprising impacts and results on the present wireless communications concepts, use cases, and applications. The Sixth Generation (6G) of wireless cellular technology is expected to support one μs or fraction/s of microsecond latency, which will support real-time application in significantly higher performance. The Sixth Generation of wireless cellular technology is expected to be initially deployed between 2030 and 2035 [70]. Although 5G is yet to be fully standardized, studies on 6G technology have already started [71].

6. 4G TO 5G IMPLEMENTATION AND TRANSITION PROCESS (DEPLOYMENT SCENARIOS)

As demonstrated in subchapter 2.5, there are two operation modes of 5G cellular networks. The first operation mode is 5G NSA (where EPC or CN of 4G are involved), and the second operation mode is 5G SA (the fully standardized operation mode of 5G, where there is no 4G network supportive parts involvement). Compared with 4G and the earlier generations of cellular network technologies, 5G wireless cellular technology promises to enable new use cases (described in subchapter 4.1) and application concepts (described in subchapter 2.5). The 5G wireless cellular technology would have to fulfill a wide variety of requirements to enable new use cases and application concepts. [19]

Furthermore, the different radio spectrum bands that 5G will utilize and the different operation conditions would add more requirements to be met by 5G. Based on the previous assumptions, there are several implementation scenarios suggested. The several implementation scenarios will facilitate the transition process from 4G to 5G SA. In the end, the different operation requirements of different use cases and radio spectrum will be met. At the same time, the transition progress will offer several benefits (explained in subchapter 2.5.1). According to [GSMA] [72], there are six deployment options of 4G and 5G. the deployment scenario options are shown in figure 13. [19]

Figure 13 shows five options of 5G deployments (Option #1 is not one of them). The different assumed migration paths among the different options are differently impacting the path's ability in addressing 5G use cases from different perspectives as below [19]:

- The perspective of UE, use cases, and the support for the early 5G network.
- The perspective of deployment of the migration step considerations of radio access network deployment.
- The perspective of both the resulted impacts on UE and network.
- The perspective of the migration step impacts on the desired result of voice service provisioning and continuity that are offered by a specific migration step.

Generally, the different migration step options offer operators different strategies for deploying 5G, depending on specific need/s of market situations, business models, and competition needs. The various options of 5G deployments required ensuring interoperability and compatibility of UE to be met and enable UE to roam across the different 5G deployments options. This means UE connectivity's ability to 5G and/or 4G networks, IP Multimedia Subsystem (IMS) services to be delivered over NR, and support roaming to/from networks with the same/different 5G deployment option.

Table 12 in Appendix A shows the different available migration paths, from high-level overview and analysis results. [19]

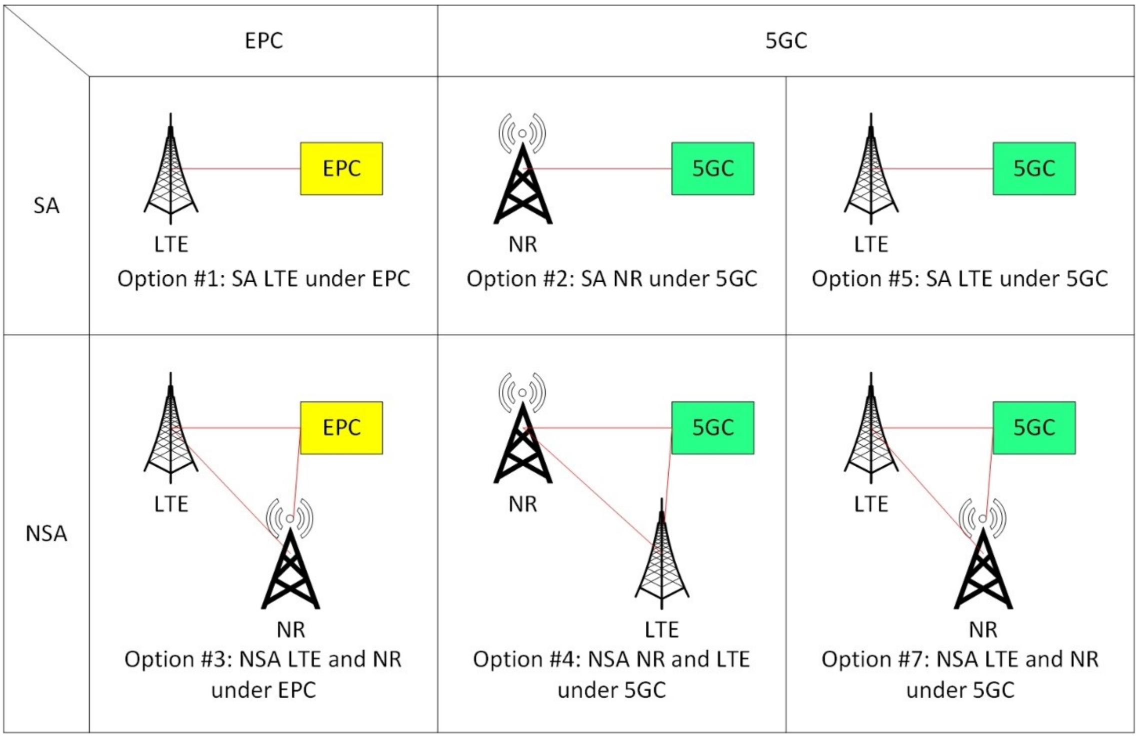

Figure 13. *The deployment options of 4G and 5G wireless cellular networks. Redrawn based on [19].*

Note: Figure 13 does not show the connections of either interface of the control plane or user plane.

This chapter focuses on Option #1 (SA under EPC), Option #3 (NSA and NR under EPC), and their main details. The reason is that Option #1 and Option #3, are representing the deployment options that 4G and 5G wireless cellular networks are accordingly deployed currently. Furthermore, the measurements are performed in wireless cellular networks deployed according to Option #1 and Option #3. In this scenario, the second path (EPS to NSA#3) in Table 12 in Appendix A is the matched path of migration step for Option #1 and Option #3. Migration Option #3 is based on extending the E-UTRAN part by utilizing new frequency bands, adding en-gNB as a SN, and the existing eNB as a MN that maintains the control plane with EPC. More details and comparisons about 5G NSA versus 5G SA are found in subchapter 2.5.1 and subchapter 4.4. Option #3 is shortening the time of 5G wireless cellular networks to be in the markets, reducing deployment and 4G system upgrade costs. Furthermore, Option #3 allows flexible use of 5G networks deployment by 4G vendors, based on the needs of capacity and the demands of high data throughput in hotspots or specific areas. However, it is important that in network planning and deployment stages, the assumptions of higher attenuation of high-frequency signals that en-gNB utilizes must be considered. [19]

Some prerequisites requirements should be met before the initial launch of 5G NSA Option #3. The radio spectrum is the first requirement in the requirements chain. In the radio spectrum part, the S-band, C bands, and mmWaves band with radio spectrum (24 GHz to 29.5 GHz and 37 GHz to 43.5 GHz) seem to be the most suitable and nominated bands to be utilized primarily in 5G deployment. On the other hand, the higher and the rapid attenuation of mmWaves with farther distances will be problematic in wide coverage ranges, especially in UL direction, where MIMO and beamforming effectiveness in UE are limited compared by MIMO and beamforming in DL direction of eNB and en-gNB. However, mmWaves will play the main role in 5G according to field trials and simulations that have been done in this regard. The 28 GHz band was used for fixed wireless access points, commercial and test roles. [19]

The second part of the requirements chain is the 4G radio network upgrades:

- The 4G radio network upgrades include the extra needed number of sites to compensate for the signal fading and offer equal coverage area per cell compared with the 4G (for DC purposes of 5G NSA). Fortunately, in simulations done on MIMO and beamforming techniques, it is showed that by utilizing those techniques, it is possible to match DL coverage provided by 1 800 MHz with 5G DL coverage by 3 500 MHz. [73]
- Upgrade the 4G wireless cellular network to support EN-DC (Option #3), which firstly requires E-UTRAN to support DC, and this includes adding en-gNB and upgrade eNB to interface and operate with en-gNB. Secondly, it requires upgrading 4G CN to interface and with en-gNB and operating with both upgraded eNB and added en-gNB. each of those two upgrades has different impacts on the 4G network (coming explanation about the different options and their impacts in 4G CN upgrades section). [73]
- Dynamic Spectrum Sharing (DSS) DSS is a software-based technology that allows operators to dynamically share and allocate radio resources among 4G and 5G to maximize spectrum resources. Therefore, more spectrum resources can be allocated to 5G as the number of 5G users increases. The same progress goes with 4G spectrum resources. This upgrade will lead to a smooth introduction of 5G in the existing 4G. [73]

The Fourth Generation Core Network upgrade is the third part of the requirements chain. This part has three options that are differing in networking among EPC, eNB, and en-gNB [73]:

- Option #3 networking mode: the X2 interface conveys NSA user plane traffic. The amount of traffic on the X2 interface between eNB and en-gNB is enormous (traffic splitting at eNB). Therefore, it requires the core network to increase BW on the S1-U interface to meet the 5G NSA requirements. [73]
- Option #3a networking mode: the traffic on the X2 interface is minimal because it carries control plane traffic only (traffic splitting in EPC).
- Option #3x networking mode is simply a combination of Option #3 and Option #3a. User plane traffic in Option #3x is partly shared on the X2 interface. Option 3#x has

become a preferable choice for 5G NSA networking because it has several features. The 4G part of the 5G NSA works as the anchor point of the control plane. Therefore, the cost of 5G NSA deployment is low, and the possibility of splitting the total traffic in the gateway between eNB and en-gNB made this option the best for backhaul limited in 4G networks. [73]

The obtained impacts of upgrades on 4G CN Elements are nothing more than a small software upgrade in CN to add or expand some parameters without needing essential upgrades of hardware.

There is an upgrading strategy that must be followed in 4G CN. That upgrading strategy includes two typical scenarios, each of them has it is own advantages and disadvantages. [73]

Scenario A

- The Physical EPC should be upgraded to support NSA.
- The capacity expansion would be based on physical EPC.

The big drawback in scenario A is that, based on the physical EPC's dedicated hardware, the EPC cannot be used in a virtualized environment when evolving to 5G SA. However, scenario A is the easiest way to upgrade EPC to 5G NSA deployment because it relies on the capabilities of the existing network equipment. [73]

Scenario B

- A new virtualized EPC network should be built to support an independent NSA operation mode.
- Interoperability should be made between the new virtualized EPC and the physical EPC.
- The capacity expansion would be based on the virtualized EPC.

Through the expansion of virtualized EPC, Scenario B can be evolved smoothly to the targeted network during the upgrading process to 5G SA. [73]

The next part is 5G deployment considerations. The 5G deployment consideration consists of several stages:

- Network planning.
- Massive MIMO order selection.
- Coverage optimization, especially in UL.
- Time slot synchronization configuration.
- NSA, and SA strategy.
- The actual network deployment steps.

The [ITU] has defined the applications of 5G in three categories, eMBB, URLLC, and mMTC (more details in Subchapter 4.1). Generally, based on [3GPP R-15] standards and since the 5G network focuses on eMBB service, the targeted 5G network should meet the typical eMBB service requirements. The requirements of typical eMBB are explained in the service requirements for 5G wireless cellular systems [73]. [74]

Back to the service requirements of 5G wireless cellular systems, several technologies and technical solutions will help to meet 5G services requirements. Massive MIMO is one of those technologies, mMIMO can improve both capacity and coverage. Massive MIMO is considered a potential enabler and solution for the 5G network, as shown in Subchapter 4.3.2. In the 5G systems, there are several options of mMIMO that can be selected based on the deployment scenario. The options of mMIMO are 16, 32, and 64 Transmitter (T). Massive MIMO technology offers beamforming and steering abilities, the transmitted signal spatially in 1D, 2D, or 3D. Forming the signal beam and steering in 3D is basically, steering signal in 2D and forming the main lobe of the signal in the third dimension. Forming the main lobe of signal in the third dimension is performed by narrowing the beam; therefore, a farther range of transmission is accomplished with a narrower angle of coverage. Or widening the beam; thus, a wider angle of coverage is accomplished, with a shorter range of transmission. Choosing either approach of beamforming or steering depends on the deployment scenario. For example, 16T with 1D beamforming is enough in Rural, Urban, and Suburban areas because users are diffused horizontally despite very small vertical diffusing of users in high buildings. Therefore, using 32T or 64T with 2D beamforming will not make a substantial difference in this kind of scenario. On the other hand, using 32T / 64T with 2D beamforming in dense-Urban high-rise scenarios will perform better and more cost-efficient than 16T / 1D beamforming. [73]

There are main constraints that may limit and drive the selection of used mMIMO and impose on making some trade-offs or compromises. However, 5G network deployment needs to take full consideration of performance, costs, installation and maintenance, space, weight limitations of installed units, and deployment scenarios, et cetera. [73]

Coverage enhancement is another step in the considerations of the 5G wireless cellular system deployment. Coverage enhancement must be taken carefully because of the differences in coverage and signal strength between UL and DL. The difference occurs because of the limited power resources and limited beamforming capability of UE on one side compared to en-gNB and gNB on the other side. [73]

Some other steps and considerations need to occur, like synchronization configuration, NSA and SA strategy, and network deployment strategy in the initial stage. Overall, the decision of which upgrades to be considered and their details are subjected to the actual upgrade requirements for the existed network, and the obtained benefits of that upgrade scenario, in comparison with another scenario. [73]

7. FIELD MEASUREMENTS

The field measurements part focuses mostly on 4G and 5G cellular networks' overall performance from upload data rate, download data, and latency perspectives, which are considered the most important variables from a subscriber point of view. The upload and download data rates matter the subscriber from the consumed time to complete data transferring or watch some high-definition video stream, et cetera. While the latency, in games or real-time applications in general.

The considered measurements in this chapter and the next chapters were performed in the third round of measurements, as the earlier two measurement rounds were discarded. The measurements are performed at different times of day, for five days in total out of eight days. The chosen locations of measurements are varied from indoor environments, besides high buildings where there is signal fading because of NLoS propagation and signal diffraction, to outdoor places where the possibility of LoS transmission is high.

The measurements will be affected dramatically by the propagation environment because the 4G uses the CA technique [25,75]. This happens because of the different attenuation intensities of different propagation environments. The different attenuation intensities will impact the received signal power, signal to interference, and noise ratio at both UE and eNB or en-gNB, differently. Eventually, the measurements vary accordingly with the received signal power, signal to interference, and noise ratio.

The disparity between measurements at different times is because of the network load's varying status and channel. Different propagation environments would affect the measurements differently. In the indoor propagation environment, the penetration losses present an additional amount of attenuation of the received signal power than the received signal power in the outdoor NLoS and the outdoor LoS propagation environments. The propagation environment's effect on the measurements can be seen by comparing the measurements of different propagation environments for the same period, especially the latency and DL throughput measurements. The different propagation environments affect 5G more than 4G measurements since 5G operates on higher frequencies than 4G, therefore, higher signal power attenuation on the 5G side.

The latency depends on different factors. Some of those factors are network status dependent like network congestion status, routing and switching, server distance, the number of nodes between UE and server (route length), et cetera. The network status impacts the latency measurements of 4G and 5G equally. The other different factors depend on local variances, more precisely en-gNB in 5G and eNB in 4G. The difference between the 4G and 5G measurements occurs mainly because of the different propagation environments of measurements and the network's load status at the time of measurement. That conclusion is based on the fact that the operation mode of 5G in the measurements field is NSA, and both 5G NSA and 4G are operating on the same core network EPC. On the other hand, the different considered technologies in eNB and en-gNB will make the difference between 4G and 5G NSA measurements and the network's load status at the time of measurement.

7.1 User Equipment capabilities

The User Equipment capabilities have been defined by [3GPP] [76].

The UE capabilities from the DL physical layer point of view are categorized into twelve different UE categories. Each category specifies the parameters of:

- The maximum number of DL-SCH transport block bits received within a Transmission Time Interval (TTI).
- The maximum number of bits of a DL-SCH transport block received within a TTI.
- The total number of soft channel bits.
- The maximum number of supported layers for spatial multiplexing in DL.

From the UL physical layer point of view, there are twelve other different categories. Each of them specifies the parameters of:

- The maximum number of UL-SCH transport block bits transmitted within a TTI.
- The maximum number of bits of UL-SCH transport block transmitted within a TTI.
- The ability to support the 64QAM modulation scheme in UL or not.

There are additional defined capabilities of UE for buffer sizes and other configurations. The most interesting capabilities of UE are the peak data rates of DL and UL.

Table 14 and Table 15 in Appendix A show the different categories of UE capabilities and their parameters. The used UE in the measurements is the OnePlus 8 5G.

7.2 Measurements software and analysis tools

The software used for performing and obtaining measurements is Rohde & Schwarz QualiPoc. The measurement software is used to check the signal strength and other parameters in detail, forcing the device manually to operate either in 4G or 5G mode. After the previous settings were done, the script of measurements was edited if needed then run. Meanwhile, the signal status and the different parameters during the measurement conducting were tracked in real-time. After the script of measurements was performed completely, the measurements' obtained data were saved in the measurement device.

The used tool for nominating locations of measurements was initially CellMapper [85]. CellMapper is a website mapping the towers of mobile networks, cells, and signal trails around the world on a map. The available information about mobile network towers' mapping is collected by individuals' reporting (crowdsourcing). Crowdsourcing is simply done by creating an account and run a log on the mobile device, then uploading that log to the website database. Some initial idea about the nominated locations for the mobile network tower was formed after checking mobile network towers' locations and the signal trails in Cellmapper. After the initial nominating of locations using CellMapper, several individual test measurements of latency and throughput of 4G and 5G were performed in the nominated locations statically, using Rohde & Schwarz QualiPoc software (the measurement device in the same location during the measurement). The same measurements were performed again in a single run of the measurement campaign. During that single run, the measurement device records latency, then switches to throughput DL then UL for many circles until the measurement campaign was manually stopped.

Meanwhile, the measurement device was moved along the whole route between the measurement locations and around the measurement locations themselves with less than ten meters. The purpose of the second test measurements was to cover the route between the measurement locations. After checking the static and the mobile measurements on the route in detail, the nominated locations of measurements by CellMapper were reidentified or reallocated if needed. Additional test measurements were performed to ensure that the identified locations' measurements were clarifying the effects of different propagation environments on the service performance and quality at UE.

The measurement files were extracted in CSV files and copied to the computer. MATLAB 2020b was the used software for measurement analysis, where the data was extracted from CSV files. In the data processing, the data files were filtered out if the script of measurements was deliberately stopped, interrupted or if the 5G service was disconnected during the execution of measurement. After the data files were filtered, MATLAB exported the data in the form of CSV files. The next stage started where a designed excel file imported the data and plotted the final figures, tables, and different statistics automatically.

7.3 Network configurations

The measurements were obtained from a commercial cellular network, “Elisa” (mobile telecommunications operator in Finland, Mobile Network Code (MNC) 05 and 21). The used subscription in measurements offered a data rate of 5 Mbps to 600 Mbps in 4G network and 10 Mbps to 1000 Mbps in 5G network [86]. The measurements' targeted parameters were the average latency of 500 times ping per measurement round for both 4G and 5G. The pinged server for latency measurements is in Tampere, Finland. The other targeted parameter of measurement is the average bit rate of upload and download.

The used server for download throughput measurements was (http://speedtest.tele2.net/1GB.zip), while the server was (http://speedtest.tele2.net/upload.php) for the upload throughput measurements. OnePlus 8 5G User Equipment was used to implement the 4G and 5G measurements. The UE of measurements was forced to connect on either 4G or 5G technology before running the measurements' script. The utilized frequency bands for 4G and 5G are shown in Table 16 in Appendix A [77].

7.4 Measurements scenarios and execution

The measurements were obtained in Tampere, Finland, as an Urban area, and Hervanta, Tampere, Finland, as a Suburban area located around 7 km southwest of Tampere city center (the previous location). Several locations of measurements were identified in each of Tampere and Hervanta. The measurement locations were chosen to cover different environments of propagation, LoS, Outdoor NLoS, and Indoor.

The periodicity of measurements was three times a day. The first round was between 06:00 – 12:00, the second round was between 12:00 – 18:00, and the third round was between 18:00 – 00:00. The whole measurements were repeated in three periods of time in October, November, and December of 2020. The third-period of measurements was 100 % succeeded, while the earlier two failed; therefore, discarded. The obtained measurements were considered as failed if the 5G performance at UE during the measurement execution was deficient compared to the overall 5G performance at UE in that measurement's location. For instance, in a specific location, the downlink throughput of 5G for several rounds of measurements was not more than 5 Mbps, while on average, it is more than 100 Mbps. The same previous approach was applied with 5G latency measurements. The failures of the two earlier periods of measurements were because of the continuous deployment of 5G networks and the upgrade of 4G networks to operate 5G NSA mode.

The third round of measurements took around eight days in mid-December 2020 (five days of measurements were valid, while the rest were discarded). Several individual measurements were performed based on the need to have an idea about locations reidentifying (based on the observations of measurements in the first and second periods). The success percentage of measurements per day was kept at 100 % for upload and download throughputs. This means that the 5G service was 100 % available during every single measurement progress. If UE could not operate on 5G operation mode at any measurement location at the time of implementing a measurement (no valid measurement of 5G), the whole measurements of that day would have been discarded, regardless of the number of successful measurements earlier on that day.

Therefore, the total number of the needed measurements per day eventually became sixty-six successful measurements in addition to, on average, twenty to thirty discarded measurements of 5G. The discarded measurements of 5G were because, in the measurement performing, it needed several rounds of running the script of measurements in some locations to switch the 5G service on. Furthermore, 5G service was dropping to 4G during the measurement, occasionally. The drop of 5G service to 4G was mostly indoor and less in the outdoor NLoS propagation environments.

In the indoor and outdoor NLoS propagation environments, it was hard to activate and keep the 5G service active for the measurement's time duration. The case was similar on snowy and rainy days in some of the outdoor NLoS propagation environments.

During the latency stage execution of the script of measurements, the measurements software had reported (Request Timed out) if the response time had exceeded 50 ms. The time limit of 50 ms was set manually in the script of measurements to prevent over waiting to get a response from the server (if the PING request had not been lost already). Therefore, the percentage of PING success was less than 100 % at some measurements in different locations.

7.5 Locations of Measurements

There was around three meters tolerance in positioning in some measurement locations when performing measurements because of the locations' daily circumstances. The total number of locations in Urban and Suburban areas is eleven, five locations in the Urban area, and six locations in the Suburban area.

7.5.1 Urban Area Locations

Five locations were identified in the city center of Tampere, Finland. The locations were nominated based on the different propagation environments explained earlier:

- Indoor propagation environment: two locations were chosen for this propagation environment:
    - The first location was in Stockman shopping mall, the ground floor (Hämeenkatu 4, 33100 Tampere). It is named “Location 1” in the datasheet of the measurements and locations map. This measurement location was covered intensely by the signal of several cells on NodeID: 1278. Both measurement and eNB/en-gNB locations are shown in figure 14 below.
    - The second location was the entrance of Koskikeskus shopping mall (Hatanpään valtatie 1, 33100 Tampere). It is named “Location 4” in the datasheet of the measurements and locations map. This measurement location was covered by the signal of several cells on NodeID: 6815. Both measurement and eNB/en-gNB locations are shown in figure 14 below.
- Outdoor propagation environment/ LoS: two locations were chosen for this propagation environment:
    - The first location was in the central square (Keskustori, 33210 Tampere). It is named “Location 3” in the measurement datasheet and locations map. This measurement location was covered by the signal of several cells on NodeID: 4558. Both measurement and eNB/en-gNB locations are shown in figure 14 below.
    - The second location was outdoor (Suvantokatu, 33100 Tampere). It is named “Location 5” in the datasheet of the measurements and locations map. This measurement location was covered by the signal of several cells on NodeID: 276. Both measurement and eNB/en-gNB locations are shown in figure 14 below.
- Outdoor propagation environment/ NLoS: one chosen location for this propagation environment:
    - This location was located on the western side of the Pirkanmaan Osuuspankki building (Hämeenkatu 12, 33100 Tampere). It is named “Location 2” in the datasheet of the measurements and locations map. This measurement location was covered strongly by the signal of several cells on NodeID: 1278.

Both measurement and eNB/en-gNB locations are shown in figure 14 below.

Figure 14. *Locations of measurements and places of eNB/en-gNB with ID numbers of eNBs/en-gNBs in Tampere, Finland (Urban area).*

7.5.2 Suburban Area Locations

Six locations were identified in Hervanta, Finland. The locations were nominated based on the different propagation environments mentioned before:

- Indoor propagation environment: three locations were chosen for this propagation environment:
  - The first location was in Duo shopping mall (Pietilänkatu 2, 33720 Tampere). It is named “Location 7” in the datasheet of the measurements and locations map. This measurement location was covered strongly by the signal of several cells on NodeID: 6760. Both measurement and eNB/en-gNB locations are shown in figure 15 below.
  - The second location was in Duo shopping mall too (Pietilänkatu 2, 33720 Tampere). It is named “Location 8” in the datasheet of the measurements and locations map. This measurement location was covered intensely by the signal of several cells on another NodeID: 1487. Both measurement and eNB/en-gNB locations are shown in figure 15 below.
  - The third location is in Tietotalo, Tampere University (Korkeakoulunkatu 1, 33720 Tampere). It is named “Location 11” in the datasheet of the measurements and locations map. This measurement location was covered intensely by the signal of several cells on another NodeID: 6781. Both measurement and eNB/en-gNB locations are shown in figure 15 below.
- Outdoor propagation environment/ LoS: two locations were chosen for this propagation environment:
  - The first location was in front of Duo shopping mall (Pietilänkatu 2, 33720 Tampere). It is named “Location 6” in the datasheet of the measurements and locations map. This measurement location was covered by the signal of several cells on NodeID: 6760. Both measurement and eNB/en-gNB locations are shown in figure 15 below.
  - The second location was outdoor on the northern side of the Tietotalo building, Tampere University (Korkeakoulunkatu 1, 33720 Tampere). It is named “Location 9” in the datasheet of the measurements and locations map. This measurement location was covered intensely by the signal of several cells on another NodeID: 2271. Both location and eNB/en-gNB locations are shown in figure 15 below.
- Outdoor propagation environment/ NLoS: one chosen location was chosen for this propagation environment:
  - This location was located among residential buildings (Pietilänkatu 9, 33720 Tampere). It is named “Location 10” in the measurement datasheet and locations map. This measurement location was covered weakly by the signal of one cell on NodeID: 6760.

Both measurement and eNB/en-gNB locations are shown in figure 15 below.

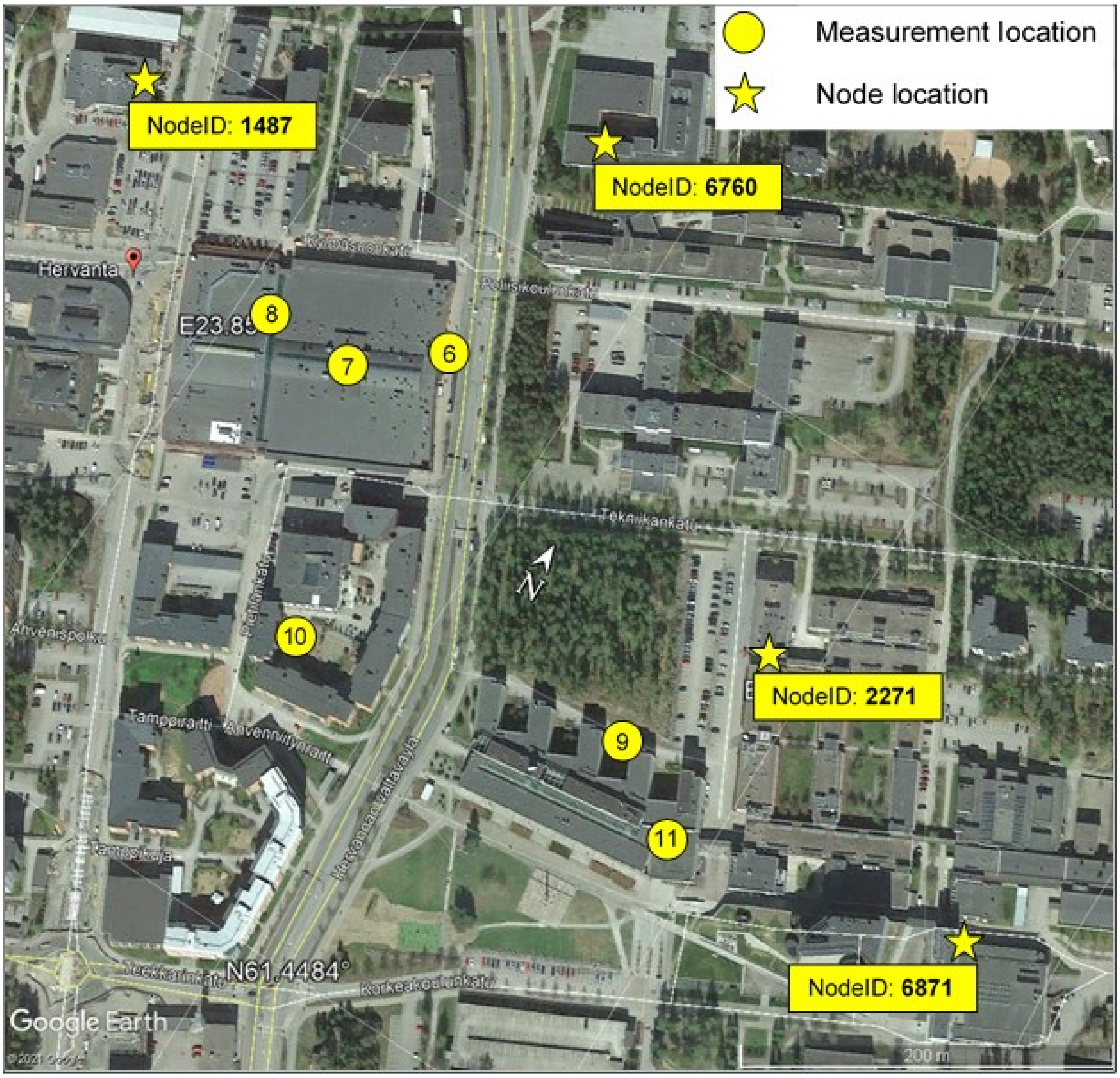

Figure 15. *Locations of measurements and places of eNB/en-gNB with ID numbers of eNBs/en-gNBs in Hervanta, Finland (Suburban area).*

8. RESULTS

As a review of the measurements, the figures show the different values and parameters for five days of 4G and 5G measurements in each location. Figure 16 shows the average percentage of Request timed out of PING and average latency. Figure 17 shows the average Block Retransmission Rate (BLRR) and Block Error Rate (BLER) percentages in latency measurements. Figure 18 shows the average BLRR percentage and average throughput in the upload. Figure 19 shows the average BLER percentage and average throughput in download. Figure 20 shows the average SINR and average RSRP. Figure 21 shows the Cumulative Distribution Function (CDF) of different measurements. Figure 22 shows the Standard Deviation (STDV) values of different measurements.

Table 7 shows different categories of 4G and 5G measurements, in Tampere city center area (Urban) and Hervanta area (Suburban), for each location individually. The graphs and the detailed values of measurements, and the related parameters in each location are attached in Appendix B for each day of the measurements.

Note: The measurement software has not captured the 5G SINR values with notation (N/A) in Table 7.

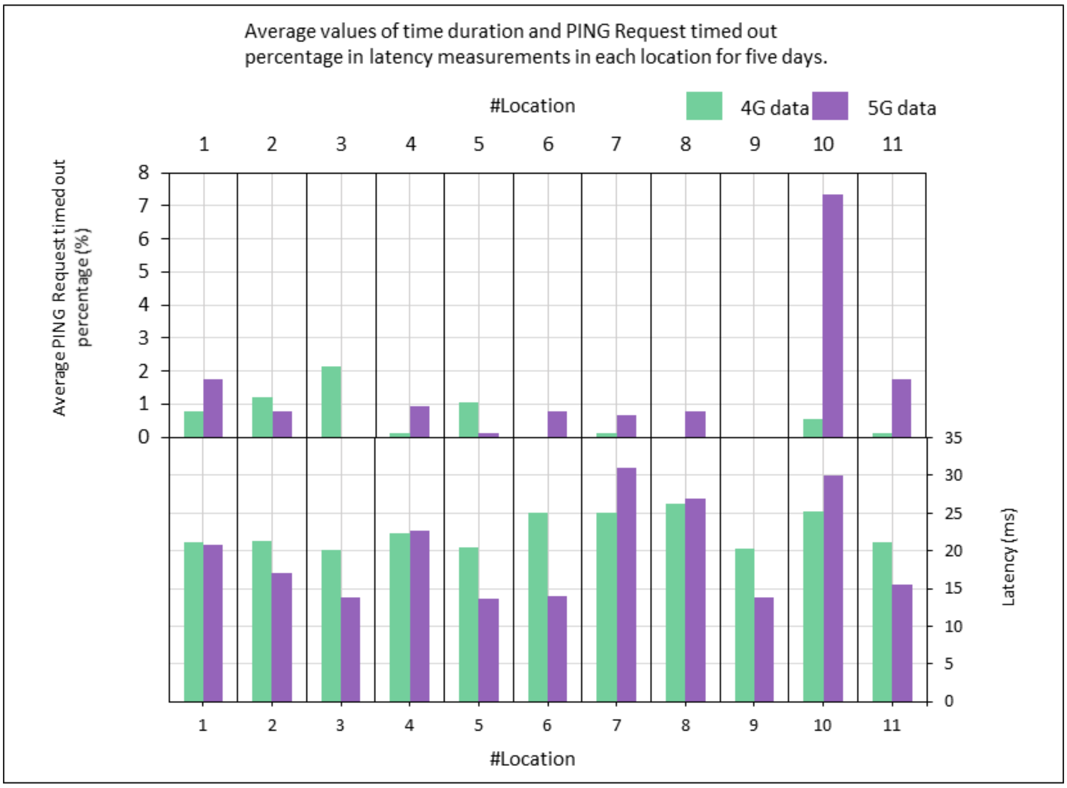

Figure 16. *Average time duration and PING Request timed out percentage in latency measurements in each location for five days.*

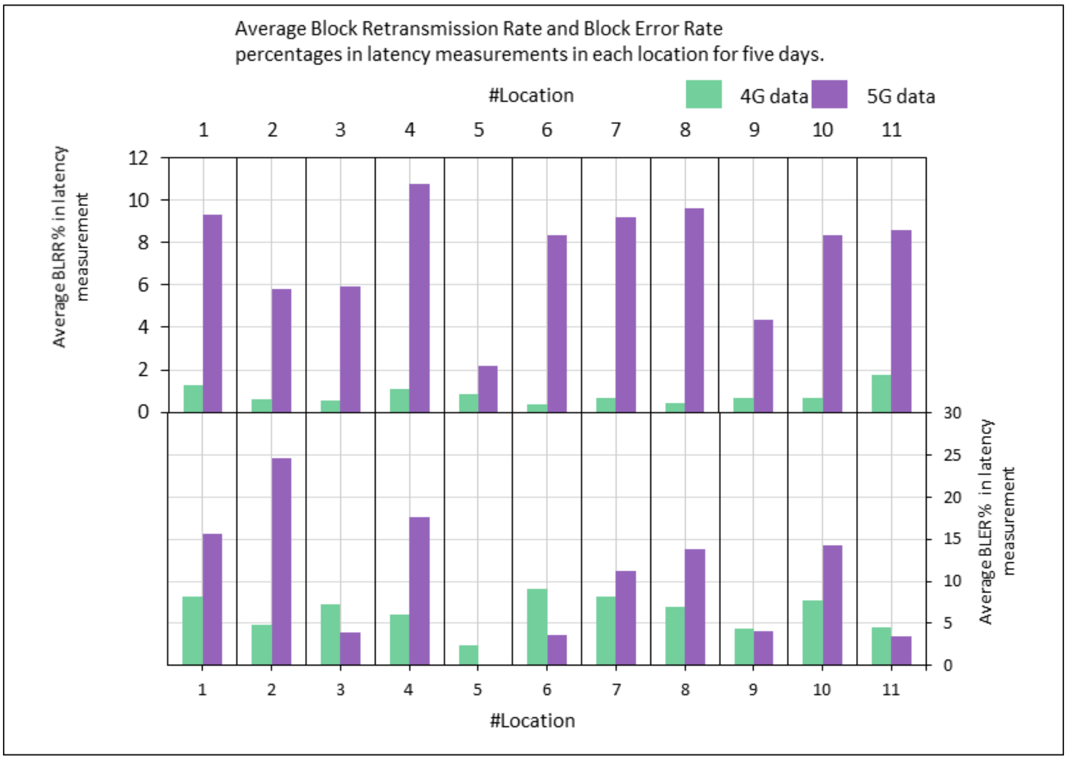

Figure 17. *Average Block Retransmission Rate and Block Error Rate percentages in latency measurements in each location for five days.*

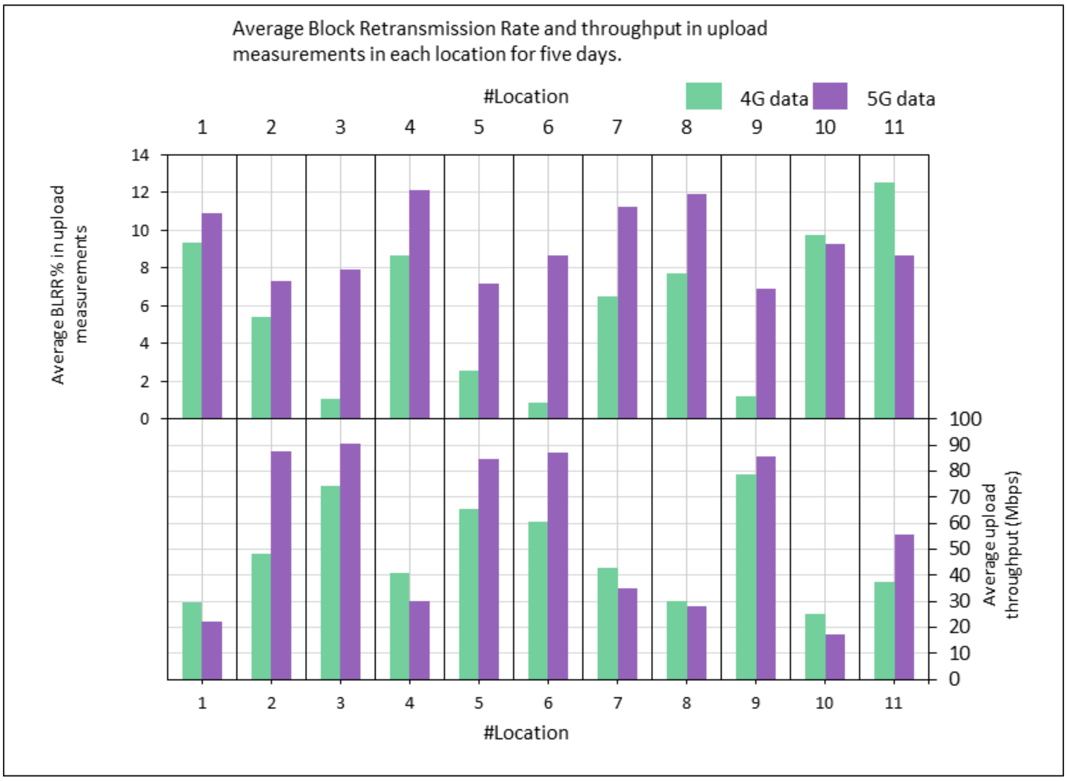

Figure 18. *Average Block Retransmission Rate percentage and average throughput in upload measurements in each location for five days.*

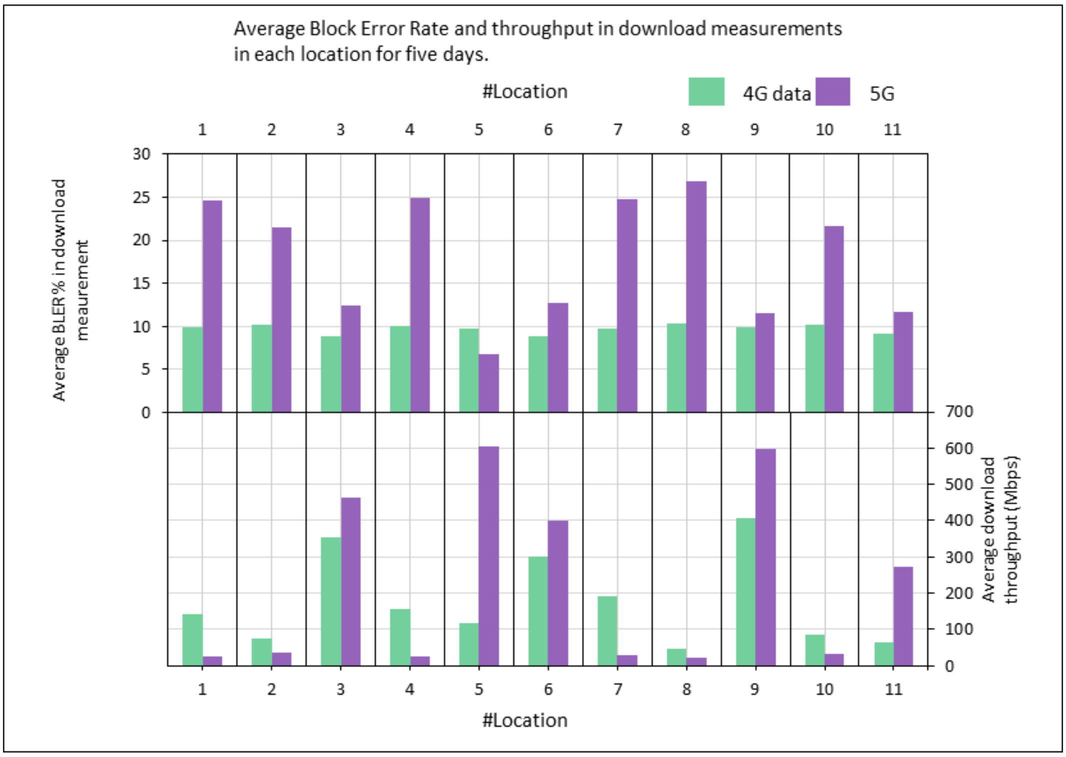

Figure 19. *Average Block Error Rate percentage and average throughput in download measurements in each location for five days.*

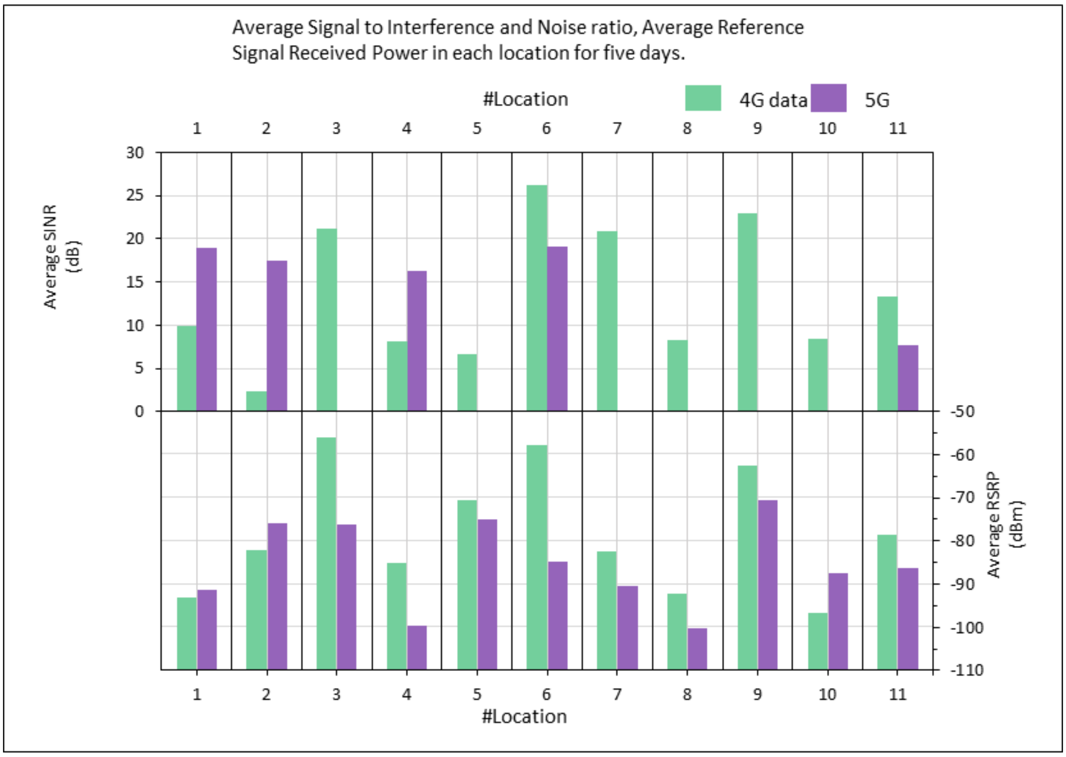

Figure 20. *Average Signal to Interference and Noise ratio, Average Reference Signal Received Power in each location for five days.*

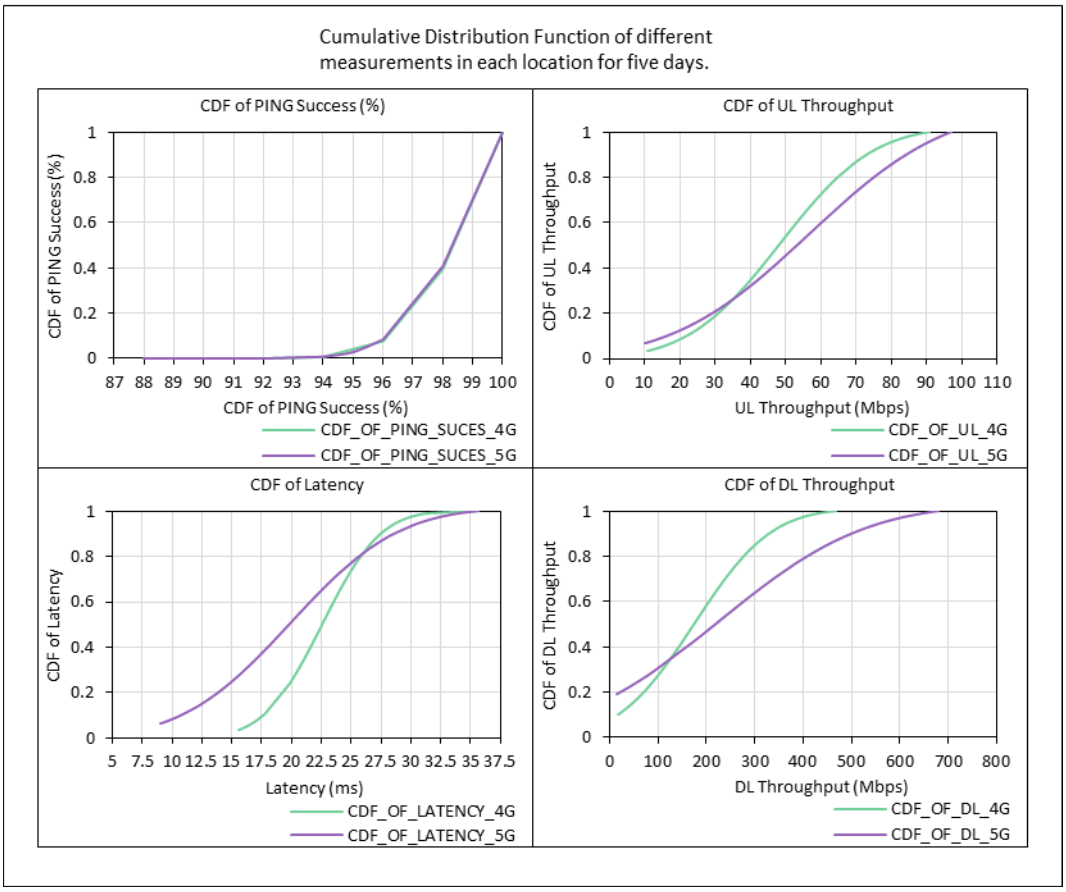

Figure 21. *Cumulative Distribution Function of different measurements in each location for five days.*

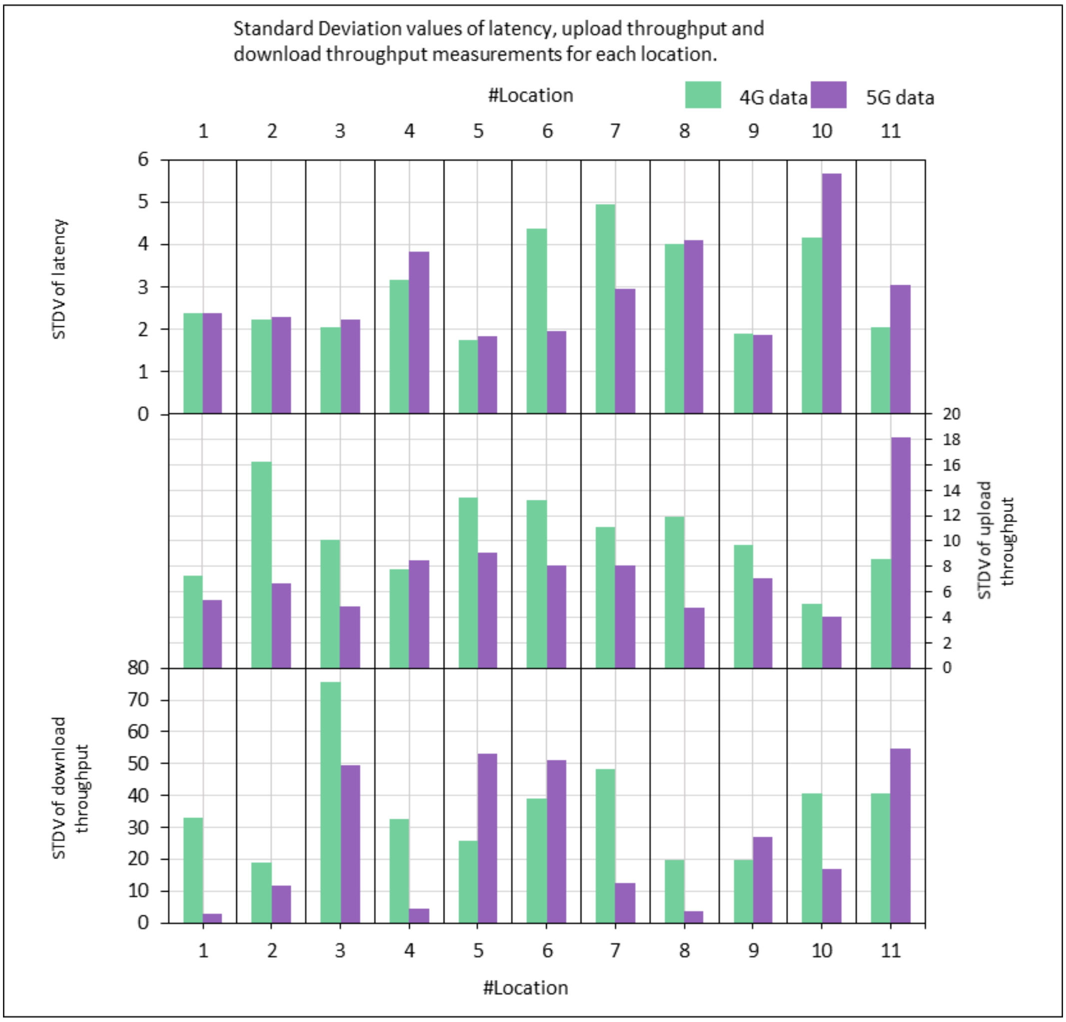

Figure 22. *Standard Deviation (STDV) values of latency, upload throughput, and download throughput measurements for each location.*

***Table 7.** The overall average values of each location's measurements and measurements at the highest and lowest performance of the 4G and 5G network.*

The green shaded cells are for 4G measurements, while the light purple shaded cells are for 5G measurements. (4G / 5G)

#Location	Latency (ms)	UL (Mbps)	DL (Mbps)	RSRP (dBm)	SINR (dB)	BLRR % on UL	BLER % on DL	AVG_PING_SUCES_%	Propagation environment	Notes
1	21.18	29.46	142.35	-93.38	9.96	9.34	9.85	99.20	Indoor	- The (N/A) values in SNIR column have not been captured by the software. - Locations 1-5, are in Tampere city center (Urban) and shaded by green. - Locations 6-11, are in Hervanta (Suburban) and shaded by pink.
	20.86	21.99	24.88	-91.39	18.92	10.91	24.56	98.27		
2	21.31	48.34	74.71	-82.44	2.33	5.40	10.20	98.80	Outdoor NLoS	
	17.08	87.60	36.57	-76.11	17.51	7.32	21.47	99.20		
3	20.13	74.32	355.04	-56.36	21.22	1.10	8.83	97.87	LoS	
	13.87	90.38	464.97	-76.26	N/A	7.97	12.41	100.00		
4	22.39	40.71	156.75	-85.30	8.15	8.69	10.06	99.87	Indoor	
	22.59	30.30	25.71	-99.85	16.31	12.15	24.99	99.07		
5	20.38	65.55	116.44	-70.67	6.67	2.57	9.81	98.94	LoS	
	13.63	84.87	604.4	-75.07	N/A	7.19	6.82	99.87		
6	25.03	60.33	301.70	-58.11	26.21	0.90	8.83	100.00	LoS	
	14.07	87.06	398.34	-84.83	19.15	8.71	12.74	99.20		
7	25.10	42.82	191.54	-82.46	20.85	6.54	9.74	99.87	Indoor	
	31.03	35.09	28.27	-90.48	N/A	11.26	24.83	99.34		
8	26.25	30.21	46.50	-92.34	8.26	7.71	10.33	100.00	Indoor	
	27.00	28.30	21.47	-100.43	N/A	11.96	26.90	99.20		
9	20.32	78.83	406.26	-62.78	23.00	1.19	9.94	100.00	LoS	
	13.80	85.83	598.53	-70.79	N/A	6.91	11.55	100.00		
10	25.23	25.30	86.42	-96.67	8.41	9.74	10.23	99.47	Outdoor NLoS	
	29.96	17.30	30.94	-87.59	N/A	9.32	21.61	92.67		
11	21.08	37.67	62.60	-78.59	13.31	12.53	9.14	99.87	Indoor	
	15.59	55.55	272.52	-86.44	7.73	8.71	11.69	98.27		
Average Urban	21.08	51.68	169.06	-63.17	14.92	5.42	9.75	98.94	Urban Area overall average.	
	17.61	63.03	231.30	-77.95	17.71	9.04	17.17	99.27		
Average Suburban	23.84	45.86	182.50	-64.57	21.10	6.43	9.70	99.87	Suburban overall average.	
	21.91	51.52	225.01	-78.16	16.44	9.48	18.22	98.12		
Overall Average	22.58	48.50	176.39	-63.88	19.26	5.97	9.72	99.45	Overall averages of both Urban and Suburban.	
	19.95	56.75	227.87	-78.06	17.25	9.31	18.14	98.65		
At the lowest performance of the network	35.66	10.81	18.69	-111.09	-5.10	21.45	11.64	88.00		
	35.68	10.17	15.83	-103.32	3.09	18.41	29.73	88.00		
At the highest performance of the network	15.58	90.78	468.97	-52.89	29.76	0.05	4.40	100.00		
	9.08	96.98	680.93	-68.51	22.72	1.83	2.99	100.00		

9. DISCUSSION AND CONCLUSIONS

Before analyzing the results, several points must be fixed to build the analyses and conclusions on a clear foundation. Below is the list of those points:

- The measurements' used analysis methods are the graphs of 4G and 5G measurements for the latency and throughputs of UL and DL. Several accompanying parameters have been represented and plotted to have more awareness about the circumstances of measurements and conditions, together with the latency and throughput measurement graphs. All the accompanying parameters and measurements are represented in the figures.
- The maximum limit of download throughput of the used subscription in measurements is 1 Gbps in the 5G operation mode (Speed range 5-600 Mbps in the 4G operation mode and 10-1000 Mbps in the 5G operation mode). [86]
- The cellular network where the measurements were obtained is commercial. Therefore, there was no available information about the network's different configurations or the network load during the measurements. This may affect the overall performance during the measurements and may cause some misleading or mismatching with the theoretical expectations, in the level of single to single measurement comparison, between 4G and 5G. Therefore, the overall average of the measurement approach is considered mostly in investigating the results.
- The CN will not play a significant role in the disparity among 4G versus 5G measurements because the CN for each of 4G and 5G is EPC, given that the measurements of 4G and 5G were obtained in the same locations and at close times of the day. Usually, the time difference between 4G and 5G measurements obtaining in each location was around 3-5 minutes.
- This means the network load status was approximately the same while performing the 4G and 5G measurements in that location. On the other hand, the utilized frequency bands in both 4G and 5G, the signal strength, the used modulation orders in UL/DL will cause the disparity among 4G versus 5G measurements. In other words, the differences between eNB and en-gNB capabilities will play the main role in the disparity of the latency and data throughput measurements between 4G and 5G.
- In the LoS propagation environment, because the propagation with UE is LoS, there is no additional attenuation on the received signal power at the UE, as in Indoor propagation environments given there is no indoor cell. Therefore, the measurements were less affected by the signal attenuation in the LoS propagation environment than Indoor propagation environments.
- As a result, the variation of measurements versus time can indicate the CN load status or performance at different times of the day. Figures 25, 27, and 31 show symmetry between the 4G and 5G measurements variation versus time in LoS propagation cases. Clearly, the symmetry is shown in latency and download throughput measurements variation versus time. The shift between the 4G and 5G graphs is because of the capability differences or eNB versus en-gNB.
- The symmetry can be disturbed partially or entirely because of the instability in the received signal power at UE and the coverage of 4G versus 5G in the measurement location. Another reason is that UE switches continuously among several beams of the transmitted signal, causing instability in the received signal power level and thus the measurements. The graphs in figure 28 show an excellent example of similar propagation cases.

- In the NLoS propagation environment, the received signal power at UE and SINR fluctuates drastically; thus, it is precarious. The fluctuations and instability of received signal power result from the additional attenuation and multipath propagation effects on the received signal power. Furthermore, drastic constructive and destructive interferences among copies of the NLoS propagated signal will occur at UE.
- Therefore, the received signal power at UE will fluctuate severely; thus, the measurements' variance is large. Figures 24 and 32 show large measurements' variation versus time, indicating drastic fluctuations in the received signal power in the NLoS propagation environment. Figures 24 and 32 show no symmetry between the 4G and 5G graphs in contrast with figures 25, 27, and 31.
- In the indoor propagation environment, the penetration losses are an additional attenuation to the received signal power copies at UE of multipath propagation, which means fewer received beams. The signal copies of multipath propagation would be detected and received by UE only if their power level and SINR are above the threshold.
- Different additional parameters affect the stability of measurements, like the impacts of the geometry of the building. The various parameters can be summarized by the different geometry of buildings, the mobile subjects inside the building, the positioning and orientation of UE. All of the various parameters affect the received signal power and SINR at UE simultaneously, destabilizing the measurements eventually. Figures 23, 26, 29, and 30 show a more considerable variance of measurements versus time in comparison with LoS related figures.

The purpose of the last three points is to clarify and understand how to extinguish the propagation environment's impact than the impact of CN on the 4G and 5G measurements represented in the figures. Understanding that concept will make it more accurate and easier to see the performance differences between 4G and 5G and separate them from the propagation impacts on each's performances.

As a result of that understanding, the conclusions regarding 4G and 5G performance comparison and the impacts of propagation environments on each performance will be more accurate.

- The variance is larger on the 4G side than the 5G because there are more 4G cells than 5G. This means it is easier for UE in 4G to change from one cell to another than 5G. Changing cells means different behavior in the received signal values and thus more variance in measurements. On the 5G side, the case is not. The UE in 5G has less ability to change the cell because of the fewer available cells to serve in the UE. Therefore, unless another cell coverage provides a better service, UE in 5G will stay connected to the current cell even if the performance is low, which would reduce the variance in measurements. By checking figures of indoor propagation environment cases, it is clear that variance in measurements of 4G is larger than 5G.

The discussion of measurements will be from two different perspectives. The first perspective of reviewing and comparing the measurements will be from the environment of propagation, for each of the Urban and Suburban areas separately.

The second perspective of reviewing and comparing the overall average of all locations' measurements will be from the Urban area versus Suburban area perspective.

9.1 Measurements comparison based on the propagation environment

This perspective investigates and shows the overall impact of different propagation environments on the service quality and performance at the UE. Furthermore, conclude the reasons behind the measurement variations in the different propagation environments. And finally, make proposals about how to enhance the service quality and network performance at UE, based on the measurement results analyses.

From Table 7, the measurements in locations of each propagation environment are averaged as in tables 8 and 9. The average values of measurements in tables 8 and 9 represent an indicator of the impact intensity of the different propagation environments on the service quality and performance at the UE.

9.1.1 Tampere city center measurements (Urban area)

In this section, observations on the Tampere city center area (Urban) measurements are reviewed, discussed, and finally, conclusions are made.

The review and comparison of Tampere city center measurements are from the propagation environment point of view regarding the upload and download throughputs. By relying on some relevant figures during the investigation of measurements, the conclusions are made.

Table 8 below shows the average values of latency and throughput measurements of each propagation environment separately.

Table 8. *Average latency and throughput measurements of each propagation environment in Tampere.*

The green shaded cells are for 4G average values, while the light pink shaded cells are for 5G average values.				4G
				5G
Measurement	Indoor	NLoS	LoS	Notes
Latency (ms)	21.8	21.3	20.2	The average values of measurements show the impact intensity of different propagation environments on network performance at UE.
	21.7	17.1	13.7	
Upload Throughput (Mbps)	35.1	48.3	69.9	
	26.1	87.6	87.6	
Download throughput (Mbps)	149.5	74.7	235.7	
	25.3	36.6	534.7	

Indoor propagation environment (Locations 1 and 4) versus outdoor LoS propagation environment (Locations 3 and 5)

By checking figures 23, 25, 26, and 27, the latency and download throughput measurements in the outdoor LoS propagation environment show symmetry between 4G and 5G in measurement variance versus time. On the other hand, the measurements data of indoor propagation environments in locations 1 and 4 have shown high instability in latency and download throughput measurements. The upload throughput measurements in locations 3 and 5 did not show stable variance versus time as in latency measurements and download throughput measurements. It is because of the limited power resources of the UE; therefore, the upload throughput will degrade more.

The 5G service quality has degraded more than 4G in the indoor environment versus the Los propagation environment.

By checking Table 8, the average values of measurements in each propagation environment have shown that in the latency measurements:

- The latency measurements of 5G have shown that the latency has increased from 13.7 ms in the LoS propagation environment to 21.7 ms in the indoor propagation environment. This means an 8 ms additional delay.
- The latency measurements of 4G have shown that the latency has increased from 20.2 ms in the LoS propagation environment to 21.8 ms in the indoor propagation environment. This means 1.6 ms of additional delay.
- As a result, the additional latency was 8 ms in 5G versus 1.6 ms in 4G.

In the upload throughput measurements:

- The upload throughput measurements of 5G have shown that the upload throughput was decreased from 87.6 Mbps in the LoS propagation environment to 26.1 Mbps in the indoor propagation environment. This means 61.5 Mbps less upload throughput.
- The upload throughput measurements of 4G have shown that the upload throughput was decreased from 69.9 Mbps in the LoS propagation environment to 35.1 Mbps in the indoor propagation environment. This means 34.8 Mbps less upload throughput.
- As a result, the drop of upload throughput was 61.5 Mbps in 5G versus 34.8 Mbps in 4G.

In the download throughput measurements:

- The download throughput measurements of 5G have shown that the download throughput was decreased from 534.7 Mbps in the LoS propagation environment to 25.3 Mbps in the indoor propagation environment. This means 509.4 Mbps less download throughput.
- The download throughput measurements of 4G have shown that the download throughput was decreased from 235.7 Mbps in the LoS propagation environment to 149.5 Mbps in the indoor propagation environment. This means 86.2 Mbps less download throughput.
- As a result, the drop of download throughput was 509.4 Mbps in 5G versus 86.2 Mbps in 4G.

Conclusion

The quality of service of 4G and 5G in the LoS propagation environment is better than in the previous comparisons' indoor propagation environment. Furthermore, the 5G service quality at the UE is more sensitive to the propagation environment change than 4G.

The main reason for that is the higher attenuation of RSRP in the 5G side, as shown in figure 20 and Table 7. Therefore, deploying indoor antennas of 5G (e.g., in locations 1 and 4) will lead to having LoS propagation with the UE (e.g., in locations 3 and 5). The indoor antennas will boost RSRP levels at UE. Thus, the indoor environment's 5G service quality level will be boosted to a closer service quality level of the LoS environment.

Outdoor NLoS propagation environment (Location 2) versus indoor (Locations 1 and 4) and outdoor (Locations 3 and 5) propagation environment in general

By checking figures 23, 24, 25, 26, and 27, the latency and download throughput measurements in the outdoor NLoS propagation environment of location 2 show more variance versus time than locations 3 and 5. On the other hand, the measurements' variation in location 2 is higher than in locations 1 and 4.

The service quality was improved slightly in the outdoor NLoS propagation environment in comparison with the indoor environment. The most noticed improvement is the upload throughput of 5G. On the other hand, in the NLoS propagation environment, the service quality at the UE is still less in comparison with the LoS propagation environment.

By checking Table 8, the values of measurements have shown that in the latency measurements:

- The latency measurements of 5G have shown that the latency was increased from 13.7 ms in the LoS propagation environment to 17.1 ms in the outdoor NLoS propagation environment. This means 3.4 ms additional delay.
- The latency measurements of 4G have shown that the latency was increased from 20.2 ms in the LoS propagation environment to 21.3 ms in the outdoor NLoS propagation environment. This means 1.1 ms of additional delay.
- As a result, the additional latency was 3.4 ms in 5G versus 1.1 ms in 4G.

In the upload throughput measurements:

- The upload throughput measurements of 5G have shown that the upload through in the LoS propagation environment is approximately equal to the upload throughput of the outdoor NLoS propagation environment. The difference was less than 100 kbps in the upload throughput.
- The upload throughput measurements of 4G have shown that the upload throughput was decreased from 69.9 Mbps in the LoS propagation environment to 48.3 Mbps in the outdoor NLoS propagation environment. This means 21.6 Mbps less upload throughput.

- As a result, the drop of upload throughput was neglected in 5G versus 21.6 Mbps in 4G.

In the download throughput measurements:

- The download throughput measurements of 5G have shown that the download throughput was decreased from 534.7 Mbps in the LoS propagation environment to 36.6 Mbps in the outdoor NLoS propagation environment. This means 498.1 Mbps less download throughput.
- The download throughput measurements of 4G have shown that the download throughput was decreased from 235.7 Mbps in the LoS propagation environment to 74.7 Mbps in the outdoor NLoS propagation environment. This means 161 Mbps less download throughput.
- As a result, the drop of download throughput was 498.1 Mbps in 5G, versus 161 Mbps in 4G.

Conclusion

From the previous comparisons, it is clear that the quality of service for both 4G and 5G in the LoS propagation environment is better than in the outdoor NLoS propagation environment. Furthermore, the 5G service quality at the UE is more sensitive to the propagation environment change than 4G. In contrast, the upload throughput performance at the UE was shown more sensitivity in 4G than in 5G.

Therefore, enhancing the coverage by deploying more en-gNBs, will be a suitable approach. The advantage of this approach is to reduce the probability of NLoS propagation occurring. Thus the service performance level of 5G at UE is boosted eventually.

9.1.2 Hervanta measurements locations (Suburban area)

In this section, observations on the Hervanta area's measurements (Suburban) are reviewed, discussed, and finally, conclusions are made.

The review and comparison of measurements in the Hervanta area will be from the propagation environment point of view regarding the upload and download throughputs. By relying on some relevant figures during the investigation of measurements, the conclusions would be made.

Table 9 below shows the average values of latency and throughput measurements of each propagation environment separately. Location 11 is not included in Table 9 because of the indoor propagation environment's particular case. In location 11, the average RSRP was relatively high compared to the other indoor propagation cases in Hervanta. Therefore, location 11 is analyzed later. Table 7 shows the precise values of RSRP.

Table 9. *Average latency and throughput measurements of each propagation environment in Hervanta (Location 11 is not included).*

The green shaded cells are for 4G percentages, while the light pink shaded cells are for 5G percentages.				4G / 5G
Measurement	Indoor	NLoS	LoS	Notes
Latency (ms)	25.7	25.2	22.7	The average values of measurements show the impact intensity of different propagation environments on network performance at UE.
	29.0	30.0	13.9	
Upload Throughput (Mbps)	36.5	25.3	69.6	
	31.7	17.3	86.4	
Download throughput (Mbps)	119.0	86.4	354.0	
	24.9	30.9	498.4	

Indoor propagation environment (Locations 7 and 8) versus outdoor LoS propagation environment (Locations 6 and 9)

By checking figures 28, 29, 30, and 31, the latency measurements, upload throughput, and download throughput in the outdoor LoS propagation environment show symmetry between 4G and 5G in measurement variance versus time, especially in location 9. On the other hand, the measurements data of indoor propagation environments in locations 7 and 8 have shown very high instability in the performance of latency and download throughput measurements.

The 5G service quality was degraded more than 4G in the indoor environment versus the Los propagation environment.

By checking Table 9, the average values of measurements in each propagation environment have shown that in the latency measurements:

- The latency measurements of 5G have shown that the latency was increased from 13.9 ms in the LoS propagation environment to 29 ms in the indoor propagation environment. This means 15.1 ms additional delay.
- The latency measurements of 4G have shown that the latency was increased from 22.7 ms in the LoS propagation environment to 25.7 ms in the indoor propagation environment. This means 3 ms of additional delay.
- As a result, the additional latency was 15.1 ms in 5G versus 3 ms in 4G.

In the upload throughput measurements:

- The upload throughput measurements of 5G have shown that the upload throughput was decreased from 86.4 Mbps in the LoS propagation environment to 31.7 Mbps in the indoor propagation environment. This means 54.7 Mbps less upload throughput.

- The upload throughput measurements of 4G have shown that the upload throughput was decreased from 69.6 Mbps in the LoS propagation environment to 36.5 Mbps in the indoor propagation environment. This means 33.1 Mbps less upload throughput.
- As a result, the drop of upload throughput was 54.7 Mbps in 5G, versus 33.1 Mbps in 4G.

In the download throughput measurements:

- The download throughput measurements of 5G have shown that the download throughput was decreased from 498.4 Mbps in the LoS propagation environment to 24.9 Mbps in the indoor propagation environment. This means 473.5 Mbps less download throughput.
- The download throughput measurements of 4G have shown that the download throughput was decreased from 354 Mbps in the LoS propagation environment to 119 Mbps in the indoor propagation environment. This means 235 Mbps less download throughput.
- As a result, the drop of download throughput was 473.5 Mbps in 5G, versus 235 Mbps in 4G.

Conclusion

From the previous comparisons, it is clear that the quality of service for both 4G and 5G in the LoS propagation environment is better than in the outdoor NLoS propagation environment. Furthermore, the 5G service quality at the UE is more sensitive to the propagation environment change than 4G. The latency performance at the UE has an extreme level of sensitivity in 5G. In 5G, the indoor propagation environment's average latency was more than twice the average latency of the LoS propagation.

The main reason for that is the higher attenuation on RSRP of 5G, as shown in figure 20 and Table 7. Therefore, deploying indoor antennas of 5G (e.g., in locations 7 and 8) will lead to having LoS propagation with the UE (e.g., in locations 6 and 9). The indoor antennas will boost RSRP levels at UE. Thus, the quality of 5G service in the indoor environment will be boosted to a closer service quality level in the LoS environment.

Outdoor NLoS propagation environment (Location 10) versus indoor (Locations 7 and 8) and outdoor (Locations 6 and 9) propagation environment in general

By checking figures 28, 29, 30, 31, and 32, the measurements of latency and download throughput in the outdoor NLoS propagation environment of location 10 show more variance versus time in comparison with locations 6 and 9. The reason is explained in points (e and f). On the other hand, the variation of the measurements versus time in location 10 is more than in locations 7 and 8.

The service quality was degraded more in the outdoor NLoS propagation environment than in the indoor environment.

By checking Table 8, the values of measurements have shown that in the latency measurements:

- The latency measurements of 5G have shown that the latency was increased from 13.9 ms in the LoS propagation environment to 30 ms in the indoor propagation environment. This means 16.1 ms additional delay.
- The latency measurements of 4G have shown that the latency was increased from 22.7 ms in the LoS propagation environment to 25.2 ms in the indoor propagation environment. This means 2.5 ms of additional delay.
- As a result, the additional latency was 16.1 ms in 5G versus 2.5 ms in 4G.

In the upload throughput measurements:

- The upload throughput measurements of 5G have shown that the upload throughput was decreased from 86.4 Mbps in the LoS propagation environment to 17.3 Mbps in the indoor propagation environment. This means 69.1 Mbps less upload throughput.
- The upload throughput measurements of 4G have shown that the upload throughput was decreased from 69.6 Mbps in the LoS propagation environment to 25.3 Mbps in the indoor propagation environment. This means 44.3 Mbps less upload throughput.
- As a result, the drop of upload throughput was 69.1 Mbps in 5G, versus 44.3 Mbps in 4G.

In the download throughput measurements:

- The download throughput measurements of 5G have shown that the download throughput was decreased from 498.4 Mbps in the LoS propagation environment to 30.9 Mbps in the indoor propagation environment. This means 467.5 Mbps less download throughput.
- The download throughput measurements of 4G have shown that the download throughput was decreased from 354 Mbps in the LoS propagation environment to 68.4 Mbps in the indoor propagation environment. This means 267.6 Mbps less download throughput.
- As a result, the drop of download throughput was 467.5 Mbps in 5G, versus 267.6 Mbps in 4G.

Conclusion

From the previous comparisons, it is clear that the quality of service for both 4G and 5G in the LoS propagation environment is better than in the outdoor NLoS propagation environment. Furthermore, the 5G service quality at the UE is more sensitive to the propagation environment change than 4G.

Therefore, enhancing the coverage by increasing the number of deployed en-gNBs, will be the right approach. The advantage of this approach is to reduce the probability of NLoS propagation occurring. Thus, the service performance level of 5G at UE is boosted eventually.

Indoor propagation environment (Location 11)

By checking the RSRP values of location 11 in Table 7, the measurements of RSRP are showing that the signal level 5G was better than the RSRP of the other two locations 7 and 8. Moreover, the RSRP of location 11 was just 2 dB less than the RSRP of location 6 (LoS propagation environment). As a result, the latency varying versus time of location 11 in figure 33 shows a relative symmetry with the latency variation versus time of locations 6 and 9. By checking Table 10 below, it is obvious that the service quality at the UE in location 11 is better than the service quality in locations 7 and 8. On the 4G side of measurements in location 11, the download throughput performance shows more degradation. The RSRP and the average number utilized carriers in downloading progress in each of the locations 7, 8, and 11 demonstrate in practice the impact of utilizing more carriers simultaneously, with higher RSRP and SINR.

Table 10. *Average latency and throughput measurements in indoor propagation environment (Locations 7 and 8 versus 11).*

<table>
<tr><td colspan="4" rowspan="2">The green shaded cells are for 4G percentages,
while the light pink shaded cells are for 5G percentages.</td><td>4G</td></tr>
<tr><td>5G</td></tr>
<tr><td>Measurement</td><td>Location 11</td><td>Location 7, 8</td><td colspan="2">Notes</td></tr>
<tr><td rowspan="2">Latency (ms)</td><td>21.1</td><td>25.7</td><td colspan="2" rowspan="8">The average values of measurements show the impact intensity of boosting RSRP and SINR on network performance at UE.</td></tr>
<tr><td>15.6</td><td>29.0</td></tr>
<tr><td rowspan="2">Upload Throughput (Mbps)</td><td>37.7</td><td>36.5</td></tr>
<tr><td>55.5</td><td>31.7</td></tr>
<tr><td rowspan="2">Download throughput (Mbps)</td><td>62.6</td><td>119.0</td></tr>
<tr><td>272.5</td><td>24.9</td></tr>
<tr><td rowspan="2">RSRP (dBm)</td><td>-78.6</td><td>-85.0</td></tr>
<tr><td>-86.4</td><td>-93.1</td></tr>
</table>

Note: The SINR 5G measurements are not considered in comparing the results of location 11 with the other locations. The reason is that the measurements software missed the values of SINR 5G of locations 7 and 8.

Conclusion

Generally, increasing the RSRP in an indoor propagation environment will boost service performance at UE. The impact of RSRP increasing is noticed clearly in the improvement of latency and download throughput performances of 5G in Table 10. This conclusion supports the conclusion of the indoor propagation environment versus the LoS propagation environment in Urban and Suburban areas.

9.2 Measurements comparison of Urban area versus Suburban area

This perspective investigates and shows the overall impact of the Urban and Suburban areas on the service quality and performance at the UE in all propagation environments gathered. Furthermore, this perspective concludes the reasons behind the measurement variations in the Urban versus Suburban areas. And finally, make proposals about how to enhance the service quality and network performance at UE, based on the measurement results analyses.

From Table 7, the measurements in locations of each Urban and Suburban area are averaged as in Table 11. The average values of measurements in Table 11 represent an indicator of the impact intensity of the Urban area versus the Suburban area on the service quality and performance at the UE.

9.2.1 Tampere city center (Urban) versus Hervanta (Suburban)

In this section, the overall average values of latency, upload throughput, and download throughput measurements of all propagation environments together are compared. This section aims to show the impact of different areas on the service performance at UE. Table 11 below shows the variation percentage of 4G and 5G levels of performance.

Table 11. *Average latency and throughput measurements in the Suburban area versus the Urban area.*

The green shaded cells are for 4G percentages, while the light pink shaded cells are for 5G percentages.				4G / 5G
Generation	Latency (ms)	Upload (Mbps)	Download (Mbps)	Notes
Urban	21.1	51.7	169.1	The average values of measurements show the impact intensity of Urban versus Suburban areas on network performance at UE.
	17.6	63.0	231.3	
Suburban	23.8	45.9	182.5	
	21.9	51.5	225.0	

By checking Table 7 and Table 11, the latency measurement is the most impacted service side at UE when moving from Urban to Suburban areas. In comparison, the upload throughput performance is less impacted, and lastly, the download throughput performance.

Overall, the Urban area has shown a better service quality at the UE, especially on the 5G. In comparison, the difference was unnoticed on the 4G side.

Conclusion

By having denser deployment of antennas in the Suburban area, the coverage will be improved and thus the service quality at UE. Especially on 5G, where the level of service performance at UE will be boosted even more because of the higher attenuation of RSRP_5G and SINR_5G at UE compared with 4G.

9.3 Conclusions summary

The summary of conclusions can be briefed in several points:

- Deploying indoor antennas of 5G will boost the RSRP_5G at UE; thus, the service is improved at UE.
- Denser deployment of 5G antennas in cities will improve the coverage so that the likelihood of having NLoS propagation cases is reduced, and the service is enhanced at UE.
- Denser deployment of 5G antennas in Suburban areas will improve the coverage, which will enhance the overall service at UE in different propagation environments.
- Although the deployment of 5G NSA has not finished until now. The obtained measurements show that the delivered level of service quality of 5G at the UE is better than the 4G. Therefore, it is logical to expect that the gap between 4G and 5G performances will increase as 5G deployment continues, where more 5G coverage will be available.
- Based on the previous comparisons and conclusions and by assuming the wider coverage of 5G SA and the role of mmWaves in 5G SA (from the perspective of wireless communications), the 5GC abilities will boost the service quality and performance.
- Finally, based on the previous conclusions, it is clear that the services' diversity and performance of the 5G SA wireless cellular network will be even beyond what 5G NSA will provide after the deployment completion.

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APPENDIX A

Table 12. *Allowed slot formats for normal cyclic prefix, according to [3GPP] [65].*

Format	Symbol number in a slot (14 Symbols)													
	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	D	D	D	D	D	D	D	D	D	D	D	D	D	D
1	U	U	U	U	U	U	U	U	U	U	U	U	U	U
2	F	F	F	F	F	F	F	F	F	F	F	F	F	F
3	D	D	D	D	D	D	D	D	D	D	D	D	D	F
4	D	D	D	D	D	D	D	D	D	D	D	D	F	F
5	D	D	D	D	D	D	D	D	D	D	D	F	F	F
6	D	D	D	D	D	D	D	D	D	D	F	F	F	F
7	D	D	D	D	D	D	D	D	D	F	F	F	F	F
8	F	F	F	F	F	F	F	F	F	F	F	F	F	U
9	F	F	F	F	F	F	F	F	F	F	F	F	U	U
10	F	U	U	U	U	U	U	U	U	U	U	U	U	U
11	F	F	U	U	U	U	U	U	U	U	U	U	U	U
12	F	F	F	U	U	U	U	U	U	U	U	U	U	U
13	F	F	F	F	U	U	U	U	U	U	U	U	U	U
14	F	F	F	F	F	U	U	U	U	U	U	U	U	U
15	F	F	F	F	F	F	U	U	U	U	U	U	U	U
16	D	F	F	F	F	F	F	F	F	F	F	F	F	F
17	D	D	F	F	F	F	F	F	F	F	F	F	F	F
18	D	D	D	F	F	F	F	F	F	F	F	F	F	F
19	D	F	F	F	F	F	F	F	F	F	F	F	F	U
20	D	D	F	F	F	F	F	F	F	F	F	F	F	U
21	D	D	D	F	F	F	F	F	F	F	F	F	F	U
22	D	F	F	F	F	F	F	F	F	F	F	F	U	U
23	D	D	F	F	F	F	F	F	F	F	F	F	U	U
24	D	D	D	F	F	F	F	F	F	F	F	F	U	U
25	D	F	F	F	F	F	F	F	F	F	F	U	U	U
26	D	D	F	F	F	F	F	F	F	F	F	U	U	U
27	D	D	D	F	F	F	F	F	F	F	F	U	U	U
28	D	D	D	D	D	D	D	D	D	D	D	D	F	U
29	D	D	D	D	D	D	D	D	D	D	D	F	F	U
30	D	D	D	D	D	D	D	D	D	D	F	F	F	U
31	D	D	D	D	D	D	D	D	D	D	D	F	U	U
32	D	D	D	D	D	D	D	D	D	D	F	F	U	U
33	D	D	D	D	D	D	D	D	D	F	F	F	U	U
34	D	F	U	U	U	U	U	U	U	U	U	U	U	U
35	D	D	F	U	U	U	U	U	U	U	U	U	U	U
36	D	D	D	F	U	U	U	U	U	U	U	U	U	U
37	D	F	F	U	U	U	U	U	U	U	U	U	U	U
38	D	D	F	F	U	U	U	U	U	U	U	U	U	U
39	D	D	D	F	F	U	U	U	U	U	U	U	U	U
40	D	F	F	F	U	U	U	U	U	U	U	U	U	U
41	D	D	F	F	F	U	U	U	U	U	U	U	U	U
42	D	D	D	F	F	F	U	U	U	U	U	U	U	U
43	D	D	D	D	D	D	D	D	D	F	F	F	F	U
44	D	D	D	D	D	D	F	F	F	F	F	F	U	U
45	D	D	D	D	D	D	F	F	U	U	U	U	U	U
46	D	D	D	D	D	F	U	D	D	D	D	D	F	U
47	D	D	F	U	U	U	U	D	D	F	U	U	U	U
48	D	F	U	U	U	U	U	D	F	U	U	U	U	U
49	D	D	D	D	F	F	U	D	D	D	D	F	F	U
50	D	D	F	F	U	U	U	D	D	F	F	U	U	U
51	D	F	F	U	U	U	U	D	F	F	U	U	U	U
52	D	F	F	F	F	F	U	D	F	F	F	F	F	U
53	D	D	F	F	F	F	U	D	D	F	F	F	F	U
54	F	F	F	F	F	F	F	D	D	D	D	D	D	D
55	D	D	F	F	F	U	U	U	D	D	D	D	D	D
56 – 254	Reserved													
255	UE determines the slot format for the slot based on TDD-UL-DL-Configuration Common, or TDD-UL-DL Configuration Dedicated and, if any, on detected DCI formats.													

Table 13. *A high-level overview of migration step analysis results [19].*

Path number	Path	Use Case	Deployment	Device and Network	Voice
1	EPS to SA#2	Full 5G use cases	5G Core benefit is	Little impact on 4G	IMS Voice Supported
			Needs to retain EPC	4G/5G system interworking required	No Circuit Switched (CS) interworking from 5GS
2	EPS to NSA#3	Limited support for 5G use case	Leverage	market No 5G Core Benefit is	Leverage existing VOLTE service
			Quick time to market	EPC procedures impact on 4G	
			No 5G Core benefit is		
3	NSA#3 to NSA#7 and SA#5	Full 5G use cases	5G Core benefit is	Impact on NR,	IMS Voice supported
		Initially limited	Needs to retain EPC	Impact on IMS	No Circuit Switched (CS) interworking from 5GS
				5GC deployment	
4	NSA#3 to NSA#3 and SA#2	Full 5G use cases	5G Core benefit is	Impact on NR,	IMS Voice supported
		Initially limited	Needs to retain EPC	Impact on IMS	No Circuit Switched (CS) interworking from 5GS
		Core migration	Wide area NR	5GC deployment	
5	NSA#3 to NSA#4 and SA#2	Full 5G use cases	5G Core benefit is	Impact on NR,	IMS Voice Supported
		Initially limited	Needs to retain EPC	Impact on IMS	No Circuit Switched (CS) interworking from 5GS
		Core migration		5GC deployment	

Table 14. *Downlink physical layer parameter values set by the field UE -Category [76].*

UE Category	Maximum number of DL-SCH transport block bits received within a TTI (Note 1)	Maximum number of bits of a DL-SCH transport block received within a TTI	Total number of soft channel bits	Maximum number of supported layers for spatial multiplexing in DL
Category 1	10296	10296	250368	1
Category 2	51024	51024	1237248	2
Category 3	102048	75376	1237248	2
Category 4	150752	75376	1827072	2
Category 5	299552	149776	3667200	4
Category 6	301504	149776 (4 layers, 64QAM) 75376 (2 layers, 64QAM)	3654144	2 or 4
Category 7	301504	149776 (4 layers, 64QAM) 75376 (2 layers, 64QAM)	3654144	2 or 4
Category 8	2998560	299856	35982720	8
Category 9	452256	149776 (4 layers, 64QAM) 75376 (2 layers, 64QAM)	5481216	2 or 4
Category 10	452256	149776 (4 layers, 64QAM) 75376 (2 layers, 64QAM)	5481216	2 or 4
Category 11	603008	149776 (4 layers, 64QAM) 195816 (4 layers, 256QAM) 75376 (2 layers, 64QAM) 97896 (2 layers, 256QAM)	7308288	2 or 4
Category 12	603008	149776 (4 layers, 64QAM) 195816 (4 layers, 256QAM) 75376 (2 layers, 64QAM) 97896 (2 layers, 256QAM)	7308288	2 or 4

Table 15. *Uplink physical layer parameter values set by the field UE Category [76].*

UE Category	Maximum number of UL-SCH transport block bits transmitted within a TTI	Maximum number of bits of an UL-SCH transport block trans-mitted within a TTI	Support for 64QAM in UL
Category 1	5160	5160	No
Category 2	25456	25456	No
Category 3	51024	51024	No
Category 4	51024	51024	No
Category 5	75376	75376	Yes
Category 6	51024	51024	No
Category 7	102048	51024	No
Category 8	1497760	149776	Yes
Category 9	51024	51024	No
Category 10	102048	51024	No
Category 11	51024	51024	No
Category 12	102048	51024	No

Table 16. *Operated frequency bands of Elisa cellular network [77].*

eNB, en-gNB receiving frequency band (MHz)	eNB, en-gNB transmitting fre-quency band (MHz)	Technology
713 – 723	768 – 778	LTE
852 – 862	811 – 821	LTE
1760.1 – 1784.9	1855.1 – 1879.9	GSM, UTRA FDD, LTE
1920.3 – 1940.1	2110.3 – 2130.1	UTRA, LTE, 5G NR
2545 – 2570	2665 – 2690	LTE, 5G NR
3480 – 3540	3480 – 3540	5G NR
3660 – 3730	3660 – 3730	5G NR

APPENDIX B

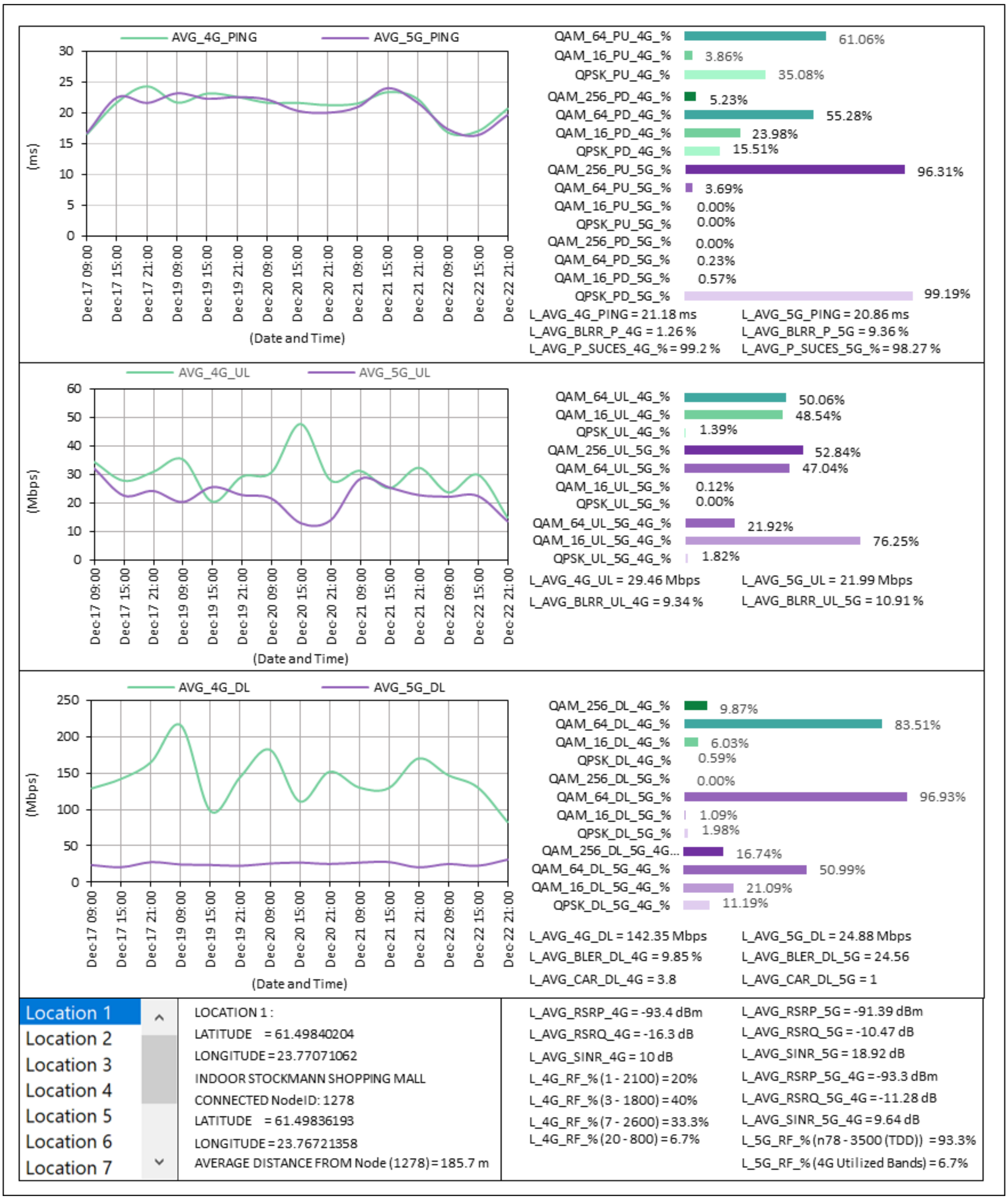

Figure 23. *Measurements and relevant parameters of location 1.*

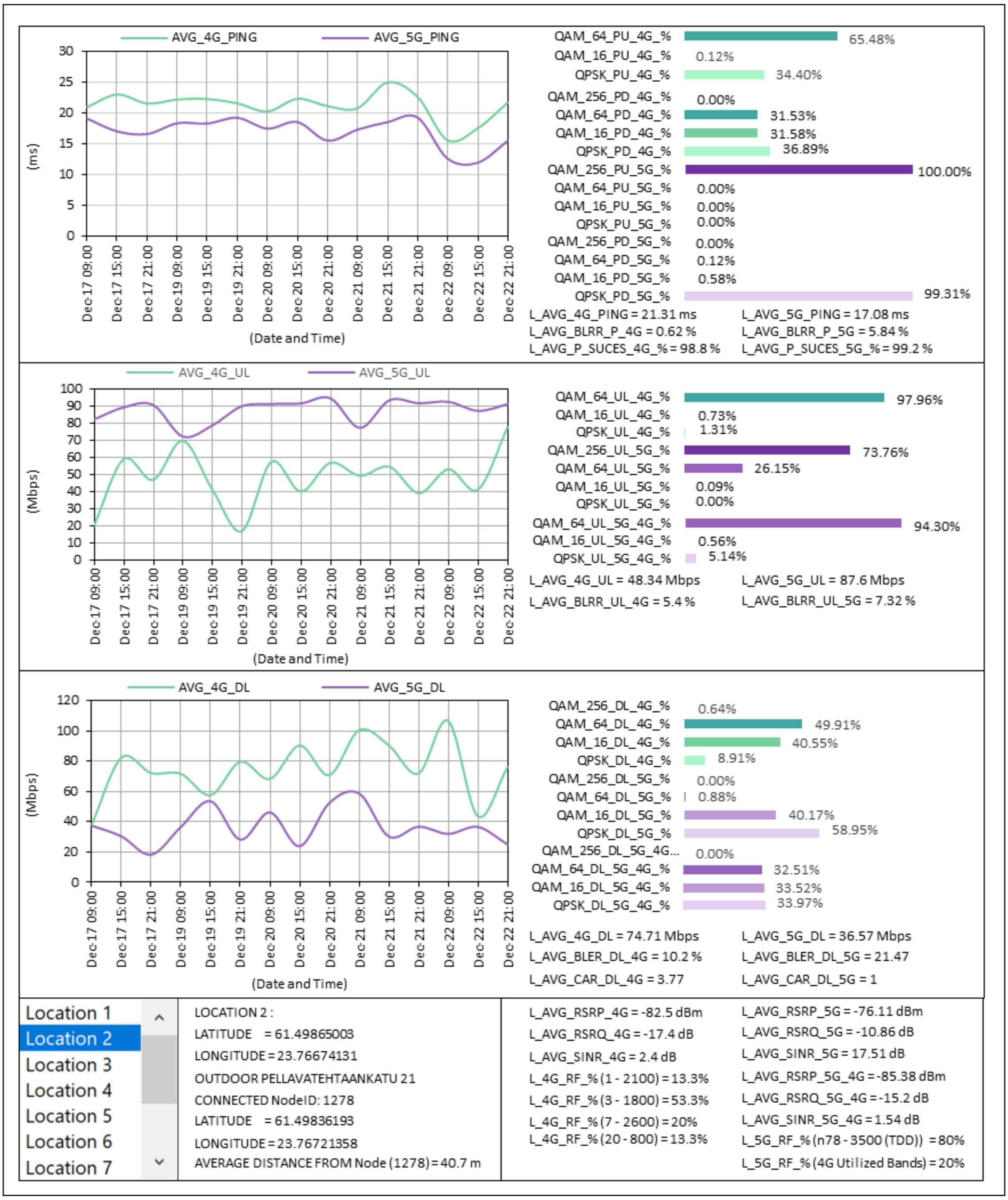

Figure 24. *Measurements and relevant parameters of location 2.*

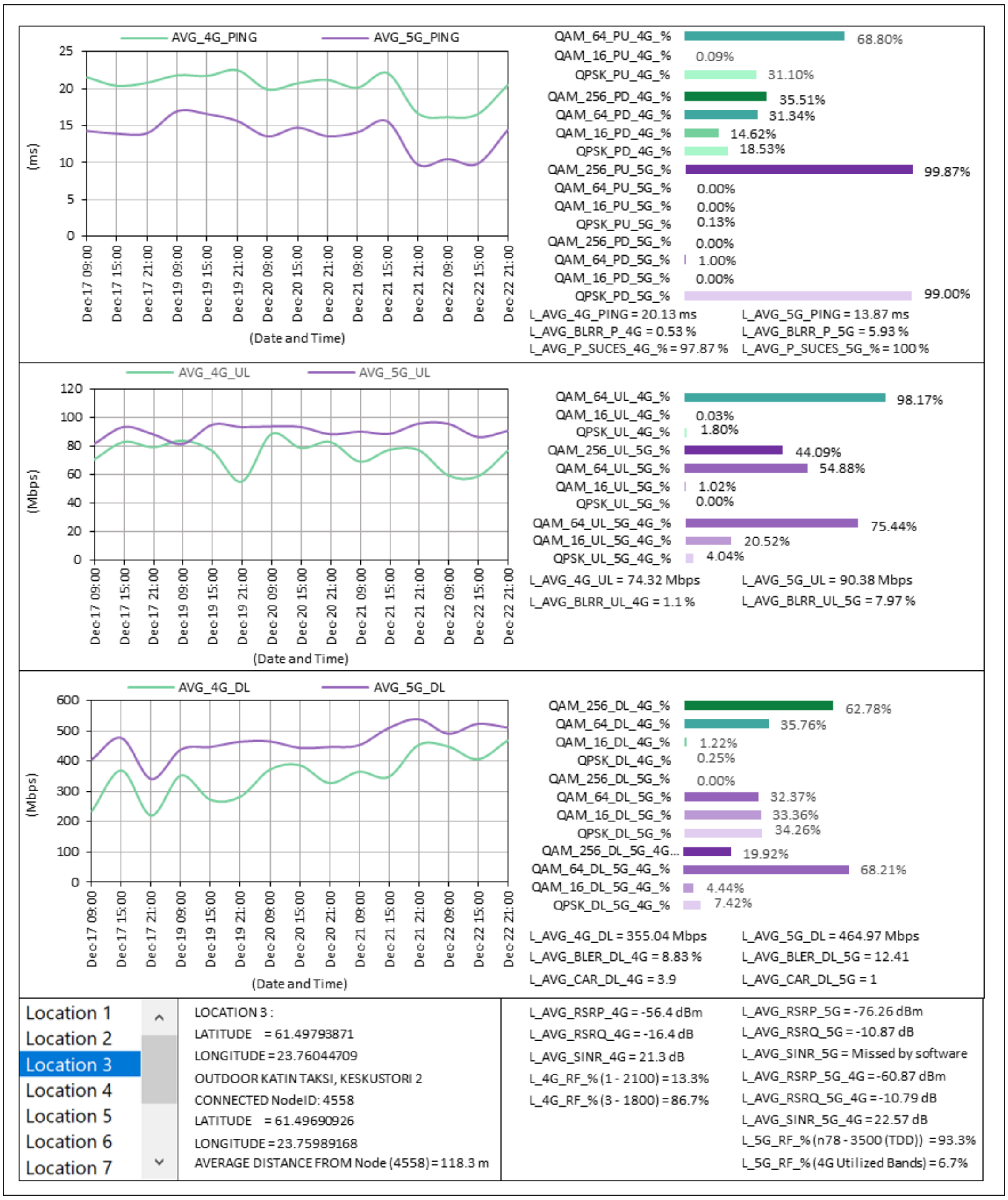

Figure 25. *Measurements and relevant parameters of location 3.*

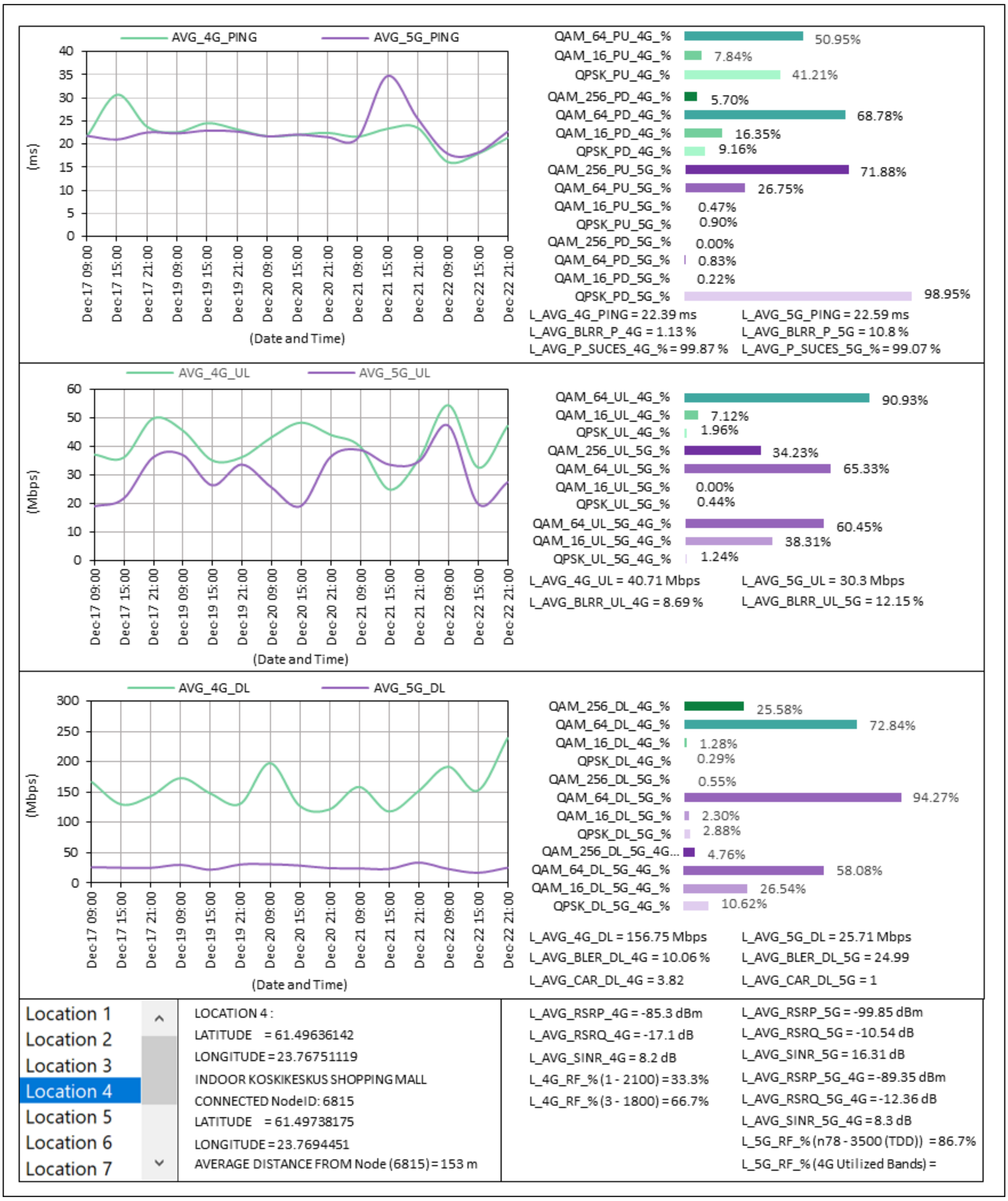

Figure 26. *Measurements and relevant parameters of location 4.*

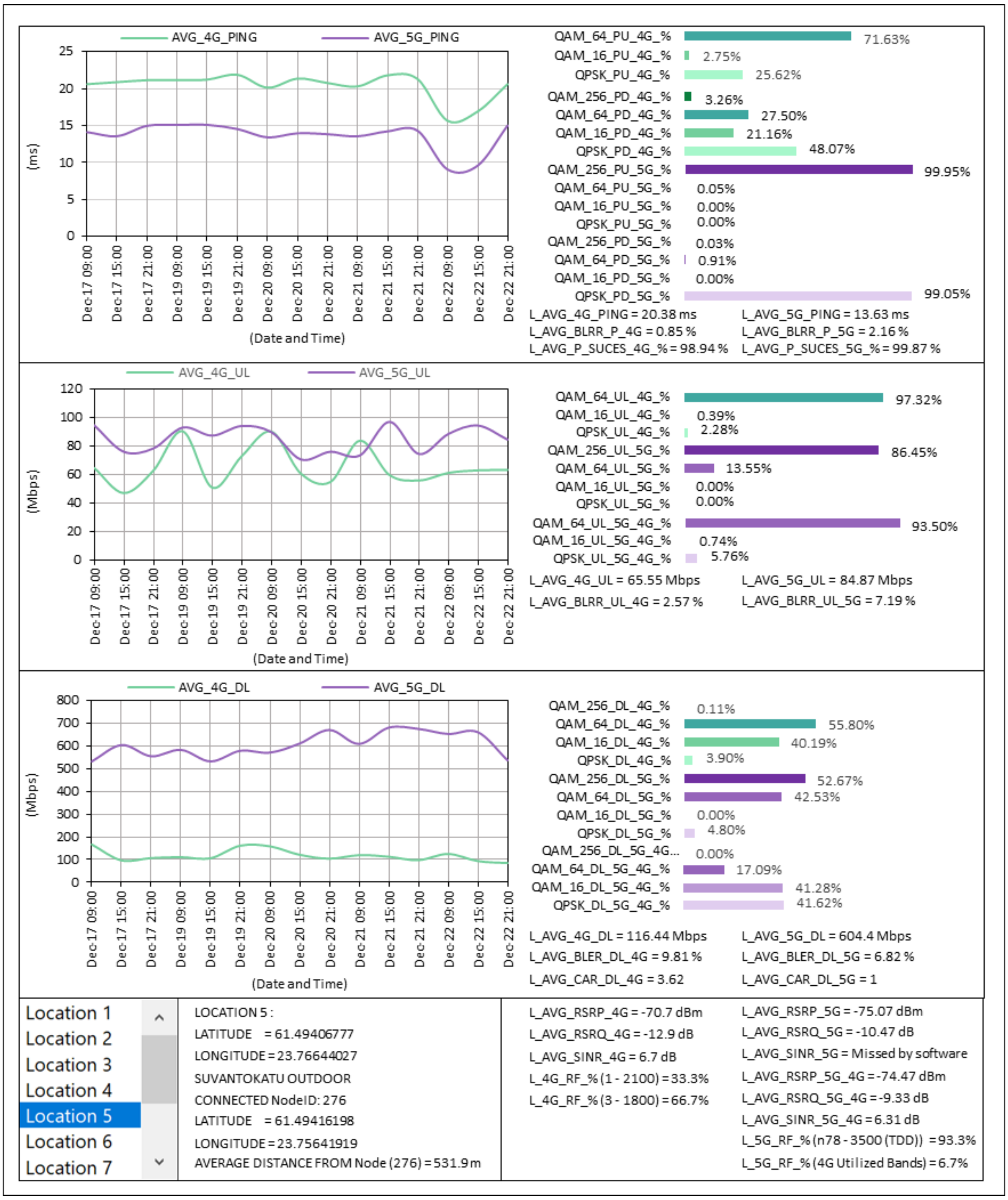

***Figure 27**. Measurements and relevant parameters of location 5.*

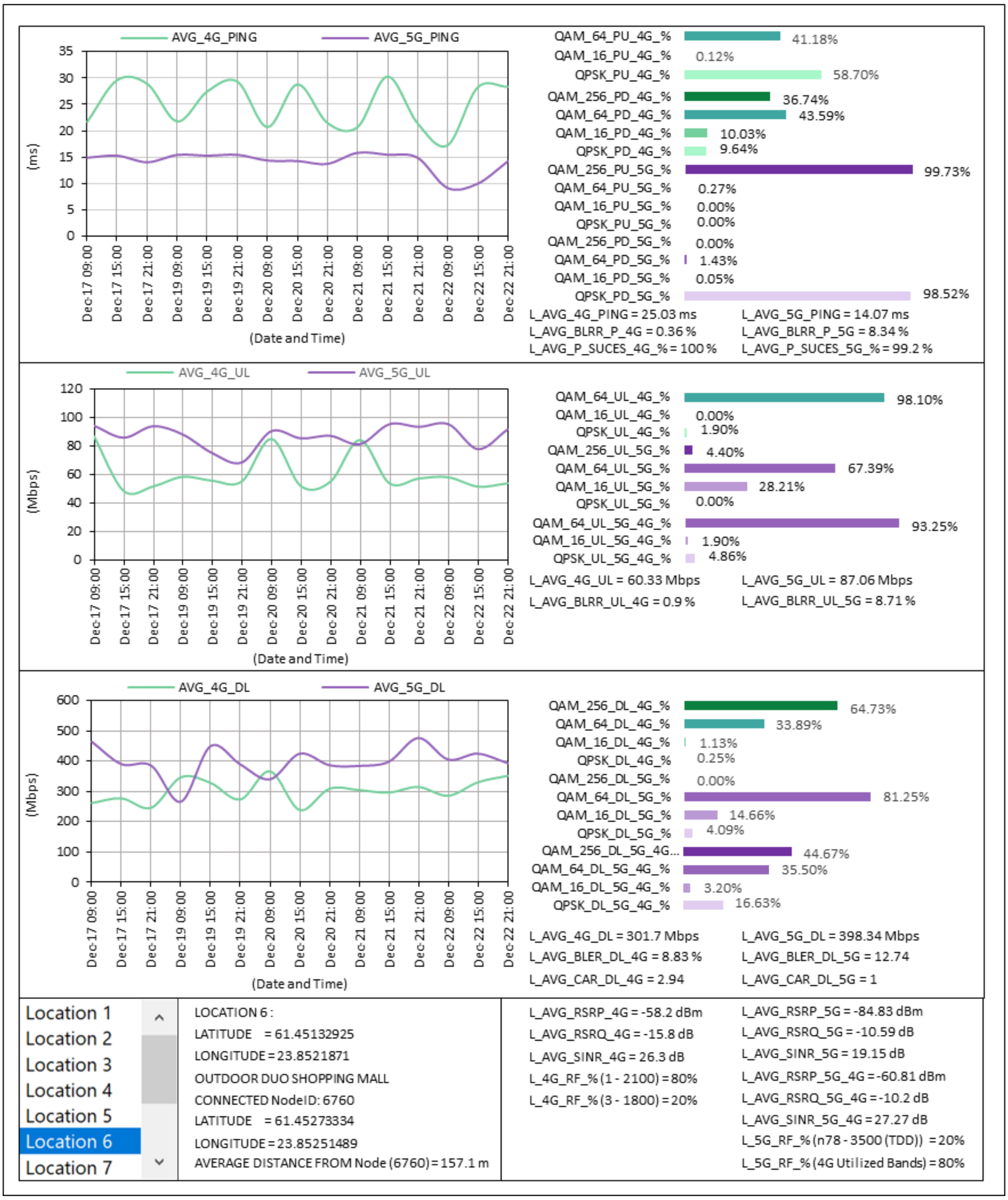

Figure 28. *Measurements and relevant parameters of location 6.*

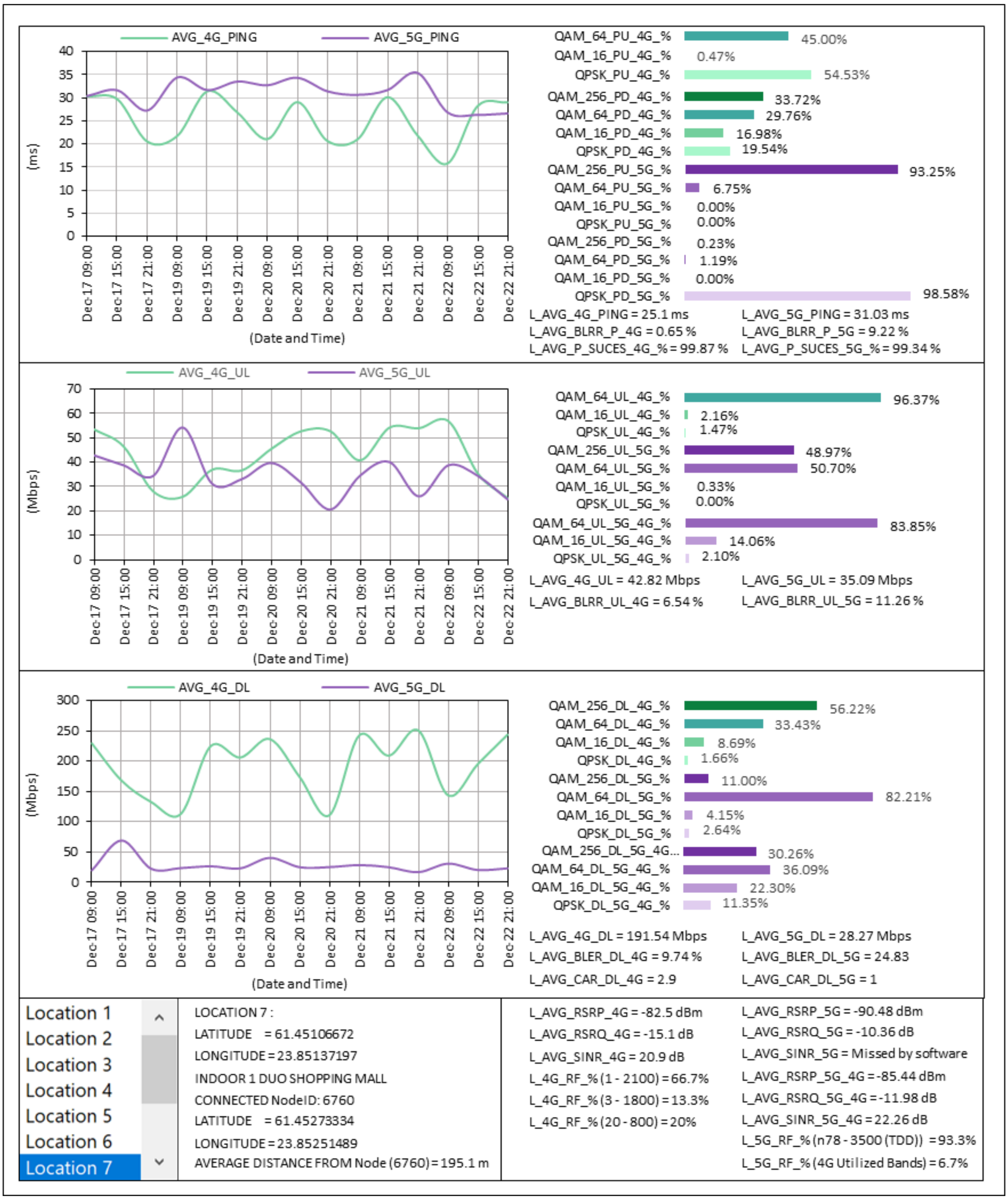

Figure 29. *Measurements and relevant parameters of location 7.*

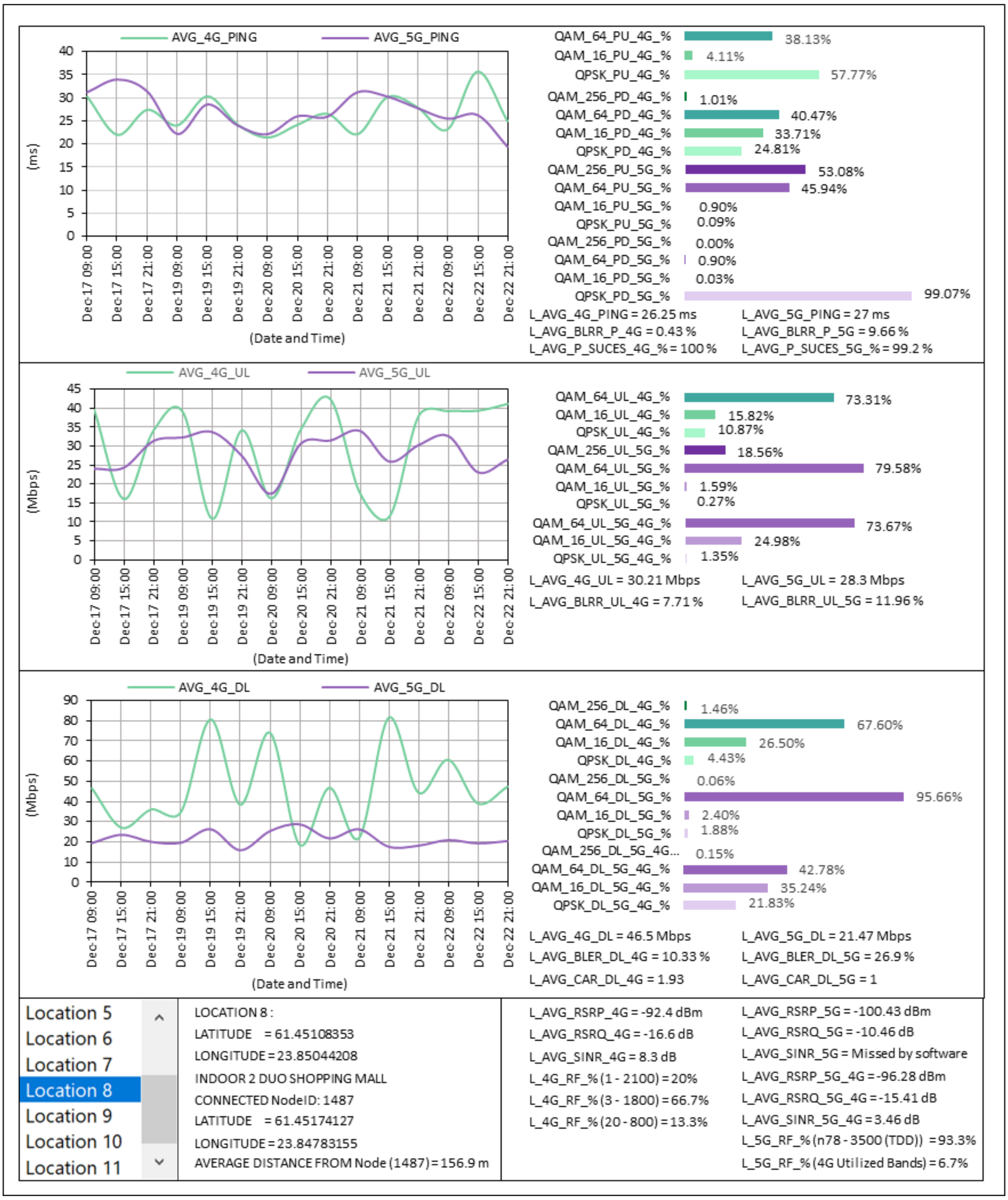

Figure 30. *Measurements and relevant parameters of location 8.*

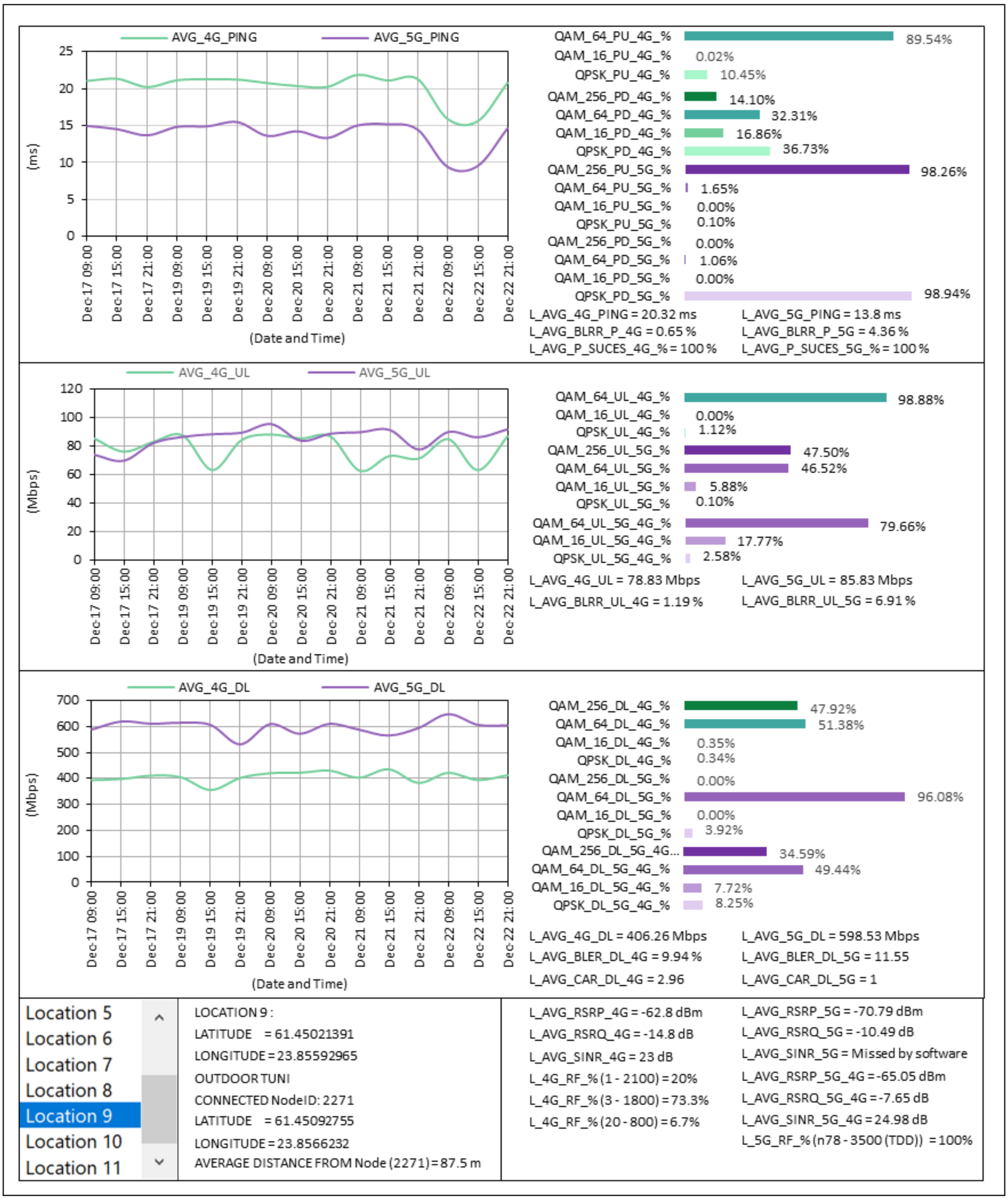

Figure 31. *Measurements and relevant parameters of location 9.*

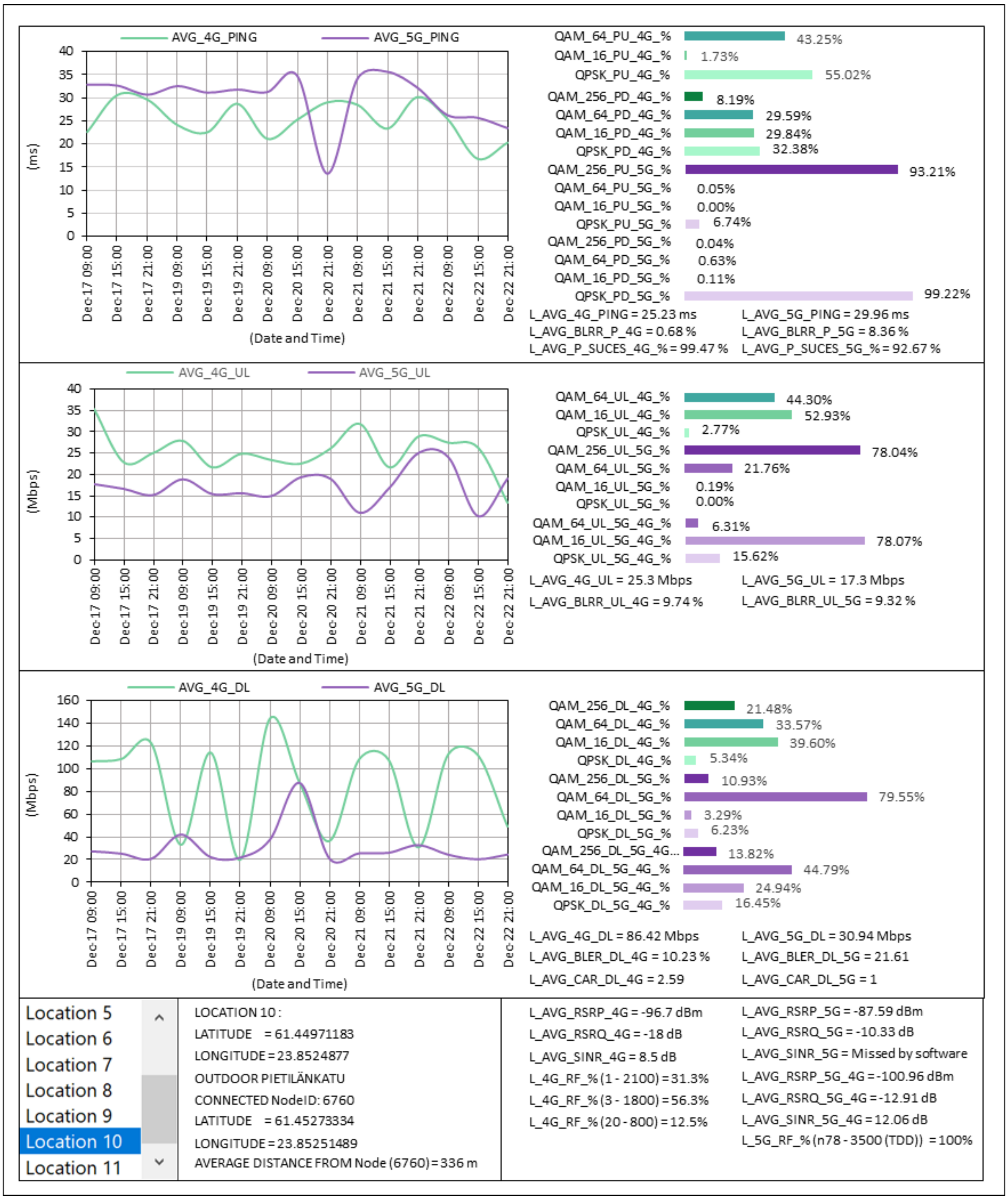

Figure 32. *Measurements and relevant parameters of location 10.*

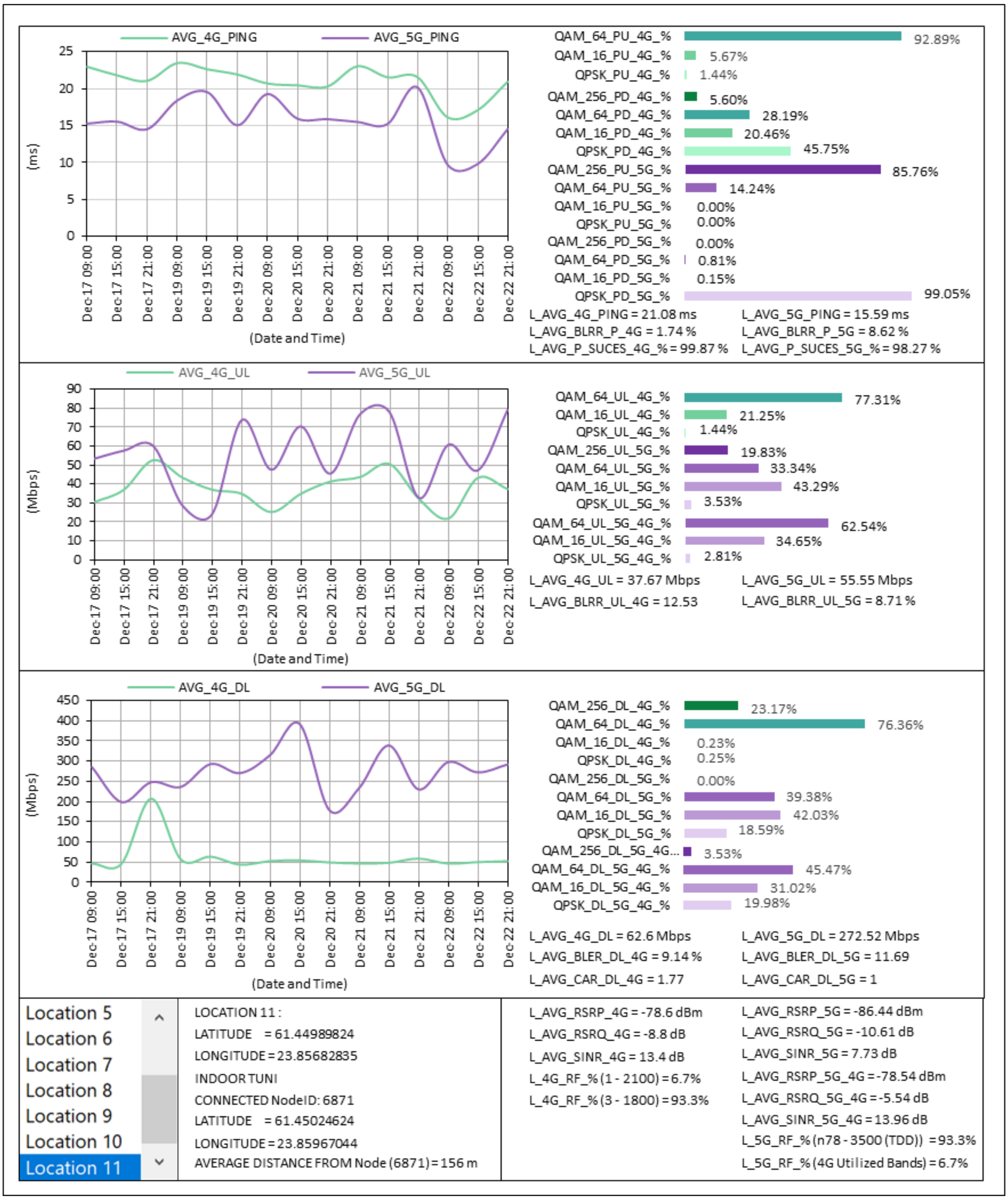

Figure 33. *Measurements and relevant parameters of location 11.*