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UTILIZATION OF CLOUD RAN ARCHITECTURE WITH ECPRI FRONTHAUL IN 5G NETWORK

Master's Thesis
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ABSTRACT

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With increased reliability, massive network capacity, and extremely reduced latency, 5G expands the mobile ecosystem into new realms. 5G impacts every industry and innovation, making transportation and conveyance safer, remote healthcare, accuracy agriculture, digitized logistics, and much more. In this age, 5G calls for new levels of flexibility and broadness in architecting, scaling, and deploying telecommunication networks, which need a further step ahead in technology and enter Cloud Technology. Cloud technology provides fascinating possibilities to complement the existing tried and tested technologies in the Radio Access Network (RAN) domain. Cloud RAN (CRAN) refers to relying on RAN functions over an inclusive platform instead of a purpose-built hardware platform. It represents a progression in wireless communication technology, leveraging the Common public radio interface (CPRI) standard, Dense Wavelength Division Multiplexing (DWDM) innovation, and millimeter wave (mmWave) propagation for extended-range signals. A CRAN network comprises of three fundamental elements. The initial element is the Distant Wireless Unit (DRU) or Remote Radio Component (RRH), utilized within a network to link wireless devices to entry points; these units are equipped with transceivers for transmitting and receiving signals. Next, a Baseband Unit (BBU) centre or hub serves as a centralized site functioning as a data processing hub. Separate BBU modules can be assembled independently or interconnected to distribute resources, adapting to the network's changing dynamics and needs. Communication among these modules boasts remarkably high bandwidth and exceptionally low latency. The BBU can be further segmented into DU (Distributed Unit) and CU (Centralized Unit). The third crucial component is a front-haul or conveyance network – the connecting layer between a baseband unit (BBU) and a set of RRUs, utilizing optical fibres, cellular links, or mmWave communication.
The goal of this thesis is to find a way to utilize the 5G RAN Architecture as efficiently as possible and for this purpose, Enhanced Common Public Radio Interface (eCPRI) or enhanced CPRI fronthaul is adopted instead of CPRI as it is a manner of splitting up the functions performed by baseband unit and putting some of that in the RRU so it can reduce the burden on the fibre. Enhanced CPRI makes it possible to send some data packets to a virtual Distributed Unit (vDU) and others to a virtual Centralized Unit (vCU) which results in reduced data traffic on fibre.
The first part of this research paper focuses on considering and learning about the 5G Cloud RAN architecture's main components, some cloud RAN history, and important components included in the 5G Cloud RAN. In the second part, research goes in depth about the fronthaul gateway technology that is eCPRI structure, its functional split, its difference from CPRI in structure and functionality, and how it is enhanced and developed. Considering CRAN specifications, it will also include some eCPRI protocol delay management and timing studies. Finally, Test cases are developed that can authenticate the low latency and high throughput of data with eCPRI fronthaul in 5G Cloud RAN as compared to CPRI fronthaul. The inspiration behind this is to recreate the model with substantial changes that work with an ideal behaviour of a subsystem, with this a tool or an environment can be obtained that maximizes the efficiency of 5G CRAN. It will also permit network architects and designers to experiment with new features, which can reduce costs, save time, improve latency. It can also provide a tool to verification engineers that will help them to generate optimal replies of the system necessary for evaluating the practical realization of that system.

Keywords: Cloud RAN, Fronthaul, Gateway, eCPRI, 5G Architecture

The originality of this thesis has been checked using the Turnitin Originality Check service.

PREFACE

In the Name of Allah, the Forever Kind, and the Forever Loving. I am extremely thankful to God for the many gifts and inner strength that He has given me, enabling me to complete my thesis endeavour with courage and competence.

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Tampere, 16 October 2023

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LIST OF SYMBOLS AND ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth generation
5G	Fifth Generation
5G NR	5G New Radio
AR	Augmented reality
ARIB	Association of Radio Industries and Business
ASIC	Application Specific Integrated Circuit
ATIS	Alliance for Telecommunication Industries
ATM	Asynchronous Transfer Mode
BBU	Baseband Unit
BS	Base Station
BTS	Base Transceiver Station
CRAN	Cloud Radio Access Network
CDMA	Code Division Multiple Access
CPRI	Common Public Radio Interface
CUPS	Control and User Plane Separation
DCs	Data Centers
E2E	End to End
eCPRI	enhanced Common Public Radio Interface
EDGE	Enhanced Data for GSM Evolution
eMBB	Enhanced Mobile Broadband
ENDC	E-UTRAN New Radio – Dual Connectivity
EPC	Evolved Packet Core
eRE	eCPRI Radio Equipment
eREC	eCPRI Radio Equipment Control
ETACS	Extended Total Access Communication System
ETSI	European Telecommunication Standard Institute
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FH	Fronthaul
FHGW	Fronthaul Gateway
FPGA	Field Programmable Gate Array
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Service
GSM	Global System for Mobile
HD	High Definition
HW/SW	Hardware/Software
IEC	International Electrotechnical Commission
IMPS	Improved Mobile Phone System
IoT	Internet of Things
ISO	International Organization for Standardization
ITS	International Transportation System
ITU	International Telecommunication Union-Telecommunication
IWF	Interworking Function
LLS	Lower layer Split
LTE	Long-Term Evolution
MCE	Mobile Cloud Engine
MG	Mobile Gateway
MIMO	Multiple Input Multiple Output
MTSO	Mobile Telephone Switching Office

mMTC	massive Machine Type Communication
MSC	Mobile Switching Centre
NSA	Non-Standalone
NVF	Network Function Virtualization
O-RAN	Open Radio Access Network
OAM	Operations, administration, and management
OBSAI	Open Base Station Architecture Initiative
PDN	Packet Data Network
PGW	PDN Gateway
PLL	Permutation of Last Layer
PSTN	Public Switched Telephone Network
PRBs	Pseudo Random Binary Sequences
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RFSW	Radio Frequency Software
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RRU	Remote Radio Unit
RU	Radio Unit
SA	Standalone
SAE	System Architecture Evolution
SCF	Site Configuration File
SDN	Software Defined Network
SGN	Service Gateway
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
SMS	Short Message Service
TACS	Total Access Communication System
TCXO	Temperature Compensated Crystal Oscillator
TRAU	Transcoder and Rate Adaption Unit
TTA	Telecommunication Technology Association
TTC	Telecommunication Technology Commission
UE	User Equipment
UICCS	Universal Integrated Circuit Cards
UMTS	Universal Mobile Telecommunication System
URLLC	Ultra-reliable and Low-latency Communications
USIM	Universal Subscriber Identity Module
UTRAN	Universal Terrestrial Radio Access Network
vCU	virtual Centralized Unit
vDU	virtual Distributed Unit
VR	Virtual Reality
VRAN	Virtual Radio Access Network
WCDMA	Wideband Code Division Multiple Access

1. INTRODUCTION

In the Late 1800s, Guglielmo Marconi paved the way for modern wireless communications, he transmitted Morse code by using electromagnetic waves. Wireless communications now have developed into a fundamental aspect of modern society, it has inspired specialized studies like remote sensing, signal processing, wireless embedded technologies, et cetera. The utilization of the radio spectrum is crucial for wireless communications, and this compelled the creation of supporting technologies, particularly those that could optimize higher frequencies. To efficiently utilize the spectrum, it was imperative to establish synchronized standards.

The mobile wireless industry has been formatting, revolutionizing, and developing its technology since the early 1970s. Mobile wireless technologies have been classified according to the features/generation that was offered, which mainly specify the type of services accessible and the data transfer speeds of each class of technologies [1].

Wireless transmission seeks to deliver top-notch, swift, and dependable communication akin to wired interaction and optical fiber. Every successive iteration of networks brought a significant set of services and milestones in the development of mobile communications and each new generation of services represents a big leap in that direction. In 1979 this journey of evolution started from First Generation (1G) and now it is the era of the Fifth Generation (5G) and still counting. Another important aspect to be discussed is wireless communication cellular architecture.[2] Its structure is divided into two fundamental components: Radio Access Network (RAN) and a Mobile Core Network (MCN). The RAN is linked to the MCN formed by a cloud platform, via a backhaul connection, and subsequently, the MCN linked to the internet and various other service providers through a fronthaul connection. The RAN constitutes the segment that establishes a connection between user equipment and other sectors of the mobile network through a wireless link. It encompasses numerous interconnected radio base stations, RF antennas, and microwave antennas. The RAN is further segregated into two distinct logical entities. The initial one is the radio unit (RU), which carries the responsibility for modulating and demodulating the transmitted as well as received signals. In contrast, the secondary entity, known as the baseband unit (BBU), oversees radio communication, radio control processing, and digital data manipulation. The BBU and RU are primarily physically apart, joined solely by an interface generally acknowledged as the fronthaul. This interface materializes as a fiber optic connection, ensuring the smooth data transmission between the RU and the BBU. Among the primary fronthaul protocols for 5G base stations, the Common Protocol Radio Interface (CPRI) and the enhanced Common Protocol Radio Interface (eCPRI) take precedence. An RAN architecture comprises multiple Remote Radio Units (RRUs) interconnected with the Baseband Unit (BBU) through the fronthaul. Consequently, the BBU establishes a link with the Core Network through the backhaul, as illustrated in the provided diagram:

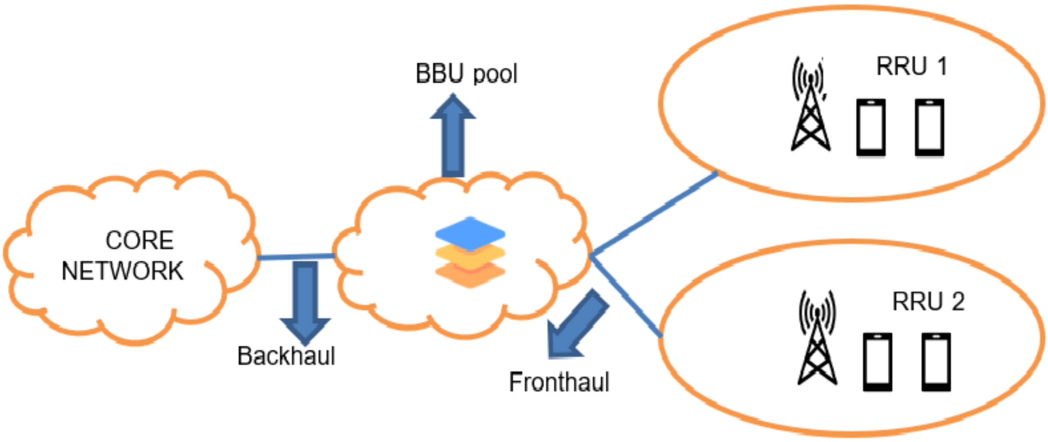


Figure 1. *The architecture of RAN.*

Timing Measurement and Testing For 5G New Radio. It illustrates that extremely low latency, heightened dependability, immense network capacity, and sustained availability are the driving forces behind 5G as a model for network advancement. It elucidates that multiple-transmitter multiple-receiver (MTMR), multi-band aggregation, extensive frequency range, and directional signal shaping are the fundamental catalysts of the upcoming generation of Radio Access Technology (RAT). This investigation primarily pertained to open RAN as opposed to Cloud RAN, yet it contributed to comprehending the transformation from CPRI to eCPRI. It demonstrates that for enhanced Network flexibility, the Open Radio Access Network (O-RAN) coalition introduces the concept of openness, disseminated to establish an unobstructed fronthaul based on the eCPRI Protocol. The initial stage of this thesis concentrated on examining the three primary components of the environment represented by BBU, 5G New Radio (5G NR), and eCPRI protocol. In the subsequent phase, the study expanded to encompass the Radio module and eCPRI, detailing all the protocol latency management and synchronization, all in accordance with the ORAN specifications. Differing from it this research is solely based on the maximum utilization of Cloud Radio Access Network (CRAN) architecture using the eCPRI fronthaul [4].

1.1 OVERVIEW

This research project involves delving into the most recent advancements in 5G Technologies. Given that networks are in the process of shifting from the conventional RAN to CRAN, this project will focus on this novel landscape. Following the setup of the necessary hardware, novel software concepts unique to the random-access network sector need to be established. Among the primary areas of investigation is the installation of Fronthaul Gateway (FHGW) within the Cloud setting. The FHGW assumes the role of a central hub, bridging the gap between the core and radio facets. After the FHGW deployment, the installation of vDU and vCU is imperative to finalize the installation of the CRAN environment.

The thesis titled "Towards 5G Mobile Networks: Exploring Cloud Radio Access Network Architecture" authored by Aleksandra Checko provided a comprehensive comprehension of the CRAN and 5G architectural paradigms. The study expounds that CRAN represents a network framework capable of tackling diverse obstacles encountered by mobile service providers in catering to the escalating demands of end-users in the context of the fifth-generation mobile networks (5G). Aleksandra's research underscores that the primary objective behind CRAN lies in the segmentation of base stations into distinct radio and baseband segments, subsequently aggregating the Baseband Units (BBUs) from numerous base stations into a centralized and virtualized BBU Pool. By means of resource sharing between the fronthaul component and other auxiliary services, the expenses associated with deploying and operating a fronthaul network can be curtailed. The potential to efficiently distribute baseband resources across multiple cells is an attribute inherent to conventional CRAN setups. Furthermore, the study identifies the viability of enhancing the efficiency of fronthaul resources through the application of packet-based fronthaul techniques. The research also delves into strategies for minimizing latency and jitter, exemplified by source scheduling and pre-emption methodologies [6].

After careful research and study, the purpose of writing this paper is to figure out ways and techniques that can be applied in 5G CRAN architecture to maximize its utilization and to figure out how eCPRI fronthaul can be utilized to its maximum extent.

1.2 RESEARCH QUESTION

The primary goal of the thesis is to employ the 5G CRAN alongside the eCPRI Front Haul Gateway. This represents a relatively novel technology that is presently undergoing developmental phases. A subset of objectives necessitates resolution prior to the implementation phase, accompanied by a set of important inquiries that must be answered beforehand.

The initial query pertains to the novelty of 5G CRAN technology, marking a decade since the usage of prior networks. What level of difficulty is involved in establishing a milieu for CRAN alongside the eCPRI FHGW. In addressing this specific inquiry, there are definite challenges to contend with. However, substantial exertion over the recent months and comprehensive research into emerging functionalities such as FHGW, vDU, and vCU have rendered the task comparatively more manageable. Though the developmental phase is ongoing, certain aspects tied to automation and hardware have posed predicaments. Yet, through systematic troubleshooting, many of these concerns have been mitigated. While configuring the eCPRI connection does not present an insurmountable hurdle, it remains imperative to thoroughly acquaint oneself with all relevant documentation before commencing the implementation of the environment.

Another question that comes up is regarding the rise of 5G CRAN, a fresh notion that has supplanted the prolonged utilization of traditional RAN. The concern at hand is how the performance impact of CRAN compares to that of the traditional RAN.

This presents a formidable challenge, necessitating a comprehensive assessment of whether CRAN can yield outcomes at least on par with traditional RAN. To achieve this, a strategic approach must be devised, underpinned by meticulous planning. With concerted efforts, the goal is to achieve commensurate results with the added complexity of burgeoning cloud demands. Notably, this escalating demand for cloud services has spurred the introduction of novel hardware components that offer superior performance. One such innovation is the RANIC card, a pioneering advancement within the domain of CRAN.

Another query is that what potential effects could arise from the integration of 5G CRAN in the future, and how advantageous is the utilization of eCPRI FHGW within a Cloud-based setting?

A fundamental motivator for transitioning from conventional RAN systems to CRAN lies in attaining heightened adaptability and improved scalability, amplified speed, and diminished latency. Unquestionably, moving forward, these aspects are poised to offer substantial benefits. Furthermore, when coupling eCPRI FHGW into the equation, the possibility of harnessing the potential of extensive MIMO concepts emerges, leading to significant advancements within the telecommunications sector.

2. 5G EVOLUTION AND CRAN ARCHITECTURE

Mobile networks have improved a lot in the past twenty years. They have become faster and can do many new things. There are five generations of mobile networks: 1G to 5G. "G" means Generation, and the number tells you which generation it is. 5G is the newest generation, and 1G is very old now. Some of the technologies used in mobile networks are Global System for Mobile (GSM), Universal Mobile Telecommunication System (UMTS), and Long-Term Evolution (LTE) and New Radio (NR) are used to enable 2G, 3G, 4G, and 5G, respectively. There are institutions in charge such as the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) each new version of mobile technology has certain rules it must follow. These rules decide things like how often it works, how fast it is, and how much delay it has.. Every new version is created after studying and improving upon the previous one. The first generation didn't focus on wireless technology until the second generation (2G) came along. This was a big change in technology because it shifted wireless networks from being analog to digital.

Third Generation (3G) set the standards for most of the wireless technology is known and benefited from. Most of the smartphone technologies were introduced in 3G such as video downloading, Web browsing, email, and picture sharing. The objectives set out for 3G mobile communication were to facilitate greater voice and data capacity, strengthen a wider range of applications, and raise data transmission at a reduced cost. The Fourth Generation (4G) is a different technology as compared to 3G. The main purpose of 4G is to provide high quality, high speed, and high capacity to users while at the same time improving security and lowering the cost of voice and data services, internet over IP, and multimedia. Gaming services, clear mobile TV, making audio and video calls through the internet, and using the internet for various tasks like storing data are all part of different applications. The latest mobile phones are made to work with older technology, so a 4G phone can still make calls and connect to the internet both the 3G and 4G networks. Now 5G network is using sophisticated, complex, and advanced technologies [7].

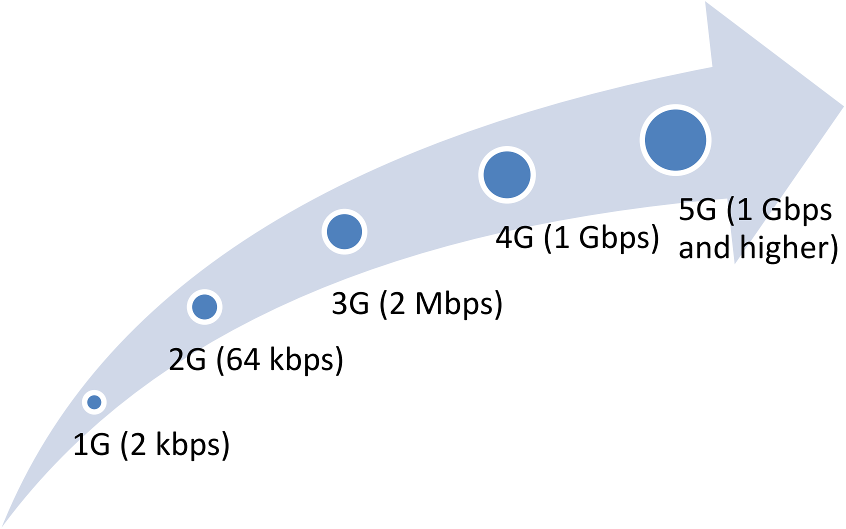


Figure 2. *Evolution of Mobile Network and its Respective Data Rate.*

The first generation can be summarized in how it all started, as in the 20th century, Mobile radio communications were used in military communications. During World War II, there was a significant development in the miniaturization of radio components, resulting in the creation of a handheld device known as the walkie-talkie. This device allowed for half-duplex communication, which meant that it could transmit or receive, but not both simultaneously, using push-to-talk technology. Upon returning from the war, veterans believed that this kind of wireless communication should be available to them in their civilian jobs. However, this was problematic, as the Public Switched Telephone Network (PSTN) was a wired system that relied on manual switching at telephone exchanges. [8] 1G, which stands for "first generation," refers to the earliest form of analog cellular technology. It was first introduced in the 1980s and relied on analog signals to transmit voice data over cell towers. The first commercially available 1G networks were launched in Japan in 1979, followed by the US in 1983. 1G was a significant improvement over traditional landline telephones as it provided wireless access to the telephone network. However, 1G had several drawbacks, including poor call quality, limited coverage, and low capacity. The analog signals used in 1G were also susceptible to interference, which led to dropped calls and reduced call quality [2].

Despite these limitations, 1G paved the way for the development of later cellular technologies, including 2G, 3G, and 4G. Its legacy can still be seen in older cellular technologies, such as AMPS (Advanced Mobile Phone System), the most popular 1G standard in North America.

Second generation cellular technology was first introduced in the early 1990s. It replaced the first-generation analog cellular technology with a digital alternative, providing improved call quality and more efficient use of the available frequency spectrum. The first commercial 2G network was launched by Radiolinja (now known as Elisa) in Finland in 1991. From there, 2G networks were gradually introduced in other countries around the world. The development of 2G technology was a significant step forward in the evolution of mobile communication, setting the stage for the development of newer and more advanced technologies like 3G, 4G, and 5G [9]. The second Generation (2G) can be described by the overview of the Global System for Mobile or GSM. The second Generation was able to transmit data at the rate of 9.6 kb/s. Major benefits were digitally encrypted conversations, more efficiency on the spectrum, greater mobile phone penetration, and the introduction of Short Message Service (SMS) [10].

Third Generation (3G) was introduced when higher demand and usage of telecommunication resulted in the establishment of 3GPP. In 1999, Universal Mobile Telecommunications Systems (UMTS) were introduced. This system uses Wideband Code Division Multiple Access (WCDMA). In 2000, governing bodies for 3GPP were formed to create global standards. Collaboration between GSM and UMTS expanded beyond ETSI and included regional standards organizations to ensure comprehensive development. These organizations included the Telecommunications Technology Association (TTA) from Korea, the Association of Radio Industries and Business (ARIB), the Telecommunication Technology Committee (TTC) from Japan, the Alliance for Telecommunications Industry (ATIS) from America, and the China Communication Standards Association (CCSA) from China. The successful creation of such a large and complex system specification required a well-structured organization, which further resulted in the birth of 3GPP and then the creation of the International Telecommunication Union (ITU) [11-13].

In the case of the Fourth Generation (4G) of telecommunications, the main aim was to make it easier for people to move around and connect with others all over the world. This new system includes something called Evolved UMTS Terrestrial Radio Access Network, which people usually just call E-UTRAN, and a thing called System Architecture Evolution (SAE). They started working on making 4G better in 2004, and after making it better a few times, they finalized something called Release 8 in June 2005. In Release 8, there are seven important things to know about it.

- Reduced delays for both connection establishment and transmission latency.
- Increased user data throughput.
- Increased cell edge bit rate.
- Reduced cost per bit, Implying Improved spectral efficiency.
- Simplified network architecture.

- Seamless mobility, indulging between different radio access technologies.
- Reasonable power consumption for mobile devices [14].

In terms of development, frequency, and data rate, different generations are compared in Table 1.

Table 1. *Comparison of different Generations and their Specification [9].*

	Development period	Technology	Frequency Bands	Data Rate	Access System	Core Network
1G	1970−1984	AMPS/NMT/TACS	0.85−1.9 GHz	2 kbps	FDMA	PSTN
2G	1980−1999	GSM	1.8 GHz	14.4−64 kbps	TDMA/CDMA	PSTN
3G	1990−2002	WCDMA	1.6−2 GHz	2 Mbps	CDMA	Packet network
4G	2000−2010	LTE/Wi-Max	2−8 GHz	200 Mbps−1 Gbps	CDMA	EPC
5G	2010−2015	MIMO/mmWaves	3−30 GHz	1 Gbps and higher	OFDM/BDMA	5GC

2.1 Telecom Generations and Network Architecture

The transition from one generation to the next is driven by industry standards, technological innovations, and the need to meet the growing demands of mobile users and emerging applications. Telecom generations refer to the different stages of technology and network architecture used in the telecommunications industry. These generations represent significant advancements in technology and standards for mobile and wireless communication. Following section represents the major telecom generations and their associated network architectures.

2.1.1 Analog Voice Technology

In December 1947, Douglas H. Ring published the first idea of a cellular mobile telephone network in the Bell Laboratories Memorandum, "Cellular Communication - Extensive Geographic Reach". Nonetheless, it wasn't until 1973 that Dr. Martin Cooper and his group at Motorola successfully engineered the initial functional cell phone. The initial mobile phones and networks relied on the Advanced Mobile Phone Service (AMPS) standard, using only unencrypted analog transmissions. Later, the AMPS standard was adjusted and adapted for use in the United Kingdom under the system was known as Total Connectivity Transmission System (TCTS). These initial-phase networks employed frequency modulation on 25 kHz wireless channels spanning from 890−905 MHz for communication cell phone transmissions, 935−995 MHz for cell base station transmissions, and 600 channels for voice transmission, they gave higher capacity and control signals. Frequency bands were made available in August 1986, expanding TACS

(ETACS) to encompass 872−905 MHz and 917−950 MHz, providing assistance for 1320 x 25 kHz channels. The below figure shows the architecture of First Generation RAN. The RAN was connected to Mobile Telephone Switching Office (MTSO) via microwaves and landline joined MTSO and PSTN [15].

Figure 3. *The Architecture of RAN in First Generation Mobile Network.*

The advantages and Disadvantages of analog voice technology can be seen as:

Advantages:

1. Simple: Analog voice technology is simple and easy to use, with no need for complex circuitry or software.
2. Reliable: Analog signals are not affected as much by interference and noise as digital signals. They can be transmitted over long distances without losing quality.
3. Cost-effective: Analog voice technology is cheaper to install and maintain than digital technology.
4. Compatible: Analog systems are compatible with most other communication systems.

Disadvantages:

1. Limited capacity: Analog systems have a limited capacity for transmitting and receiving data, which can limit the number of calls and make it difficult to expand the system.
2. Quality issues: Analog voice technology is vulnerable to distortion and noise, leading to poor call quality.

3. Security: Analog systems are less secure than digital systems, making them more vulnerable to eavesdropping and interception.
4. Old technology: Analog voice technology is an outdated technology that is being replaced by digital technology.

2.1.2 Digitization of GSM

The Global System for Mobile Communications (GSM) impact on the field of communication was significant in terms of creating a standardized and accessible communication system that paved the way for a range of new technologies and applications. Global System for Mobile communication, was a turning point in the field of communication for several reasons:

1. Standardization: GSM established a standardized communication protocol across the world, allowing for global interoperability and overcoming the limitations of incompatible systems.
2. Increased Capacity: GSM's digital technology allowed for more calls to be made on a single frequency, thus increasing the capacity of the network.
3. Data transmission: GSM introduced the capability to transmit data alongside voice, which paved the way for a range of new applications such as text messaging and mobile internet browsing.
4. Accessibility: With the launch of GSM, mobile communication became more affordable and accessible to the general population, leading to a rapid increase in mobile phone ownership.

The European Postal Communications Council established a working group known as the Groupe Special Mobile (GSM) three years before the UK introduced its initial TACS network. The purpose of the group was to standardize public mobile communication systems in the 900 MHz bands and was convened in Stockholm in December 1982. At first, there was no guarantee that the GSM Task Force would choose a digital system. Their objective was to pinpoint a solitary interoperable system that could be deployed across Europe and adapted to match the expected usage pattern.

The UK authorities declared that the highest 10 MHz within the current mobile frequency ranges (905−915 MHz and 950−960 MHz) would be allocated for GSM usage and would not be freed up for additional TACS growth. Furthermore, as a reaction to the DTI Consultation Paper titled "Mobile Communications", frequencies within the 1800 MHz spectrum (1710−1785 MHz for mobile and 1805−1880 MHz for base station) were also unlocked for 2G deployment. From a structural perspective, as illustrated in Figure 4, within each cell of a mobile network, the radio interface is overseen by a Base Transceiver

Station (BTS), which represents the observable component of the network as it functions as the radio tower that can be seen on rooftops and roads. The BTS is connected to a Base Station Controller (BSC) via landline or point-to-point microwave, and each BSC is responsible for managing the radio network and handling call handover between multiple BTS.

The BSC links to a Mobile Switching Centre (MSC) through a Transcoder and Rate Adaptation Unit (TRAU), which changes the 13 kbit/s voice codec from GSM-specific norms to the 64 kbit/s standards of the Public Switched Telephone Network (PSTN). TRAU also facilitates traditional switched data services. The MSC functions as the heart of the circuit-switched exchange, overseeing validation, call establishment and termination, billing, as well as mobile phone location tracking operations. Several MSCs might exist within the network. The MSC establishes a bridge to the external PSTN. The digital access network employs a fusion of frequency division multiplexing, where the accessible channels are distributed every 200 kHz, and time division multiplexing, which governs transmission within these channels on a precise time schedule.

As digital transmission systems inevitably enable the transmission of non-voice services, short message services became a reality, and people started connecting their mobile phones to data networks, especially Internet access, which is now the Internet. During the 1990s, mobile operators faced a growing need for data services that were unsuitable for circuit-switched GSM networks. This can be compared to the rise in demand for dial-up internet in homes, which led to advancements in modem technology and ultimately spurred the transition to digital subscriber line (broadband) access [17].

The structure of the GSM network can be categorized into three primary domains:

- Mobile station (MS)
- Base-Station Subsystem (BSS)
- Network and Switching Subsystem (NSS)

Mobile stations (MS) most widely known as cell or mobile phones are the section of a GSM mobile communications network that the user sees and operates. Mobile stations are connected to BTS which are mobile towers that are seen with RF antennas and Microwave antennas on them. BTS is connected to BSC. BSC controls a group of BTSs and is often co-located with one of the BTS. BTS and BSC are part of the Base Station Sub-system. Next comes NSS or The Network Switching Subsystem, commonly known as the core network, which is comprised of various components that function as the main control and interface for the entire mobile network. It is a data network that includes several entities such as the Mobile Service Switching Centre (MSC), which serves as a typical switching node within a Public Switched Telephone Network (PSTN). MSC provides an interface to the PSTN, allowing mobile communication calls to be routed to landline-connected phones. Additionally, the Home Location Register (HLR), Visitor Location Register (VLR), and Equipment Identity Register (EIR) are also integral parts of the NSS.

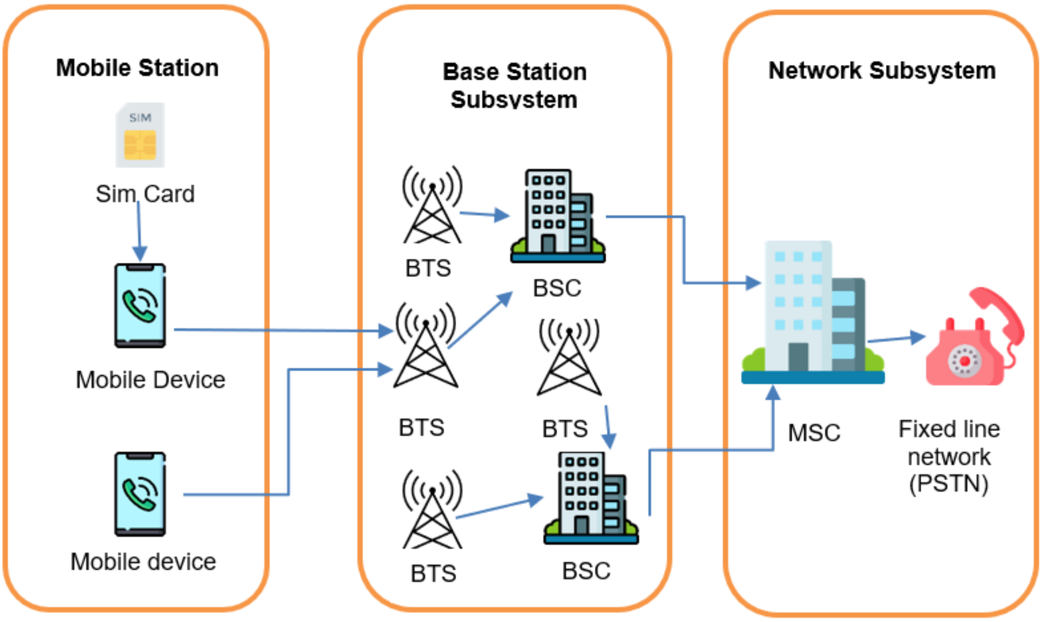


Figure 4. *Mobile Network Architecture for GSM.*

To improve the cellular network, it was changed to support a way of sending small packets of data called General Packet Radio Service (GPRS). This allowed data to be sent faster and separate from voice calls. The data went through a few different nodes before connecting to external networks like the Internet. Within the BSC, these data streams are separated from voice and forwarded to the Serving GPRS Support Node (SGSN). It was connected through a Gateway GPRS Support Node (GGSN) to a packet-switched core data network and external data networks such as the Internet. The provision of this always-on, best-effort (2.5G) data service has further increased the consumption of data services. Demand for higher data rates continued to grow and eventually, this 2G network evolved to 2.75G with the introduction of the enhanced data rates of GSM Evolution (EDGE) offering rates of hundreds of kbit/s. This was achieved by changing the modulation and data coding techniques used in the radio access network, especially the air interface.

2.1.3 UMTS Technology and data transfer

By 1992 there was a worldwide agreement to allocate frequencies in the 2100 MHz Within the Balanced Scorecard (BSC), these data streams get segregated from voice and are sent to the Serving GPRS Support Node (SGSN). It was linked via a Gateway GPRS Support Node (GGSN) to a packet-switched fundamental data network and external data systems like the World Wide Web. The availability of this always-connected, top-priority (2.5G) data provision has further amplified the usage of data-related services. The desire for swifter data speeds continued to surge and over time, this 2G infrastructure progressed to 2.75G with the introduction of the improved data rates of GSM Evolution (EDGE), providing speeds of hundreds of kilobits per second. This accomplishment was made by altering the modulation and data encoding methods employed in the wireless access network, particularly the wireless interface.

RNCs called a Radio Network Subsystem (RNS). In most cases, there were many RNCs for scalability, so it was general to have multiple RNSs within the UTRAN. The RNC was a network controller that is architecturally a peer of the GSM BSC. Additionally, the RNC played a key role in mobility management with soft handover in UMTS. A Media Gateway (MGW) managed to transcode and to interwork between the 3G RAN and the circuit-switched 2G core network, but in practice, many carriers were deploying parallel 2G and 3G core networks and were integrated after 3G proved itself and worked stably. Transcoding and interworking capabilities include termination of ATM traffic over a time division multiplexed interfaces from UTRAN to International Telecommunication Union-Telecommunication (ITU-T).

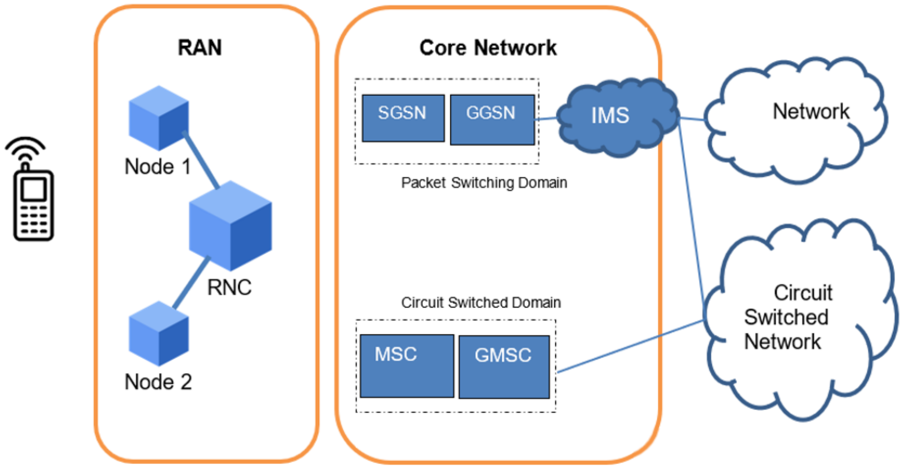


Figure 5. *Mobile Network Architecture for Third Generation.*

Cellular operators decided to either deploy dual-band cellular antennas supporting GSM and UMTS in spatial or polarization diversity configurations or deploy separate antennas. The panel antenna on the top header frame (It typically consists of a metal or plastic frame and is mounted on top of the panel, allowing the antenna to be easily installed or removed from its mounting structure) is a dual-band antenna (1800 MHz and 2100 MHz).

The bottom installation contains individual antennas for 900 MHz GSM and 2100 MHz UMTS [18].

By the end of the 20th century following things were observed in terms the advantages and disadvantages:

Advantages:

1. High-speed data transfer: UMTS enables high-speed data transfer, which is up to 384 kbps for packet-switched data and up to 2 Mbps for circuit-switched data. This allows users to access the internet, download files, and stream videos at a faster rate.
2. Improved network coverage: UMTS technology provides better network coverage than the previous 2G technology. This means that users can make calls and access the internet in more areas.
3. Enhanced features: UMTS technology supports advanced features like video calls, mobile TV, and high-resolution video streaming.
4. Improved call quality: UMTS technology provides better call quality due to its improved voice codec and signal processing.

Disadvantages:

1. Expensive infrastructure: UMTS technology requires expensive infrastructure like base stations, antennas, and other equipment. This makes it difficult for small-scale businesses to implement.
2. High power consumption: UMTS technology requires high power consumption, which may lead to faster battery drain on mobile devices.
3. Limited bandwidth: UMTS technology has limited bandwidth, which may cause network congestion during peak hours. This can result in slower data transfer speeds.
4. Incompatibility with older devices: UMTS technology is not compatible with older devices, which means that users may need to upgrade their devices to access the network.

2.1.4 Long-Term Term Evolution:

Long Term Evolution (LTE) is a wireless communication standard used for 4G mobile networks that offer faster data transfer speeds, increased capacity, and improved performance compared to 3G networks. LTE evolved from 3G mobile networks through a series of standardization efforts and technological advancements. The first major step towards LTE was taken in 2004 when the 3rd Generation Partnership Project (3GPP) began working on the Long-Term Evolution System Architecture Evolution (LTE-SAE) project. The goal was to develop a new wireless communication standard that could offer higher data rates, lower latency, and greater spectral efficiency than the existing 3G networks. The network architecture of 3G technology is a comprehensive cell-based network architecture. LTE high-level network architecture consists of three main components:

- User Equipment (UE)
- Evolved Universal Terrestrial Radio Access Network (E-UTRAN)
- Evolved Packet Core (EPC)

Enhanced Packet Core communicates with packet data networks such as the Internet, business private networks, or the IP Multimedia Subsystem. Mobile devices have the following core modules.

- All communication functions are handled by Mobile Termination (MT)
- The data stream is terminated at the Terminal Equipment (TE)
- The SIM card for the LTE kit is known as the (UICC) Universal Integrated Circuit Card.

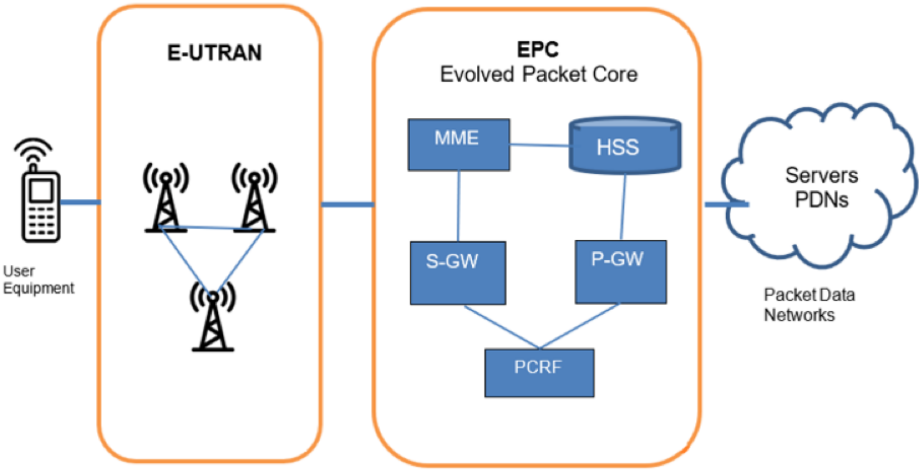


Figure 6. *Network Architecture of 4G LTE.*

Subscriber Identity Module or SIM cards for LTE devices are known as Universal Integrated Circuit Cards (UICCS). The information stored in the Universal Subscriber Identity Module (USIM) card is like that of a 3G SIM card, such as the user's phone number, home network ID, and security key. 4G, also known as LTE, is the 4th generation cellular network. Fourth Generation provided more reliable mobile broadband internet services for mobile devices, computers, tablets, and laptops. Mobile devices have taken over the market due to the speed and efficiency of 4G. Fourth Generation is still not deployed worldwide and developing countries are still installing their 4G Mobile Network equipment. The pros and cons of 4G are:

- The 4G service is not accessible in some countries.
- It is multifaceted and requires skilled personnel to manage the system.
- Long-standing versions of smartphones cannot make use of this technology [19].

If the 4G mobile network is further described in its advantages and disadvantages following observations can be seen:

- Faster data speeds: Networks offer faster download and upload speeds compared to 3G networks. This helps stream videos or music, downloading large files, and using real-time communications apps.
- Improved network reliability: Networks backed by 4G, provide better coverage and fewer dropped calls, which is a big plus for those who rely on their mobile devices for work or travel.
- Enhanced connectivity: It provides improved connectivity in remote areas and can also support a greater number of connected devices.
- Better video and audio quality: With 4G networks video and audio quality is improved with smoother streaming and better clarity for phone calls.

Even with all the above benefits, 4G still lacks in the following fields:

- Data usage: Faster data speeds may result in higher data usage, which could mean higher monthly bills for consumers.
- Limited coverage: While 4G networks are expanding rapidly, there are still many areas where it is not yet available or not providing optimal coverage.
- Expensive devices: Devices that are 4G capable, can be more expensive compared to 3G devices, which may make them out of reach for some users on a budget.
- Battery life: Connecting to a 4G network can sometimes use more power on a mobile device which can cause the battery to drain at a faster rate than it would if connected to a 3G network.

Third Generation Partnership Project (3GPP) released the first version of the LTE standard, which offered peak download speeds of up to 100 Mbps and upload speeds of up to 50 Mbps. Over the next few years, various enhancements were made to the LTE standard to improve its performance, reliability, and capacity. These included:

- LTE-Advanced: This was a major upgrade to the LTE standard, which offered peak download speeds of up to 1 Gbps and upload speeds of up to 500 Mbps. Features such as carrier aggregation were also introduced by LTE-Advanced, which allowed multiple frequency bands to be used simultaneously to increase bandwidth and data rates.
- LTE-Advanced Pro: This was another upgrade to the LTE standard, which introduced features such as 256-QAM (Quadrature Amplitude Modulation) and massive MIMO (Multiple Input Multiple Output) to further increase data rates and capacity.
- 5G-NR: This is the latest wireless communication standard developed by 3GPP, which is designed to offer even faster data transfer speeds, lower latency, and greater capacity than LTE. Currently, 5G-NR networks are being deployed in many countries around the world.

The technology of LTE evolved from 3G mobile networks through a series of standardization efforts and technological advancements, which have led to the development of faster, more reliable, and more efficient wireless communication networks.

2.2 Introduction to 5G and Next-Generation Architecture

The advent of Fifth Generation technology has revolutionized the way of using cell phones, providing them with much higher bandwidth than ever before. These stunning advancements have left users astounded, as they have never experienced such cutting-edge technology previously. Nowadays, mobile users are highly aware of the latest mobile technology and are demanding the advanced features that come with Fifth Generation devices, making them the most popular and sought-after smartphones on the market. Some possibilities are needed to be discussed regarding the 5G network framework enabled and how connected operations (Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (URLLC), and Massive Machine Type Communications (mMTC) can profit from these opportunities.

With its Next-Generation network framework, 5G can support thousands of new operations (mMTC, URLLC, AR/VR, Cloud Computing, Network Slicing, and Edge Computing) in both the consumer and production sectors. The possibilities of 5G are endless as bandwidth increases exponentially over existing networks. These advancements will enable operations in perpendicular requests like manufacturing, healthcare, and transportation, where 5G will play a crucial part in everything from advanced plant robotization to completely independent vehicles. To develop profitable business options and operations for 5G, it's helpful to have at least an introductory understanding of the 5G network framework that underpins all these new operations. Next Generation Architecture (NGA) refers to the underlying framework of the next generation of mobile telecommunications technology, which is expected to be more capable and powerful than current 4G networks. The 5G NGA is designed to provide high-speed internet, low latency, and massive connectivity to support a wide range of emerging applications and services, such as autonomous driving, remote surgery, and virtual reality. The architecture includes a range of new technologies such as network slicing, edge computing, and virtualization. The 5G NGA will enable greater levels of automation and intelligence in network management, providing a more efficient and cost-effective way of delivering services to users.

It is important to be noted that the 5G application is still developing. The process of planting the 5G network started numerous times agone and involved establishing a new structure, most of it funded by the major wireless carriers. The 3GPP norms behind the 5G network framework were introduced by 3GPP, the association that develops transnational norms for all mobile dispatches. The International Telecommunications Union (ITU) establishes guidelines and timelines for mobile communication systems, introducing a new generation approximately every decade. These guidelines are subsequently translated into technical specifications by the 3GPP across a series of releases.

5G technology represents a significant advancement from 4G LTE, which was followed on from 3G and 2G. As with previous generations, there will be a transition period during which multiple network generations coexist. Beforehand adopters always want to get new technologies as soon as possible, but those who have made large investments in large-scale deployment with network technologies like 2G, 3G, and 4G want to take advantage of these investments. The network framework of 5G mobile technology is a significant enhancement over the former framework. 5G networks provide better security than current 4G networks. So, 5G technology offers three major benefits.

- Advanced data transfer rates of over several gigabits.
- Large bandwidth allowed for a huge number of IoT biases per square kilometre.
- Low latency down to a single number of milliseconds.

This is critical in operations like connected vehicles in International Transportation System (ITS) operations and independent vehicles where immediate response is needed. Designing a 5G network framework to support demanding operations is complex.

2.3 5G Cloud RAN

Through relentless efforts and backbone carriers, the digital revolution is compelled to create a better digital world. Coordinated End-to-End (E2E) enabling agile, automated, and intelligent operations to businesses and (E2E) architecture is required. A comprehensive cloud model of networks, operating systems, and services is a prerequisite for this long-awaited digital transformation. The "all cloud" approach is a definitive study of hardware resource pools, distributed software program architectures, and automated provisioning. The operator transforms the network into a network structure based on Data Centres (DCs) and runs all functions and service programs in cloud DCs (called cloud-native architecture). Within 5G technology, a single community infrastructure can meet different service needs. This cloud native E2E network architecture has the following characteristics:

- It will use CRAN to restructure the RAN, provide huge links for different needs, and implement on-demand to provide the RAN capabilities needed in 5G.
- Simplify the middle network architecture and implement on-demand configuration of network functions through separation of management and consumer planes, thing-based functions, and integrated database management.
- Implement automatic community disconnection service, maintenance, and termination of numerous offerings to reduce operating costs through agile community O&M.

In the exciting era of 5G, new communication poses challenges to existing networks in terms of technology and business fashion. Next-generation mobile networks have to meet a variety of requirements. The International Telecommunications Union (ITU) classifies 5G mobile community services into three classes: Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (URLLC), and Massive Machine Type Communications (mMTC).

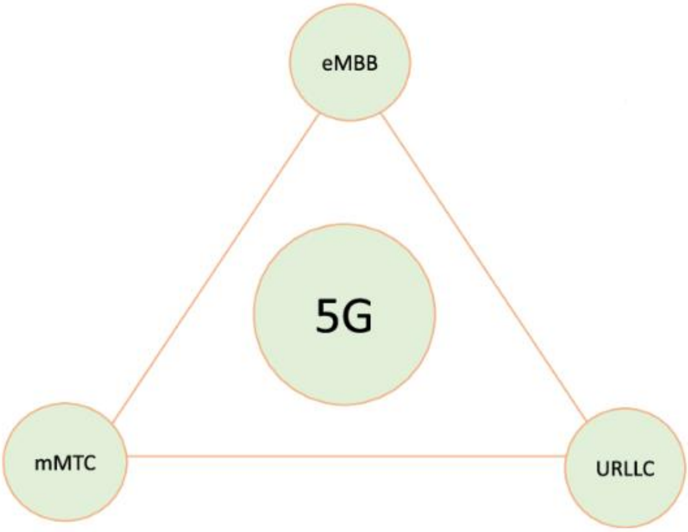


Figure 7. *Classifications of 5G.*

Three classifications of 5G, and their specifications are as follows:

1. **Enhanced Mobile Broadband (eMBB)**

Enhanced Mobile Broadband (eMBB) is a key feature of 5G networks that provides faster and more reliable data communication between mobile devices and networks. Here are some of the specifications and features of eMBB:

- Increased bandwidth: It provides higher bandwidth compared to 4G networks, which can reach up to 20 Gbps.
- Lower latency: It provides lower latency, which is the time it takes for data to travel from one point to another. 5G networks can achieve a latency of 1 millisecond, which is 10 times faster than 4G networks.
- Improved Spectral Efficiency: New technologies are utilized in eMBB such as beamforming and Massive MIMO to increase the spectral efficiency of the network.
- High-speed mobile broadband: It offers high-speed connectivity to mobile devices such as smartphones, tablets, and laptops.
- Improved Network Capacity: networks of 5G can support up to 1 million devices per square kilometre, making it possible for multiple users to simultaneously use high-bandwidth applications such as video streaming and online gaming.
- Better Signal Coverage: It uses an advanced network architecture that includes small cell technology, which improves signal coverage and quality in urban areas.

- Interoperability: It can work with existing 4G networks, making it easier for network operators to upgrade their infrastructure.

In summary, eMBB provides faster data transfer speeds, lower latency, improved network capacity, increased spectral efficiency, and improved signal coverage. These features make it possible for users to enjoy high-bandwidth applications such as video streaming, online gaming, and virtual/augmented reality experiences on mobile devices with improved quality of service.

2. Ultra-Reliable Low Latency Communications (URLLC)

Ultra-Reliable Low-Latency Communication (URLLC) is a type of 5G technology that provides extremely reliable and fast communication services. The main specifications and features of URLLC are:

- Latency: It minimizes delay in communication, allowing for real-time and near-instantaneous communication, which is essential in critical applications like remote surgery, autonomous vehicles, and industrial automation.
- Reliability: It provides a very high level of network reliability with ultra-low packet loss rates, making it ideal for applications that require an uninterrupted connection such as industrial IoT systems.
- Bandwidth: sufficient bandwidth is offered by URLLC to meet the demands of high traffic applications such as file sharing and video streaming.
- Quality of Service: It offers the ability to provide differentiated services and guarantees the quality of service, depending on the requirements of the application.
- Security: It provides enhanced security with improved encryption and authentication mechanisms to protect sensitive data from unauthorized access.
- Tightly integrated network: It integrates the network on a higher level with the application, optimizing the network resources and minimizing latency, thus providing an enhanced end-to-end service.

3. Massive Machine-Type Communications (mMTC)

Massive Machine-type communication or mMTC, which is a type of communication designed for the Internet of Things (IoT) and Machine-to-Machine (M2M) applications that require high quality service. The specifications and features of mMTC are:

- Low power consumption: it is designed to consume minimal power, which is important for devices that are expected to operate on a battery for a long time.

- Low data rates: The communication requirements of IoT devices are usually small, and mMTC is designed to support low data rates. This makes transmission more efficient and effective.
- High reliability: The mMTC communication must be reliable, as many IoT applications are mission critical. It employs advanced error correction techniques such as repetition coding and interleaving to ensure reliable communication.
- Scalability: It must support many low-power IoT devices to ensure seamless communication between devices. Technologies such as narrowband IoT (NB-IoT) and LTE-M can support many devices in each area.
- Security: devices of IoT are vulnerable to cyber-attacks, and mMTC communication must be secure. The communication network should be protected from unauthorized access to prevent data breaches and minimize the potential for harm to individuals or organizations.
- Low latency: Applications and devices need to transmit data quickly, and mMTC ensures low latency to facilitate real-time communication.
- Long-range coverage: It must provide long-range coverage to communicate with IoT devices in remote locations.
- High device density support: It must support a high density of connected IoT devices in a limited geographical area, ensuring efficient communication between devices.

In summary, eMBB provides faster speeds and improved user experiences, URLLC enables mission-critical applications, and mMTC facilitates the connection of a vast number of devices in IoT applications. The eMBB intends to meet people's demand for more and more virtual lifestyles, with excess bandwidth consisting of high-definition (HD) movies, virtual reality (VR), and augmented reality (AR). The service of URLLC strives to meet the expectations of the traumatized digital industry, focusing on products with latency issues such as supported and automated consumption and pervasive control. Aiming to meet the demands of a more advanced virtual society, mMTC specializes in services with excessive connectivity density requirements, such as smart cities and smart agriculture [20].

Expanding mobile network coverage will enrich the telecom network ecosystem. Some traditional industries such as healthcare, energy, automotive, and municipalities are involved in creating this environment. Fifth Generation is the beginning of the promotion of digitization from private entertainment to social networking. Digitization presents great opportunities for the mobile talk industry but poses serious challenges for mobile technology. With the support of software-defined networking (SDN) and network function virtualization (NFV), 5G networks have become completely cloud-based, encompassing access, transport, and core networks. The advent of the cloud improves support for various 5G services, enabling key technologies for E2E community slicing, on-demand delivery of service anchors, and element-based network functions. CRAN consists of a website and a cell cloud engine. This facility addresses the unique requirements and coordinates multiple services at numerous site types for RAN time sources that require different computing resources. The network manages coverage through dynamic policies, semi-static consumers, and static network information that is stored in a centralized database at the core of the network. Control planes that are based on things and person planes that are programmable allow for network function orchestration, enabling networks to choose the appropriate control plane or user plane functions based on the requirements of different manufacturers.

A deployment community comprises SDN controllers and underlying forwarding nodes. The SDN controller generates specific forwarding paths for records based on community topology and carrier requirements. At the highest level of the community structure, automatic E2E clipping and control over resources useful to the community are implemented. CRAN uses. The Mobile Cloud Engine (MCE) helps organize RAN tasks quickly or not quickly, depending on what different companies need. It uses unique vendor instructions and resource settings to turn RAN into a cloud. Quick tasks include things like planning the network, adjusting links, managing power, dealing with interference, retransmitting data, and changing how data is sent. These things need to happen very quickly and need a lot of processing power. So, when setting up sites, there should be special equipment with powerful processors close by. Not-so-quick tasks include moving connections between cells, picking which cell to connect to, keeping communication secret from aircraft, and combining multiple connections into one. These tasks don't need to happen super quickly and can tolerate a small delay, so they work well in centralized setups. You can use regular processors for these tasks, either online or on a website, depending on what the provider needs.

The MCE can manage many tasks at once, depending on the time, frequency, and location. Network functions can be set up in different parts of the network to work as well as possible and add extra abilities.for each network. To understand different types of RAN it is most important to understand D-RAN which stands for “Distributed RAN.

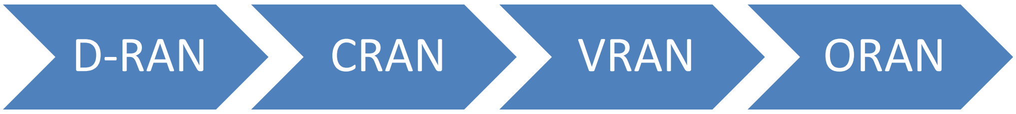


Figure 8. *Distributed RAN and its Further classifications.*

The diagram below shows D-RAN. In traditional cellular networks, the Base Band Unit (BBU) and Remote Radio Unit (RRU) are both located at each cell site and are connected through fronthaul. This setup ensures that each cell site has all the necessary radio functions and is connected to the core network through backhaul [21].

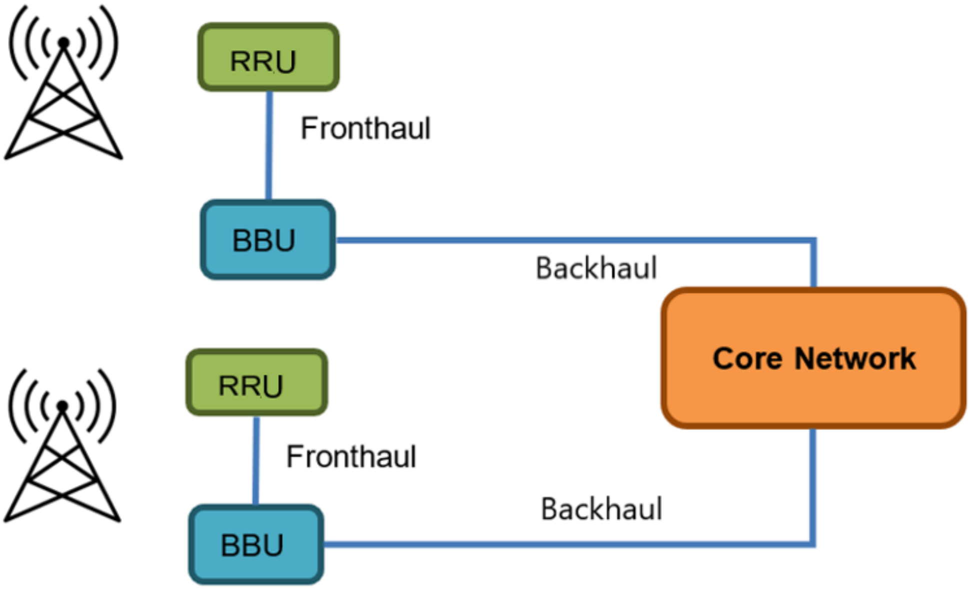


Figure 9. *Distributed RAN.*

2.3.1 CRAN vs O-RAN

In CRAN, the BBU is centralized, and only the antenna and RRU are located at each cell site. This centralization, also known as BBU pool, gives rise to the term centralized/Cloud RAN or CRAN.

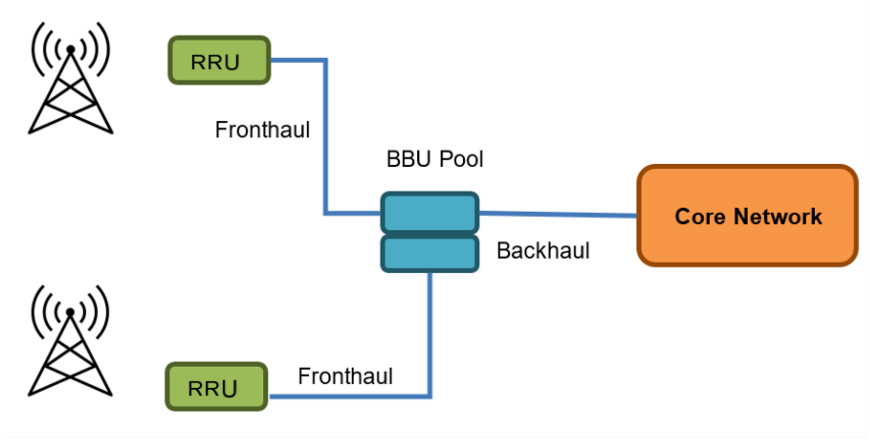


Figure 10. *Centralized or CRAN.*

This centralization also leads to the creation of an interface called fronthaul between the RRU and BBU pool. CRAN offers several benefits, including reduced CapEx and OpEx since deployment and maintenance costs decrease per cell site due to the centralization of BBUs. It also enhances spectral efficiency and reduces inter-channel interferences as centralized BBUs share resources among multiple RRUs. Furthermore, CRAN can be set up with an additional split of BBUs into Distribution Unit (DU) and Centralized Unit (CU). In this setup, the CU is situated closer to the core network, resulting in a new interface called mid-haul.

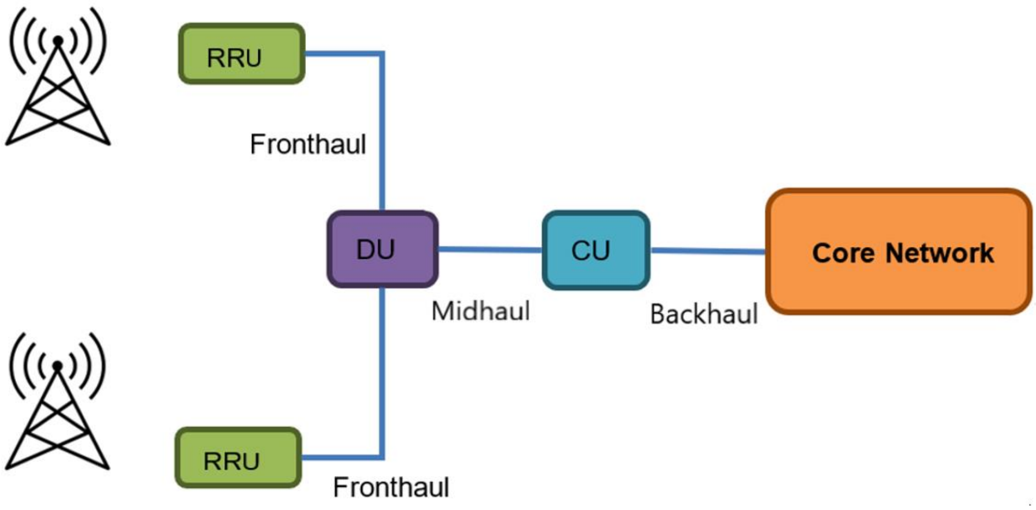


Figure 11. *CRAN with Split BBU.*

VRAN or Virtualized RAN dissociates the software from Hardware by virtualizing functions of the network. It uses virtualization technologies such as Network Function Virtualization (NVF) or containers to implement CU and DU over an x86 server. This is the same as running different functions in a software.

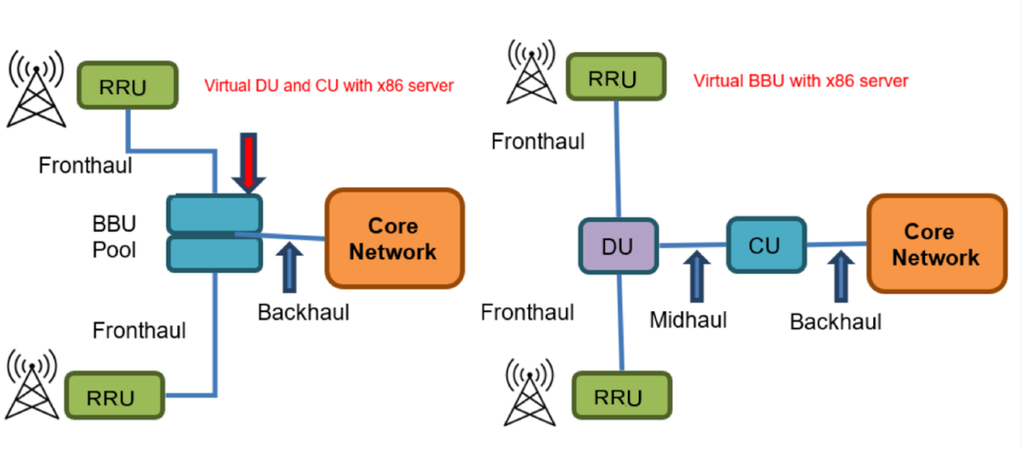


Figure 12. Virtualized RAN Architecture.

It can be said that there is no core difference between vRAN and CRAN except that conventionally CRAN uses exclusive hardware while vRAN uses Network Functions on the server platform. Or it can be said that vRAN is a type of CRAN. Because of VRAN hardware/software decoupling flexibility and scalability can be achieved. This can result in a decrease in hardware costs [21].

2.3.2 CRAN vs VRAN

ORAN, also known as Open RAN, elevates VRAN to a higher level. In traditional VRAN setups, the network is closed, meaning that the Radio Unit (RU), Distribution Unit (DU), and Central Unit (CU) must all be purchased from the same vendor.

The O-RAN group is now busy creating rules that will open up the connection between the RRU and DU, and also between the DU and CU. This will let customers use parts from different companies, instead of only one company, for all three parts. This will make an Open RAN network.

These newly developed open components are referred to as O-RU, O-DU, and O-CU (with "O" representing "Open"). They consist of integrated base station software on top of readily available server hardware.

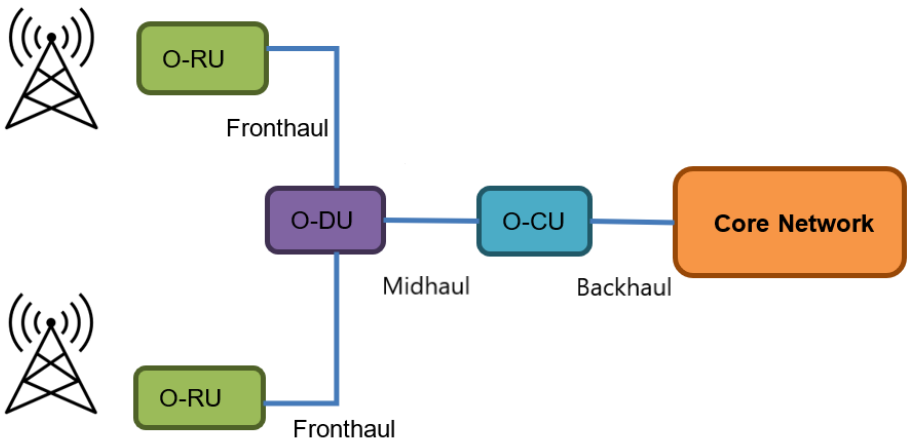


Figure 13. *Open RAN Architecture.*

So as compared to CRAN, in ORAN both BBU and RRU are opened and in ORAN the components (RU, DU, CU) are not needed to be from the same vendor [21] [22].

2.4 CRAN Architecture

The important components of the CRAN architecture in a 5G mobile network are as follows:

1. Baseband Unit (BBU): The BBU is responsible for the processing and coding of wireless signals in the base station.
2. Remote Radio Unit (RRU): The RRU is located at the cell site and is responsible for transmitting and receiving radio signals.
3. Remote PHY Device (RPD): The RPD provides high-speed connectivity between the BBU and RRU by converting the electrical signals from the BBU to optical signals.
4. Centralized Unit (CU): The CU manages the overall operation of the CRAN system and is responsible for coordinating the communication between BBUs and RRUs.
5. Distributed Unit (DU): The DU is responsible for signalling and control functions within the CRAN system.
6. Virtualized Network Function (VNF): The VNF is a software component within the CRAN architecture that is responsible for implementing specific network functions.

7. Cloud Infrastructure: The cloud infrastructure provides the necessary processing, storage, and network resources required by the CRAN system.

The CRAN architecture in 5G mobile networks aims to centralize the processing and management functions of the network, which helps to improve performance, increase scalability, and reduce costs [23].

Three primary components of a CRAN architecture and their working can be described as follows.

A BBU hotel.

A centralized facility functions as a hub for processing data. The units can be configured in a stack without requiring direct linkage or interconnection and are capable of dynamically allocating resources based on network demands. The units communicate with each other through high-speed, low-latency connections. BBU pools are typically located in a cloud environment with each BBU providing robust storage and compute resources. CRANs can fully centralize network functions to the BBU pool for the sake of easier management and maintenance.

The following are important specifications of BBU in CRAN architecture:

- Capacity: The BBU should have sufficient capacity to handle the traffic and meet the requirements of the network.
- Flexibility: The BBU should be flexible enough to accommodate multiple CRAN nodes and various types of traffic.
- Low Latency: The BBU should have low latency to ensure quick response times and fast data transfer.
- Redundancy: The BBU should have redundancy features, such as backup power, to ensure that the network remains operational even in case of power outages or hardware failures.
- Security: It should have robust security measures to protect against cyber threats and prevent unauthorized access to the network.
- Scalability: It should be scalable to accommodate growth in the network and handle increased traffic loads.
- Interoperability: It should be interoperable with other network components and protocols to ensure seamless communication between the various nodes of the network.

- Reliability: It should be reliable and ensure consistent network performance to meet the demands of the end-users.

A remote radio unit (RRU) network.

Also called a remote radio head, an RRU is a conventional network that connects wireless devices to access points. The network of remote radio unit’s links wireless gadgets like cell phones to various access points or cell towers. The RRU gets radio signals from mobile devices and sends that signal to the BBU for turning it into digital data.

Below are the important specifications of RRU in CRAN Architecture:

- Frequency Band: The RRU should support the frequency band that is required by the network operator.
- Transmit Power: The RRU should have enough transmit power to cover the required coverage area.
- Input Power: The RRU should have a suitable input power range to be compatible with the fronthaul interface.
- Size and Weight: It should be small and lightweight to be suitable for installation on poles and rooftops.
- Temperature Range: It should have a suitable operating temperature range to work in different climates.

A fronthaul or transport network.

Also called a mobile switching centre, A fronthaul or transmission network serves as the link between a BBU and a group of RRUs which employ cellular, fiber optic, or mmWave communication. The fronthaul connects the BBU pool to the RRU network. It needs a lot of data capacity to handle the heavy traffic needs of modern cell networks. Lots of CRANs use optical fiber or mmWave communication for their fronthaul connections. [24] Simple CRAN Architecture is shown in Figure 14.

Below are the important specifications of fronthaul in CRAN Architecture:

- Bandwidth: Fronthaul should have enough bandwidth to support the traffic requirements of the network.
- Latency: Fronthaul should have low latency to avoid delay in the delivery of data traffic.
- Capacity: Fronthaul should have a suitable capacity to handle the traffic requirements of the network.

- Protocols: Fronthaul should support the protocols that are required by the RRU and by the network operator.
- Distance: Fronthaul should have a suitable distance range to connect the RRU with the processing unit at the central location.

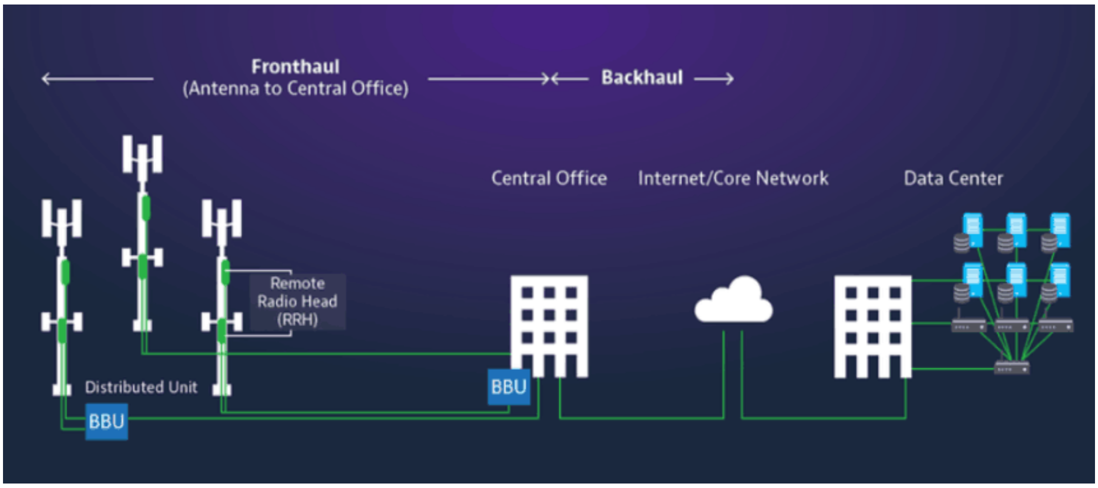


Figure 14. *Cloud RAN Architecture.*

2.5 CRAN Deployment

Core Network and 5G RAN can be connected in several different ways. Two types of architecture are standardized by 3GPP in terms of how LTE and 5G RAN nodes are connected to the Core Network.

In Standalone (SA) architecture, each eNB or gNB has both control plane and user plane direct connections to the Core Network (either EPC or NGC) In Non-Standalone (NSA) architecture, only one node (eNB or gNB) has both a control plane and user plane connection to the Core Network, the other one being controlled by the first one through the X2-C interface and has only user plane path to the Core network. For explanation.

NSA Architecture: The NSA architecture is a transitional architecture that relies on the existing 4G (LTE) network infrastructure to provide initial 5G services. The 5G NR (New Radio) is added as an extension to the LTE base station, and the 5G core network is not fully independent. The LTE network is used as an anchor for 5G connectivity, meaning that 5G devices connect to the LTE network first, then data is transferred to the 5G network for faster performance. The Non-Standalone architecture is the early version of 5G, which relies on existing 4G infrastructure for certain functionalities like control signaling while 5G provides additional data bandwidth. It is a relatively easier and faster option to deploy because it doesn't require as much investment in new infrastructure. However, NSA's limitations include inferior and not fully optimized performance and high dependability on the 4G network.

SA Architecture: The SA architecture, on the other hand, is a fully independent 5G network that does not rely on the existing 4G infrastructure. It has a complete end-to-end 5G network architecture, including both the 5G radio access network (RAN) and the 5G core network. In SA, a completely new 5G core network is used, which allows for advanced features such as network slicing, virtualization, and edge computing. The Standalone architecture is a completely new 5G network that doesn't need legacy 4G infrastructure, providing better capabilities and performance. It enables the full capabilities of 5G, including the ability to support new use cases such as industrial IoT, augmented reality, and more. The main difference between SA and NSA is that the former is fully independent while the latter requires a 4G anchor to provide initial 5G services. The structure difference is shown below Figure 15. Overall, it depends on the needs, budget, and objectives of the 5G deployment. Both architectures have their advantages, limitations, and costs.

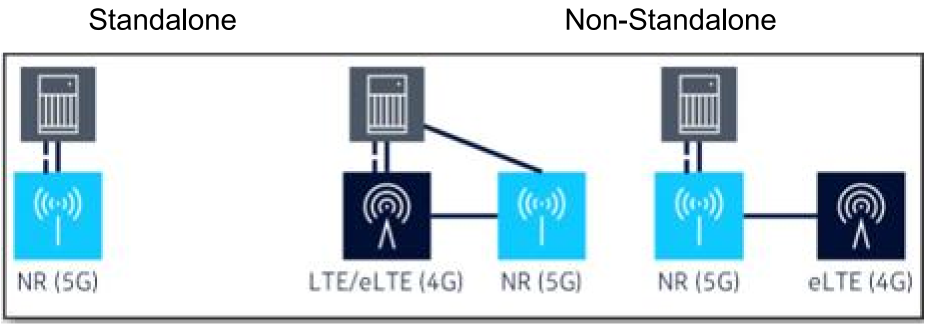


Figure 15. *Types of RAN Deployment.*

The non-standalone solution enables operators to launch 5G services in a shorter time, leveraging existing LTE RAN and Evolved Packet Core (EPC) to anchor 5G NR with the usage of E-UTRA-NR Dual Connectivity (EN-DC) functionality. This approach provides a seamless option to deploy 5G services with a very low impact on the existing network. It focuses on the extreme Mobile Broadband (eMBB) scenarios driven mainly by the highly achievable peak user throughputs.

Deployments using standalone options simplify network architecture a lot and improve its efficiency. Standalone architecture is intended rather for more advanced 5G services characterized by very low latencies known also as Ultra-Reliable and Low Latency Communications (URLLC).

However, simplification of the overall network architecture and its efficiency improvement in the 5G SA deployments might be more challenging during 5G ramp-up activities due to certain requirements that must be fulfilled from the very beginning, such as:

- Availability of 5G Next Generation Core.
- Availability of user terminals (UEs/CPEs) supporting 5G SA deployments.
- Assurance of adjoining 5G coverage or implementation and optimization of inter-RAT handovers and fallback options to overlaying LTE/3G networks in case of spotty 5G coverage.

One of the main decisions for the operators to make for their network architecture is whether to go for a centralized or distributed architecture. It is also likely that there will be hybrid deployments mixing these concepts as well as different BTS deployments, due to different use cases (for example wide coverage or highest data speeds, rural or city centres, enterprise, or public networks). This applies mostly to the vDU location in the network, which can be either centralized or distributed [25].

3. 5G FRONTHAUL GATEWAY

Fronthaul, also recognized as wireless fronthaul, is a concept that pertains to the fiber-dependent linkage of centralized baseband hubs (CBUs) and distant radio modules (DRMs) at the entry level of the system. This originated with the progressions of LTE-Advanced systems, which obtained ITU endorsement in 2012. Fronthaul harmonizes the backhaul associations between the central network and CBU, empowering associated functionalities denser network coverage and rapid transfer of data. Fronthaul gateway for Cloud Radio Access Network is a key component in the deployment of CRAN architecture. It acts as an interface between the centralized cloud-based processing units and the distributed radio access network (RAN) nodes, which include base stations and remote radio heads. The fronthaul gateway is responsible for converting the digital signals carried over the optical or electrical fronthaul links from RAN nodes to a standardized protocol that can be processed by the centralized processing units. It also handles the synchronization between remote nodes and centralized units, along with providing redundancy and resiliency for the CRAN architecture.

Fronthaul gateway (FHGW) plays an important role in enhancing the performance, capacity, and scalability of CRAN networks, by enabling the use of shared resources and enabling better coordination among RAN nodes. This, in turn, can result in improved user experience, reduced latency, and increased network efficiency.

In the past few years, there has been rapid progress in fronthaul technology driven by the growing need for CRAN deployments and the rise of fifth generation (5G) technology. The advent of 5G has expanded the capabilities of fronthaul to encompass all previous generations of wireless communications. The arrangement and adaptability of fronthaul setups play a crucial role in effectively managing the latency, reliability, and data transfer requirements of advanced applications running on 5G networks.

Fronthaul is composed of independent radio heads and centralized baseband controllers that are set up at distant cell sites. These RRHs and BBUs serve as functional modules, and the hardware facilitating their operations is positioned on the cellular towers [26].

Figure 16. *Fronthaul Gateway.*

In this scenario, the RRH hardware remains situated at the cell site. However, the BBU gets moved to a centralized position, allowing it to cater to several RRHs concurrently. The fronthaul optical system functions as the connection bridging numerous RRHs with the centralized BBU location.

Both Fronthaul and Backhaul technologies play a crucial role in establishing a connection between the end-user or node and the network. The key difference between the two lies in the sector of the network on which they are deployed. Fronthaul refers to the networking infrastructure that facilitates the communication between remote cell sites and BBU. Conversely, backhaul connects the cellular network to the wired infrastructure or the internet. Precisely, a wireless backhaul constitutes a wireless communication mechanism that moves data from a distant point to a central network hub, which might be either the internet or the network of a private enterprise. Within fronthaul technologies, the standalone RRHs positioned at the cellular sites are detached from the baseband controller, thus extending the signal reach of the cell tower.

Fronthaul must deliver strict latency, capacity, and synchronization conditions, in CRAN which is considerably more rigorous when compared to those of a DRAN backhaul connection. If the fronthaul network does not meet these strict requirements (like non-ideal fronthaul), this will have an impact on spectral efficiency and more radios may be needed to balance that. In the worst-case situation, degradations can lead to loss of synchronization and instability which might risk service completely.

The CRAN BTS as a logical entity consists of the Centralized Unit (CU) and the Distributed Unit (DU). CRAN deployment with virtualized CU and DU, together with FHGW, transport, radios, management solutions, et cetra is needed for the E2E system. FHGW is a network element deployed in the RAN Fronthaul Network. It is always deployed as part of the CRAN E2E solution.

Fronthaul Gateway can be deployed as a CPRI-eCPRI converter, it enables using the legacy CPRI-based radios to ethernet-base All-in-Cloud BTS with the CPRI radio interfaces remaining unchanged. Common Public Radio Interface is a communication protocol used to transmit data between the radio equipment control (REC) and the radio equipment (RE) in a wireless network. In traditional wireless networks such as 4G CPRI is a critical communication protocol however, in 5G networks, a new communication protocol, the eCPRI, is used to enhance the wireless network's performance which allows for a more flexible and efficient allocation of resources. To upgrade 4G networks to 5G, fronthaul gateways are used to convert the CPRI signals from the existing 4G REC and RE into eCPRI signals, which are then transmitted to the 5G baseband unit (BBU).

The fronthaul gateway receives the CPRI signals from the 4G REC and RE, processes and converts them into eCPRI signals, these signals are then transmitted over optical fibre to the 5G BBU. At the other end, the 5G BBU receives the eCPRI signals, processes them, and transmits them to the 5G's core network. The BBU also sends control signals down the fronthaul link to the 4G REC and RE. In summary, a FHGW acts as a bridge between the 4G network and the 5G network, converting CPRI signals from the 4G REC and RE into eCPRI signals. This enables the deployment of 5G networks using existing 4G infrastructure, minimizing the need for expensive new equipment and ensuring a smooth, cost-effective transition to 5G technology. Additionally, FHGW can be deployed as an ethernet switch that is, connecting the native eCPRI radios to the vDU and thus providing a compact and cost-competitive solution for ethernet switching, connection aggregation, and radio synchronization.

Fronthaul Gateway (FHGW) links old radios that used CPRI technology have been replaced with new radios that use Ethernet technology, and they are now part of a cloud based BTS architecture. However, the interfaces for the radios have not changed. The Fronthaul Gateway is the first solution designed to work well with cloud deployments at the edge and far-edge, providing an efficient way to connect them [27].

The first solution of the Fronthaul Gateway is specifically designed to support cloud deployments at the edge and far-edge by combining hardware and software optimizations, virtualization, and open standards. It offers an extremely compact path by leveraging a small form factor hardware platform and software-defined networking (SDN) capabilities to reduce the overall footprint and power consumption. The solution includes a hardware platform that combines a low-power, high-performance processor with offload accelerators to handle the demanding real-time requirements of fronthaul traffic. This hardware platform is designed to be modular, allowing for easy expansion and customization to support a wide range of fronthaul interfaces and protocols. The software components of the solution are designed to leverage virtualization and open standards to provide a flexible and scalable deployment model. The Fronthaul Gateway uses virtualization to isolate different functions and services, allowing for a highly modular architecture that can be easily customized and scaled to meet specific deployment requirements.

3.1 CPRI and Enhanced CPRI

Fifth Generation fronthaul enables advanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communications (uRLLC), for Internet of Things (IoT) ecosystems. It delivers rapid connectivity, minimal delays, and boosts front-line transport capability. This enhancement elevates network effectiveness, rendering it increasingly adaptable and streamlined. Nonetheless, prior to implementation, numerous elements necessitate evaluation, including spectrum category, available fiber infrastructure, expertise, and network topology. The emergence of next-generation RAN has expedited the deployment of fronthaul fiber. This deployment is supported by split fronthaul architecture, multiplexing, and virtualization, with eCPRI fronthaul playing a critical role in 5G technology.

Before the advent of fourth generation (4G) technologies, fiber optics were the predominant transport network. Radio components were linked to different centralized regulators through CPRI, a protocol that was established in 2003 and emerged as the prevailing transport standard in contemporary fronthaul networks [28].

There are different techniques to maximize fiber utilization in the RAN domain, such as radio CPRI cascading; multiplexing many radios onto a common, high capacity CPRI interface; and high band fronthaul sharing, where multiple radios are time multiplexed. Multiple types of fronthaul networks exist to improve speed and minimize latency. Here are some examples of these networks:

- The fronthaul network of eCPRI assists in establishing a standardized split architecture that is intrinsic to the 5G fronthaul components. This architecture effectively separates the RRHs from the BBUs. By doing so, it reduces the demand for high data rates and simplifies the complexity associated with communication between the radio equipment and radio equipment control.
- Passive optical networks (PONs). It uses optical splitters and point to the multipoint topology. This fronthaul network employs optical splitters and operates on a point-to-multipoint topology. Optical splitters are utilized to distribute optical signals from a single source to multiple endpoints, enabling efficient connectivity within the fronthaul

network. The point-to-multipoint topology ensures that data is transmitted from a central point (such as a Baseband Unit or a centralized controller) to multiple remote endpoints (such as Remote Radio Heads) simultaneously.

- Wavelength-division multiplexing (WDM). These networks utilize laser beams to merge multiple signals, each operating at different infrared wavelengths, for transmission through fiber-optic cables. By employing this technique, they significantly improve the efficiency of fronthaul fiber links.

The radio base station system consists of two nodes, namely the eCPRI Radio Equipment Control (eREC) and the eCPRI Radio Equipment (eRE). The radio base station system must have a minimum of two eCPRI nodes, with at least one of each type: eREC and eRE.

The purpose of the CPRI is to establish standardized requirements for the primary core interface of radio base stations. This interface, known as eCPRI, connects the eRE and the eREC through a fronthaul transport network. In comparison to CPRI, eCPRI enables a reduction in data rate demands between the eRE and eREC by employing a flexible functional decomposition. This decomposition helps manage the complexity of the eRE while maintaining efficient communication with the eREC. [29]

Both CPRI and eCPRI have their pros and cons and working area of topologies and technologies. The use of different bandwidths and forward compatibility are pros of CPRI. On the other hand, eCPRI can be called future oriented as it reduces the hardware requirements for the antenna site which not only reduces the first-time cost but also the operational cost like power consumption. As compared to CPRI, the bandwidth requirement of eCPRI is much less, as eCPRI supports software-based upgradations, so new features can be executed as and when necessary. Additionally, as eCPRI uses Ethernet cable, the traffic from multiple sources can be carried through it and eCPRI ensures reduced jittering and low latency for high-priority traffic.[30]

The eCPRI helps CRANs that work well with the usual distributed RAN (DRAN) model. When RAN compute nodes are placed in central hub sites, it's easier to coordinate the Radio Access Network and make better use of the baseband. In DRANs with eCPRI, onsite networking is more efficient because it reduces the capacity needed on the fronthaul network. It also improves link trunking and allows for more ports in Ethernet/IP switching.

Both CPRI and eCPRI have their benefits but eCPRI (enhanced Common Public Radio Interface) is needed after CPRI (Common Public Radio Interface) because of the following reasons:

- Real-time performance: The CPRI was designed to transport data in a traditional radio access network (RAN) architecture. But, as 5G networks are moving towards centralized RAN (CRAN) architecture, eCPRI is needed to provide real-time performance as it highly supports time-sensitive data transport.
- Bandwidth Efficiency: enhanced CPRI provides bandwidth flexibility and efficiency since the traffic in a CRAN is not evenly distributed across all base station nodes. With eCPRI, the traffic can be distributed across different base station nodes depending on traffic requirements.
- Cost Reduction: enhanced CPRI simplifies the hardware (BTS) design. It eliminates the need for expensive optical equipment that was required in CPRI-based baseband unit (BBU) placement commonly used for distributed RAN architecture.
- Scalability: enhanced CPRI supports more flexible networking topologies and opens the possibility of connecting a much larger number of remote radio heads (RRH) to a single BBU unit, improving the overall scalability of the network.
- Interoperability: enhanced CPRI supports both Radio-over-Ethernet (RoE) and Radio-over-Fibre (RoF), thus making it easier for different vendors to interoperate in a CRAN environment

3.2 Structural Architecture of eCPRI

To achieve deployment flexibility for the Radio Base Station, this can be split into two important parts: the eCPRI Radio Equipment Control (eREC) and the eCPRI Radio Equipment (eRE). These parts can be put in different places, with the eRE closer to the antenna, and the eREC in a more reachable spot. They are connected through a transport network.

The eREC usually deals with some physical layer tasks and higher-level tasks related to the air connection. In contrast, the eRE handles other physical layer jobs and analog radio functions. Control, management, and synchronization signals are changed into packets, combined, and sent over the transport network (also called the fronthaul network) connecting the eREC(s) and eRE(s). The eCPRI doesn't make you use specific network and data link protocols for network setup. So, you can use any network type as long as it meets eCPRI needs. When possible, eCPRI uses established standard protocols. Furthermore, eCPRI and CPRI can coexist within a system, allowing for compatibility and integration between the two.

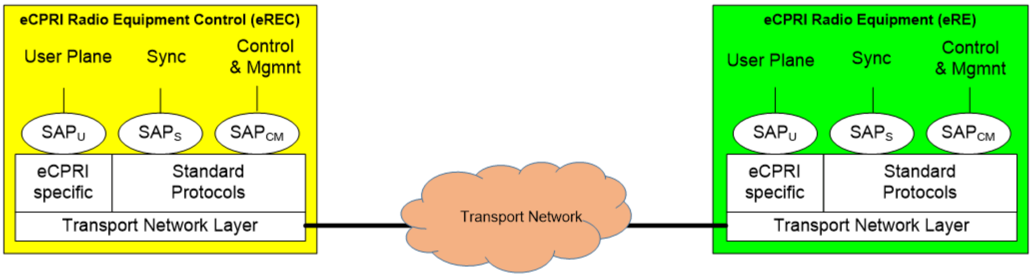


Figure 17. *Radio Equipment and Radio Equipment Control with eCPRI.*

Figure 18 showcases the eCPRI/CPRI Interworking Functions (IWF) types 0, 1, and 2. In IWF type 0, it is possible to establish a connection where an RE behaves as an eRE from the perspective of the eREC. Similarly, it allows the RE to provide REC functionality when viewed from the RE's standpoint. Types 1 and 2 of the IWF collectively enable the establishment of a logical connection between REC and RE nodes [31].

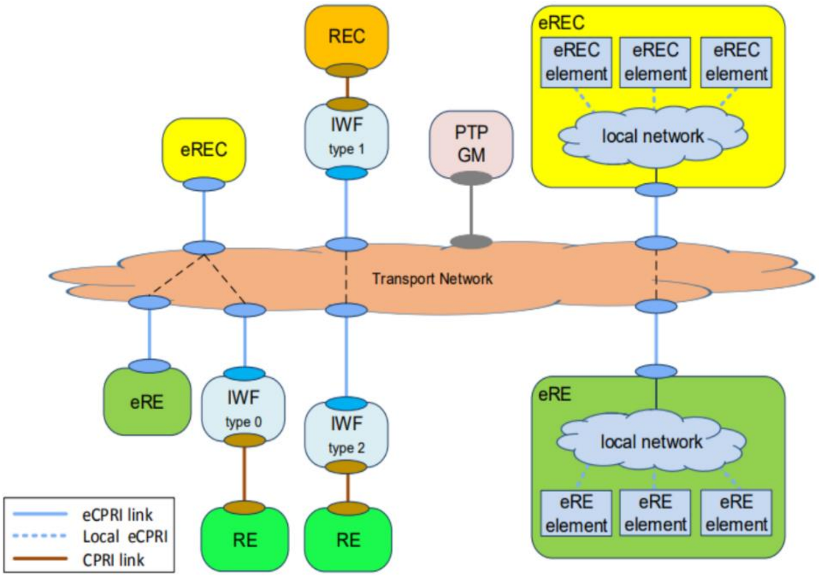


Figure 18. *System Architecture Network Topology with eCPRI and IWF types 0,1.*

3.3 Synchronization of eCPRI

The synchronization of eCPRI is needed because it helps to ensure that the data transfer between radio units (RU) and baseband units (BBU) is accurate and error-free. The synchronization process establishes precise timing and alignment between these units, allowing for the accurate transfer of synchronization signals, control data, and user data. Without proper synchronization, the data transfer between the RU and BBU could experience timing errors, resulting in reduced network performance, data loss, and system downtime. Therefore, eCPRI synchronization is crucial for ensuring the reliable operation of 5G networks. The eCPRI nodes retrieve synchronization and timing information from a designated synchronization reference source. The air interface of the eRE complies with the synchronization and timing requirements specified by 3GPP. It's important to note that the transmission of synchronization information does not occur through the eCPRI-specific protocol. Instead, a separate mechanism is utilized due to the criticality of timing. This synchronization information flow is considered time-sensitive and occupies only a small portion of the overall bandwidth between eCPRI nodes.

Synchronization of eCPRI refers to the process of ensuring that the timing and phase of the data signals transmitted between the network elements (such as base stations and remote radio heads) are aligned and synchronized. Synchronization is critical to ensure that the radio signals transmitted and received by the equipment are properly coordinated to avoid interference and ensure reliable communication. Various synchronization mechanisms utilize eCPRI, including IEEE 1588 Precision Time Protocol (PTP), to ensure accurate timing and phase alignment between network elements.

An eCPRI node gets the frequency and timing from its sync source. In an eCPRI setup, every eCPRI nodes (both eRECs and eREs) must have the same time. There are various ways to sync eREC and eRE.

This synchronization is achieved by the Common Public Radio Interface (CPRI) synchronization messages. These messages contain timing information that is used by both the eRE and eREC to maintain synchronization. A combination of synchronization protocols are used to ensure proper communication and coordination between the different components of the 5G mobile network

3.3.1 Synchronization of eRE

The timing accuracy requirements for the eRE node in an eCPRI installation depend on the supported features. Four distinct categories of timing synchronization requirements are applicable, each catering to different accuracy needs for various use cases. These categories offer varying levels of timing precision at the fronthaul network's edge, specifically at the input port of the eRE. By understanding the anticipated timing accuracy provided, it becomes feasible to design an eRE that meets the final timing accuracy requirements for the air interface. The eRE also complies with the transmission frequency accuracy and phase noise requirements mandated by 3GPP (implied requirement).

The synchronization process of eRE in eCPRI synchronization involves the following steps:

1. Timing reference signal distribution: A timing reference signal (TRS) is generated by the BBU and distributed to the eRE modules in the RRHs over the eCPRI interface. The TRS is used as the timing reference for synchronization.
2. Timing Reference Signal processing: The eRE module in each RRH receives the TRS and processes it to generate a local timing reference. The processing includes filtering, amplification, and phase/frequency adjustment.
3. Synchronization signal generation: The eRE module generates a synchronization signal using the local timing reference. The synchronization signal is sent back to the BBU over the eCPRI interface.
4. Synchronization algorithm: The BBU receives the synchronization signal from each eRE module and uses a synchronization algorithm to calculate the timing offset and adjust the timing of each RRH to synchronize it with the BBU.
5. Synchronization monitoring: The eRE module continuously monitors the synchronization status and reports any synchronization errors to the BBU. The BBU can take corrective action to maintain synchronization if needed.

By using the eRE module for synchronization, the CRAN mobile network can maintain accurate synchronization between the BBU and RRHs, which is essential for efficient and effective communication between the network components.

3.3.2 Synchronization of eREC

The timing accuracy requirement for the eREC is more lenient compared to the requirement imposed on the eRE. The eREC does not necessarily require a high-quality frequency source since it is the eRE that generates the frequency for local air transmission. However, there exists a vendor-specific requirement for the eREC's timing accuracy. This requirement ensures that the eREC can transmit data to the eRE at the correct time, allowing the eRE sufficient processing time before transmitting the data on the air interface. It also accounts for buffer management due to variations in network latency.

To achieve synchronization between the eRE and eREC, a time synchronization protocol called Precision Time Protocol (PTP) is utilized. This protocol ensures that both the eRE and eREC devices share a common time reference and are synchronized with each other. The synchronization process of eREC in eCPRI is as follows:

1. Enhanced REC obtains the synchronization reference signal from the synchronization source, which may be a Global Navigation Satellite System (GNSS) or a Precision Time Protocol (TP) server.

2. Enhanced REC timestamps the eCPRI packets received from the Remote Radio Head (RRH) based on the synchronization signal obtained in step 1.
3. Enhanced REC adjusts the timestamp of the eCPRI packets to compensate for the propagation delay between the RRH and the baseband unit (BBU). This is necessary to ensure that the timing reference used by the BBU is accurate.
4. Enhanced REC sends the synchronized eCPRI packets to the BBU, which uses the timestamp information to reconstruct the original timing of the transmitted data.

The synchronization process ensures that the RRH and the BBU are synchronized with each other, and that the timing information used in the mobile network is accurate and reliable. This is crucial for maintaining the quality of the network and ensuring that mobile devices can seamlessly connect to the network and enjoy reliable connectivity and high-speed data transfer.

3.3.3 Synchronization of IWFs

The synchronization requirements for IWF type 0 are similar to those of an eRE, The synchronization requirements for IWF types 1 and 2 are still developing.

The IWF is responsible for converting the eCPRI protocol used by the radio equipment into the network protocol used by the transport network. The IWF is synchronized using either PTP or another synchronization protocol known as SyncE (Synchronous Ethernet) [28].

The synchronization process of IWF in eCPRI synchronization involves the following steps:

1. Radio units (RUs) connected to remote radio heads (RRHs) transmit eCPRI synchronization messages to the IWF.
2. The IWF receives the eCPRI synchronization messages from the RUs and uses the timing information to synchronize the various RRHs.
3. The IWF then generates a common time reference (CTR) signal for all the RRHs based on the received eCPRI synchronization messages.
4. The CTR signal is transmitted to the baseband unit (BBU) for use in synchronizing the digital baseband processing.
5. The BBU sends a synchronization confirmation message to the IWF to confirm successful synchronization.

The IWF continues to monitor the synchronization status of the RRHs and sends correction messages if necessary to maintain synchronization. The synchronization process of IWF in eCPRI synchronization in the CRAN mobile network ensures that all the RRHs are synchronized with a common time reference, which leads to efficient and reliable communication between the RUs and the BBU in the mobile network.

3.4 The eCPRI Stack Over IP

The eCPRI protocol stack over IP is a framework for transmitting CPRI data over packet-based networks. Enhanced CPRI is a highly efficient protocol designed for the next generation of 5G mobile networks, which requires ultra-low latency and high bandwidth connections for real-time communication [31].

The eCPRI protocol stack over IP consists of three layers:

1. Packet layer: This is the lowest layer of the protocol stack, responsible for transmitting individual packets between network nodes. It uses standard IP addressing and routing to ensure proper packet delivery.
2. Transport layer: This layer provides reliable, message-oriented communication between network nodes. It manages data flow control, error detection, and recovery, ensuring high data transmission performance.
3. Application layer: This layer provides the interface between applications and the network. It handles the higher-level functions required for communication, such as packet fragmentation and reassembly, compression, encryption, and quality of service (QoS) management.

The enhanced CPRI protocol stack over IP enables efficient and reliable transmission of CPRI data at high speeds, providing a critical foundation for real-time 5G communication networks. In fifth generation Centralized Radio Access Network (CRAN), the function of eCPRI (enhanced Common Public Radio Interface) Stack over IP is critical for the efficient communication and management of data between the Central Unit (CU) and Remote Radio Unit (RRU).

The importance of eCPRI lies in its ability to compress, decompress and transport the Radio Unit (RU) data over packet networks, reducing the fronthaul bandwidth requirements. This is particularly crucial in 5G CRAN, where latency and bandwidth are crucial factors. Hence, eCPRI over IP allows for efficient transmission of high-speed data, enabling CRAN to support a vast number of devices and services simultaneously.

The functioning of eCPRI Stack over IP in 5G CRAN includes several critical components. The first component is the compression technique, which compresses the radio signals in the RRU and transmits them to the CU. This compression technique is known as "line-rate compression" and allows for the transfer of fewer data bits over the network, thereby, reducing the fronthaul bandwidth requirements.

The second component of eCPRI over IP is the decompression technique, which decompresses the compressed data from the RU. This process is performed by the CU, which receives the data from the RRU and creates a bitstream that can be delivered to the core network.

The third component is the transport network, which utilizes IP technology to transport eCPRI packets. This network is responsible for carrying the compressed data between the RRU and CU, using a packet-switched network.

In summary, eCPRI Stack over IP in 5G CRAN plays a vital role in enabling high-speed and efficient data transfer between the RRU and CU, reducing fronthaul bandwidth requirements and supporting a vast number of devices and services simultaneously.

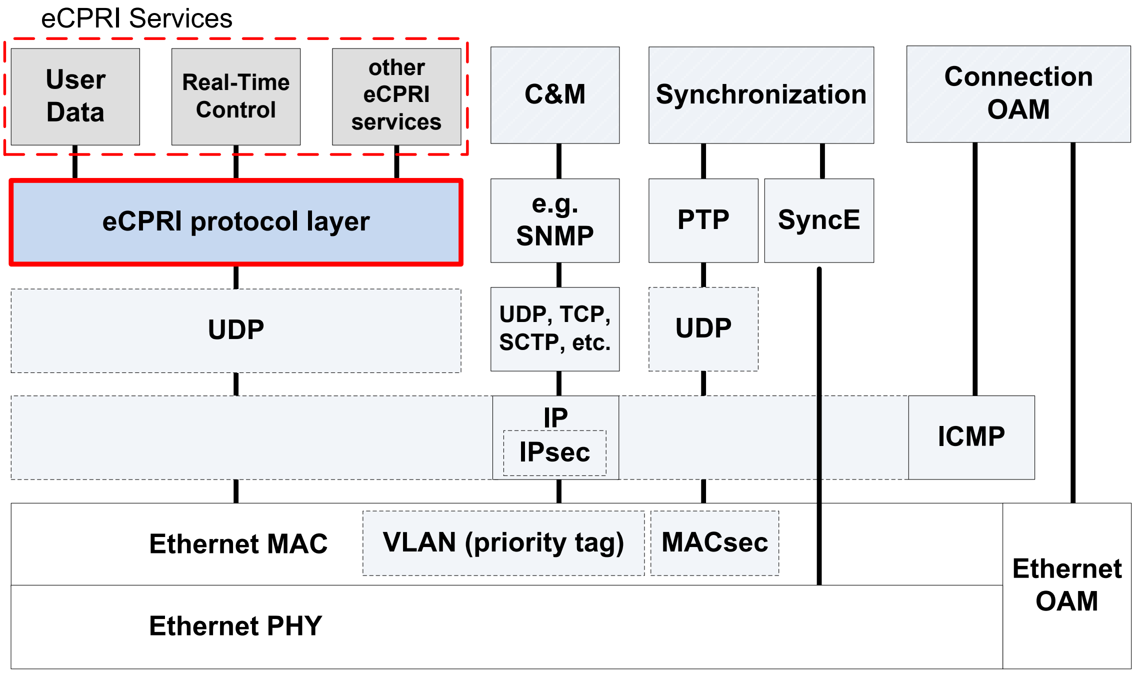


Figure 19. *The eCPRI stack over IP.*

3.5 MULTIPLE ANTENNA SYSTEM

MIMO stands for multiple-input multiple-output, a principle employed in wireless communication where numerous sets of multiple antennas are utilized at both the sending and receiving terminals, depending on the system's capacity. The primary objective behind deploying multiple antennas at both the transmitting and receiving terminals is to augment the system's performance. This approach exploits the benefits of employing multiple antennas within the same frequency spectrum, leading to improved system performance and a reduction in interference [35].

Illustrated in diagram 20 are multiple antennas situated at the transmission terminal, mirroring the configuration at the reception terminal. This diagrammatic representation encapsulates the operational concept of the system. In the same diagram, the transmitter terminal is symbolized by the modulator, while the receiver terminal is represented by the demodulator. Each terminal is equipped with an array of antennas, as evidenced by the depiction, and the connecting arrows symbolize the exchange of communication signals between these antennas.

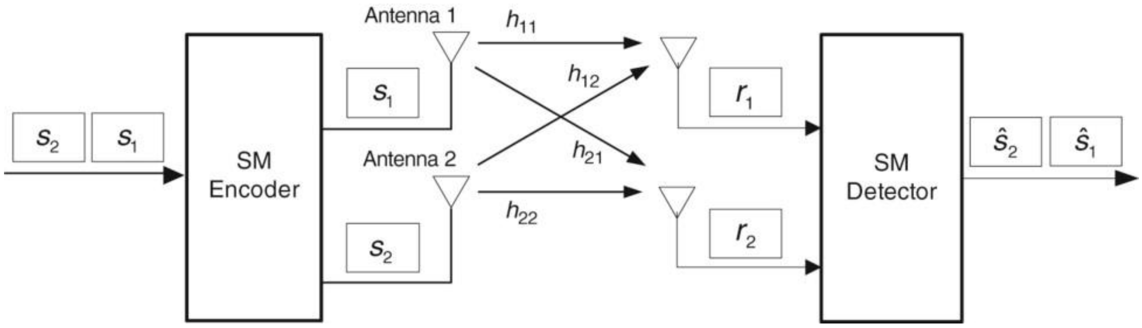


Figure 20. *MIMO Architecture [35].*

Various categories of MIMO systems find utilizations in wireless transmission. A portion of these pertain to SIMO configurations. As the label suggests, SIMO represents Single Input, Multiple Output. Within these arrangements, sending utilizes just one antenna, while receiving incorporates multiple antennas. On the other hand, there exists MISO, which slightly differs from SIMO. MISO stands for Multiple Input, Single Output, indicating that multiple inputs function at the transmitting end, but only a single output appears at the receiving end.

Illustratively, within Figure 20, a MIMO configuration surfaces, elucidating that transmission hinges on numerous inputs, and reciprocally, multiple outputs materialize during reception. The prevalence of MIMO is pronounced in contemporary times, coinciding with the progression of networks and the emergence of fresh technologies.

In parallel, a novel advancement in the realm of Multiple Antenna systems surfaces, recognized as massive MIMO. Noteworthy for its extensive array of antennas at both the transmitting and receiving terminals, massive MIMO leads to remarkable enhancements in system capacity. Concurrently, it augments spectral efficiency. Particularly salient is its burgeoning adoption within satellite communication systems. Figure 21 presents an illustration embodying a 2x2 MIMO configuration. In the context of massive MIMO, a staggering arrangement of 64x64 antennas comes into play, yielding unprecedented capabilities.

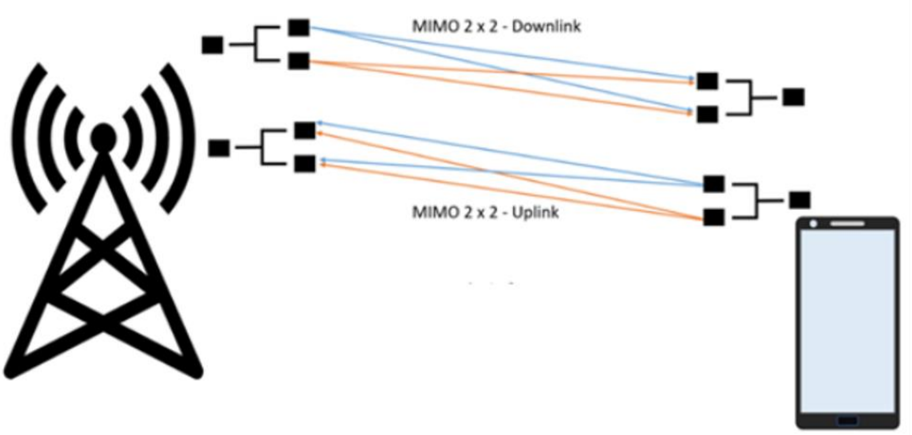


Figure 21. *2x2 MIMO Illustration [35].*

Several advantages of massive MIMO include enhanced coverage even in densely populated regions, heightened energy efficiency, amplified system capacity enabled by numerous concurrent antenna connections, and a noteworthy enhancement in spectral efficiency.

3.6 BEAMFORMING

Another crucial technique employed to enhance system performance is beamforming. Beamforming involves the concept of concentrating on the precise direction with elevated signal strength. This is accomplished by adjusting the phase and magnitude of the signal in that direction. A concentrated stream is formed in the path where the signal intensity is stronger, and the combination of individual components helps generate this focused stream, thereby increasing the strength of the signal [36].

In contemporary times, beamforming finds utility not only in radar systems but also in cellular systems. The advantage of employing beamforming lies in its ability to mitigate interference, extend the system's range, and enhance the Signal-to-Interference-plus-Noise Ratio (SINR). Figure 22 illustrates the core principle of beamforming. The diagram visually demonstrates how, at the transmitting end, specialized beams are directed towards a specific direction characterized by maximum signal strength.

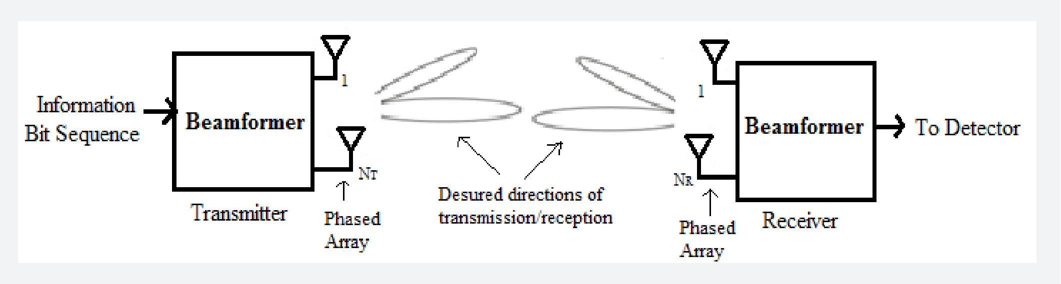


Figure 22. *Beamforming principle [36].*

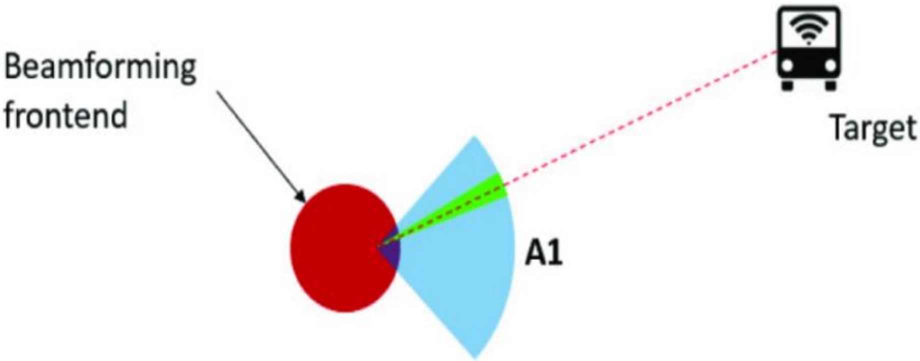


Figure 23. *Beamforming target finding.*

Figure 23 illustrates the process of configuring a beam to shape signals originating from multiple orientations, guiding them towards a designated course referred to as the objective. Once all signals are successfully channeled in this singular direction, a principal beam materializes, exhibiting optimal power and signal integrity. This arrangement substantially heightens performance [37,38].

The beamforming yields a directional amplification. As evident from the diagram, the central beam secures supplementary amplification, a contrast to the conventional array where diversity is noticeable, but amplification remains limited. In the context of a conventional array, signal excellence can be ameliorated through the fusion of diverse signals stemming from distinct trajectories. Conversely, beamforming engenders signal enhancement by orchestrating the alignment of incoming signals towards a solitary point, thus augmenting the array's amplification potential and elevating signal quality.

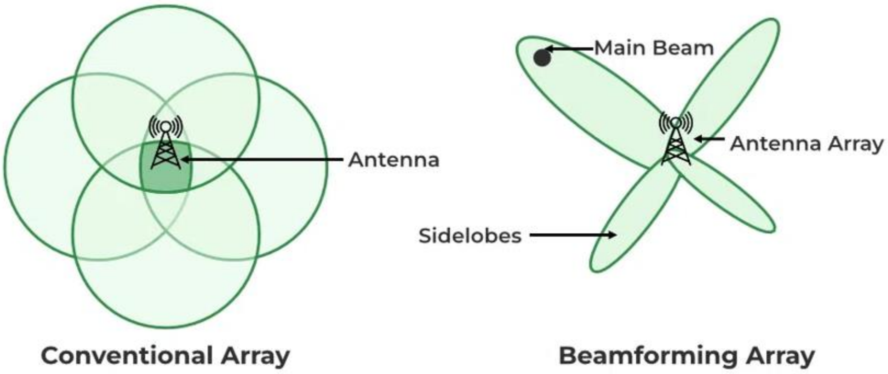


Figure 24. *Beamforming vs Traditional Array finding.*

In Figure 24, a comparison is presented between a traditional array and a beamforming array.

3.6.1 HYBRID BEAMFORMING

Combined beamforming integrates both analog and digital techniques to capitalize on their respective advantages. This strategy optimizes performance by utilizing the expansive coverage of analog beamforming for wider ranges and enhancing precision with digital beamforming for finer accuracy. As such, a hybrid beamforming approach is adopted within wireless communication systems. The operational depiction of this hybrid beamforming architecture is illustrated in Figure 25 [39].

Hybrid beamforming predominantly finds utility within the context of Frequency Range 2 (FR2), encompassing bands ranging from band n257 to n261. It predominantly thrives in mmWave frequencies exceeding 30 GHz, where superior precision and accuracy are essential. Over shorter distances, mmWave frequencies deliver amplified data throughput, underpinning robust and dependable communication [40].

To provide a comparative overview, Table 2 contrasts hybrid beamforming with analog and digital beamforming techniques. Subsequent sections delve into comprehensive discussions on both analog and digital beamforming approaches.

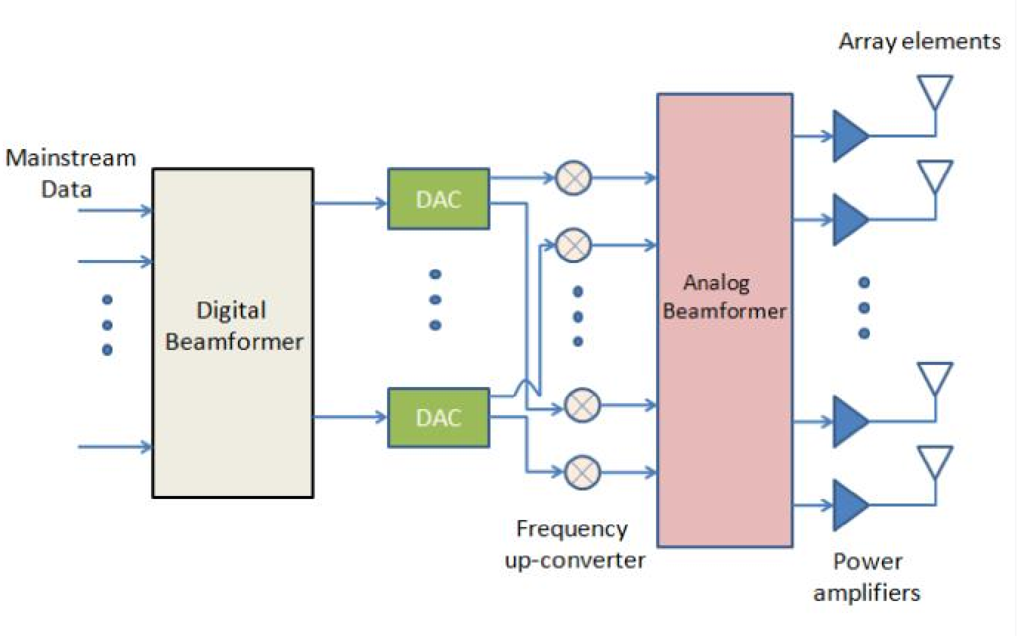


Figure 25. *Hybrid structure of beamforming [39].*

Figure 25 depicts the functional idea of hybrid beamforming, combining analog and digital beamforming methodologies.

3.6.2 ANALOG BEAMFORMING

In today's era of advanced advancements, a variety of beamforming techniques are employed, and one of the primary methods used in beamforming involves analog technology. Within the realm of analog beamforming, the primary objective is to enhance signal strength, while also prioritizing the crucial aspect of signal quality. This consideration becomes especially significant as the signal must be directed toward a specific target at both the transmission and reception ends [41]. The arrangement of analog beamforming can be visualized in Figure 26.

Analog beamforming entails the amalgamation of numerous antennas in a manner that generates a focused signal beam in a predetermined direction. This is achieved by meticulously adjusting altering the magnitude and stage of the signal within each individual antenna element. The ultimate aim of analog beamforming revolves around mitigating interference and minimizing signal propagation effects, thereby leading to an augmentation in the signal-to-noise ratio [42]. Notably, the implementation of analog beamforming is characterized by reduced intricacies and cost-effectiveness. This renders it suitable for applications where the antenna count is limited. Nevertheless, it is essential to acknowledge that while analog beamforming boasts simplicity, it also harbors certain limitations. Specifically, it lacks the degree of flexibility and scalability attributed to the constrained number of available antennas.

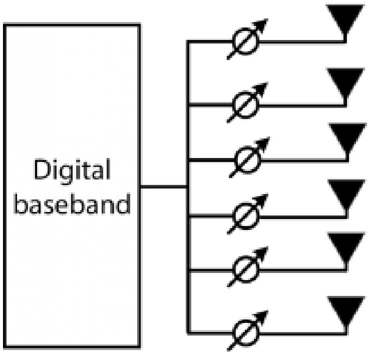


Figure 26. *Analog beamforming method [42].*

3.6.3 DIGITAL BEAMFORMING

Another prevalent method in beamforming, digital beamforming is utilized, which is applied in more complex systems, as opposed to analog beamforming. With the digital method, every individual antenna captures the incoming signal within its array.

Subsequently, the signal collected by each antenna is subjected to sampling, wherein its phase and amplitude are dynamically adjusted. During this progression, signal filtration is executed within each discrete antenna element. Once these individual processes are accomplished, the resultant signals are directed to a digital signal processor (DSP). The principal function of the DSP is to amalgamate these disparate signals, and after this fusion, the DSP undertakes the task of forming a focused beam in a designated direction [42,43].

Digital beamforming boasts greater adaptability and scalability, making it a preferred choice, especially due to its capability to generate a remarkably precise and accurate beam. Its predominant utilization takes place in multifaceted systems. Nonetheless, it is noteworthy that digital beamforming is accompanied by a relatively higher cost compared to analog beamforming. Moreover, both these techniques carry their respective drawbacks [44].

4. CPRI AND ENHANCED CPRI COMPARISON

As eCPRI is a protocol used for connecting remote radio heads (RRHs) to baseband units (BBUs) in a cloud radio access network (CRAN). In this architecture, the vDU (virtualized Distributed Unit) acts as the BBU, and the vCU (virtualized Central Unit) acts as the control and management unit. Physically, eCPRI is typically implemented using a fiber optic cable that connects the RRH to the vDU/vCU. This connection allows for high-speed data transmission and low-latency communication between the RRH and the virtualized units. The fibre optic cable can be connected directly to the vDU/vCU or through a switch or router, depending on the network architecture. Overall, the physical connection of eCPRI to vDU and vCU is critical for the performance and efficiency of CRANs, as it enables the fast and reliable transmission of data between the RRH and the virtualized units.

The eCPRI and vDU/vCU connection typically involves the use of Ethernet ports. The specific ports may vary depending on the equipment being used, but common ports include:

- 10 Gigabit Ethernet (10GbE)
- 25 Gigabit Ethernet (25GbE)
- 40 Gigabit Ethernet (40GbE)
- 100 Gigabit Ethernet (100GbE)

In addition, eCPRI and vDU/vCU may also use specific data plane protocols, such as UDP/IP, to transport the data between the devices. As shown below, Fronthaul, Midhaul, and Backhaul are used to connect RU, DU, and CU and the core network. They describe transport network architecture.

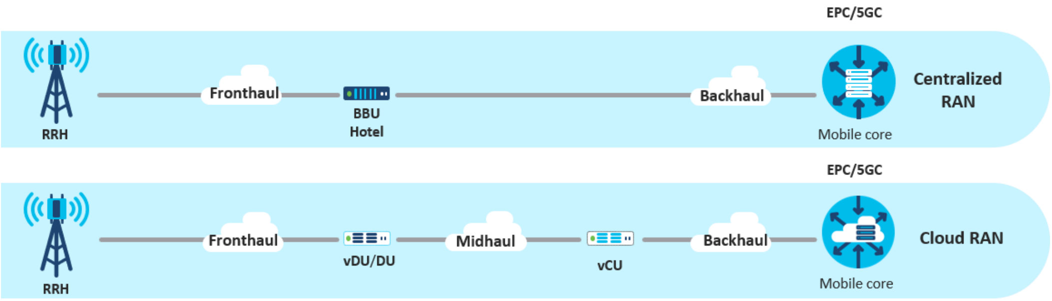


Figure 27. *Connection of different components of Mobile Network.*

The following are the parameters that are important to check while working on eCPRI:

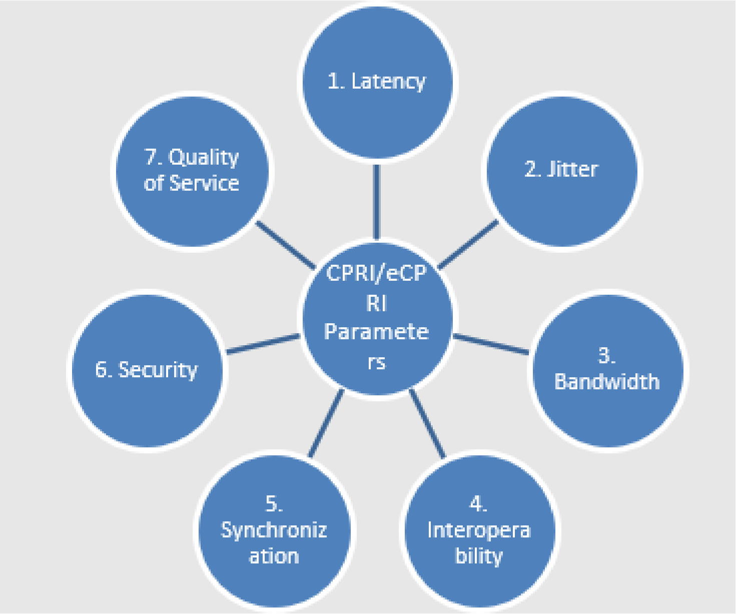


Figure 28. *Important CPRI and eCPRI parameters.*

When eCPRI is under study following are the parameters that can be worked on to find out the maximum usability and serviceability of eCPRI in a Radio Access Network.

1. Latency: It is essential to measure the latency of the eCPRI network to ensure that it is within the acceptable range for the application.
2. Jitter: Jitter is the variation in latency, which can cause packet loss or delays. It is important to measure and control jitter to ensure that the eCPRI network is reliable.
3. Bandwidth: The bandwidth requirements of the eCPRI network vary depending on the application. It is essential to ensure that the network can handle the required data rates.
4. Quality of Service (QoS): Quality of Service refers to the ability of the network to prioritize traffic based on its importance. It is important to ensure that the eCPRI network can provide the required level of QoS for the application.
5. Synchronization: Synchronization is critical for eCPRI networks since it is an essential component of the radio access network. It is essential to ensure that the network can provide the required level of synchronization accuracy.

6. Security: enhanced CPRI networks can be vulnerable to cyber-attacks. It is important to ensure that the network is secure and that the necessary security measures are in place.
7. Interoperability: enhanced CPRI networks may need to connect with other networks or devices. It is important to ensure that the network is interoperable with other networks and devices.

When both CPRI and eCPRI are experimented on with the above-given parameters following observations are noted:

1. LATENCY

The latency of CPRI depends on the distance between the radio equipment and the baseband equipment and the type of fibre optic cable used. It typically ranges from a few microseconds to several milliseconds.

Enhanced Common Public Radio Interface is a newer version of CPRI that introduces some enhancements aimed at reducing latency. One of these enhancements is the ability to split the data into smaller and more frequent packets, which reduces the time it takes for the data to travel between the radio equipment and the baseband equipment. In addition, eCPRI supports a time-sensitive networking (TSN) feature that allows for even more precise synchronization of time-critical data.

It can be concluded, eCPRI has the potential to reduce latency compared to CPRI, but the actual reduction in latency will depend on various factors, such as the specific implementation of eCPRI and the network topology.

2. JITTER

Both CPRI and eCPRI aim to provide low latency and low jitter performance for real-time transmission of data. However, eCPRI is designed to provide a more efficient and flexible approach to transport the same data as CPRI but with reduced bandwidth requirements as well as lower jitter. In terms of jitter, CPRI has limited support for clock distribution and synchronization, which can result in higher jitter performance. On the other hand, eCPRI implements advanced mechanisms to ensure highly accurate and precise clock synchronization between the RRH and RU, which can result in significantly lower jitter performance. Therefore, eCPRI is generally preferred over CPRI for applications that require ultra-low latency and low-jitter performance.

3. BANDWIDTH

Common Public Radio Interface uses a point-to-point connection between the RRH and BBU, which leads to high bandwidth requirements when transmitting data. It is designed to handle large amounts of data, commonly transmitting 1 to 10 Gbps of traffic, and has a relatively high signaling overhead. It uses a fixed-bandwidth connection that is tailored to the specific needs of the RRH and BBU.

Enhanced CPRI, on the other hand, is a more advanced protocol that can aggregate and compress traffic, reducing the overall bandwidth requirements while increasing efficiency. It also enables distributed processing by dividing the processing tasks of the RAN between the RRH and BBU, further reducing the bandwidth requirements. Enhanced CPRI can transmit up to 25 Gbps of traffic, and it is signalling overhead is lower than that of CPRI.

In conclusion, eCPRI has more advanced features than CPRI, such as traffic aggregation, compression, and distributed processing, which reduce the overall bandwidth requirements. However, CPRI has a more straightforward and fixed approach to bandwidth usage, which can be ideal for certain applications.

4. QUALITY OF SERVICE (QOS)

The CPRI is a well-established standard that has been used for many years in traditional cell site architectures. It provides a transparent interface between the baseband processing unit and the remote radio unit, enabling either proprietary or standardized interfaces between the two. It is used for the transport of raw digitized RF signals, and it is not suitable for advanced functionalities such as spectral compression, decompression, or other functionalities that require data processing.

Enhanced CPRI is an evolution of CPRI and provides more flexibility and scalability in the design of wireless networks. It aims to reduce the amount of data being transported over the fronthaul link by shifting some of the baseband processing to the radio unit. As eCPRI offers a highly efficient way of transmitting only the relevant information, resulting in better QoS. Moreover, eCPRI supports latency-critical services such as 5G low-latency applications, by enabling highly precise synchronization between the baseband processing unit and the radio unit.

In conclusion, while CPRI has been widely used in traditional cell site architectures and provides a reliable interface between the baseband and the radio unit, eCPRI offers more flexibility and scalability in designing wireless networks while providing better QoS. However, the choice of which interface to use would depend on the specific requirements of the wireless network.

5. SYNCHRONIZATION

When it comes to synchronization, CPRI uses a dedicated synchronization channel to transmit synchronization information between the transmitting and receiving devices. The synchronization information includes synchronization pulse and timing information, which ensures that the signals are aligned and synchronized at both ends of the CPRI link. However, with traditional CPRI, there can be a significant delay in transmitting synchronization information, which can result in synchronization errors.

On the other hand, eCPRI enhances synchronization by providing a more efficient synchronization mechanism. Since, eCPRI uses a distributed synchronization mode, which means that synchronization information is shared across multiple devices in the network. This allows for more precise synchronization and reduces the risk of errors caused by delays in information transmission. Overall, eCPRI provides a more efficient and reliable synchronization mechanism than traditional CPRI. However, the practicality of using eCPRI depends on the specific network architecture and requirements of the telecom operator.

6. SECURITY

In terms of security, both CPRI and eCPRI use encryption to protect the communication between RECs and REs. However, eCPRI provides enhanced security features compared to CPRI.

Enhanced CPRI supports secure communication between virtualized and software-defined network functions, making it more robust and resilient against cyber-attacks. It also supports distributed security functions such as key management, which provides an additional layer of protection for sensitive information.

It can be concluded that eCPRI is considered more secure due to its enhanced security features and the support for secure communication between virtualized and software-defined network functions.

7. INTEROPERABILITY

To compare CPRI and eCPRI for interoperability, each protocol's features have to be considered, as how well they complement each other. The following are some factors that can help compare the two protocols:

- Bandwidth: enhanced CPRI is designed to offer higher bandwidth and lower latency compared to CPRI. This makes it more suitable for 5G applications and high-speed data transfer.

- Functionality: Common Public Radio Interface is a functional protocol that is more suited to conventional radio access networks (RANs). Enhanced CPRI, on the other hand, is designed to be more flexible, supporting new features such as dynamic bandwidth allocation and software-defined networking.
- Scalability: enhanced CPRI is designed to be more scalable than CPRI, meaning it can support a higher number of radio heads in a single network than CPRI. This makes it more cost-effective for large-scale deployments.
- Compatibility: While both protocols are designed for different applications, they can still work together in the same network. This means that there should be no compatibility issues when deploying both protocols side-by-side.

In conclusion, both CPRI and eCPRI have their unique features and abilities. Although they are designed for different applications, they should be interoperable and compatible when deployed together in a network.

8. UPLOADING THROUGHPUT

In enhanced CPRI, upload throughput refers to the maximum amount of data that can be transmitted from a remote radio unit (RRU) to a centralized unit (CU) over the fronthaul network in each period. This measurement usually refers to the maximum number of bits per second (bps) that can be transmitted from the RRU to the CU. It is a critical performance parametre that impacts the overall system capacity and affects the quality of service provided to end users. High upload throughput is essential for supporting advanced features like beamforming, massive MIMO, and other radio access techniques that require substantial amounts of data to be transmitted between the RRU and CU.

When it comes to uploading throughput, both CPRI and eCPRI can provide high bandwidth capacity. The specific throughput will depend on the implementation, hardware, and network conditions. Overall, eCPRI may offer a slight advantage in throughput due to its more efficient data compression and standard Ethernet connections.

9. DOWNLOADING THROUGHPUT

Download throughput in eCPRI refers to the amount of data that can be transmitted from the central unit to the remote radio unit over the eCPRI interface. It is usually measured in terms of data rate (in Mbps or Gbps) and indicates the maximum speed at which data can be downloaded from the central unit to the remote radio unit. Higher download throughput is desirable as it allows for faster data transfer and enables the remote radio unit to process more data in real time.

When it comes to downloading throughput, eCPRI has an advantage over CPRI as it can support higher data rates due to its increased efficiency and reduced overhead. However, the actual download throughput would depend on several factors including the network infrastructure, signal strength, and device capabilities. Therefore, it is difficult to make a direct comparison between CPRI and eCPRI for download throughput without considering these factors. Both CPRI and eCPRI can be used in 5G fronthaul. While eCPRI is more suitable than CPRI in 5G fronthaul. Here are ten different network performances based on CPRI.

4.1 Time Delay Management in eCPRI

Timing delay measurement in eCPRI is a technique used to measure the delay or latency in the transmission of data between the radio unit and the baseband unit in a wireless communication system. It is a critical parametre that determines the quality of service and user experience in mobile networks. The eCPRI timing delay measurement is performed by sending a specific signal from the radio unit to the baseband unit and measuring the time it takes for the signal to travel back. The delay is then calculated by subtracting the measured round-trip time from the expected round-trip time. The eCPRI timing delay measurement is important for ensuring the synchronization of the radio and baseband units and maintaining the quality of service in mobile networks [31].

Enhanced CPRI timing refers to the synchronization of a central unit and remote radio heads in a 5G network that uses the eCPRI standard for fronthaul communication. It ensures that the data transmitted between the baseband unit and radio heads are properly timed and aligned to avoid errors and inefficiencies. Timing synchronization is critical in 5G networks to achieve high performance and low latency for applications such as autonomous vehicles or remote surgery. Time delay measurement can be improved by following techniques:

- Use timestamping techniques: One way to improve time delay measurement in eCPRI is to implement timestamping techniques. This involves adding timestamp information to packets as they are sent and received, which allows for accurate measurement of the delay between packets.
- Use high-accuracy clocks: Using high-accuracy clocks can also improve time delay measurement. This can include implementing GPS synchronization or using specialized clock sources that provide high levels of accuracy.

- Minimize network congestion: Network congestion can cause delays in packet transmission and reception, which can impact time delay measurement. Minimizing network congestion can help ensure that packets are transmitted and received promptly, which can lead to more accurate time delay measurements.
- Implement QoS measures: Implementing Quality of Service (QoS) measures can prioritize eCPRI traffic and ensure that it receives the necessary resources for timely transmission and reception.
- Conduct regular testing: Regular testing of the eCPRI network can help identify and address any issues that may impact time delay measurement, ensuring that data is accurate and reliable.

Both CPRI and eCPRI are interfaces that are used for connecting Radio Access Networks (RAN) and Centralized Units (CU) in 5G mobile networking. However, they differ in their time delay management as follows:

- CPRI: The CPRI is a proprietary protocol that uses optical fibres for connecting RAN and CU. It can support a maximum distance of 10 km and has a time delay of around 10 microseconds. The delay is constant and does not change based on the distance between RAN and CU.
- eCPRI: enhanced CPRI is an open standard protocol that uses Ethernet cables for connecting RAN and CU. It can support a maximum distance of 40 km and has a time delay of around 500 nanoseconds. The delay is variable and depends on the distance between RAN and CU.

It can be summarized as, eCPRI has a lower time delay than CPRI and can support longer distances. Furthermore, eCPRI manages time delay through the timestamping of packets, while CPRI manages time delay through the synchronization of clocks.

4.2 Differences between CPRI & eCPRI Structure

Two ports of CPRI that are master port and slave port, are directly connected with electrical or optical cables. On the other hand, eCPRI does not support any physical level ports.

1. Logical Connections

The CPRI supports the following logical connections:

- Point to Point: One REC with one RE
- Point to Multi-Points: One REC with several REb

The eCPRI supports the following logical connections:

- Point to Point
- Point to Multi-points
- Multi-points to Multi-points

2. Network Topology

- The network topology is the combination of links, nodes, et cetra. to make the arrangements of a communication network. In CPRI, the network topology relies upon the REC/RE functions. Whereas, the eCPRI's network topology includes eRECs/eREs nodes, transport network (fronthaul network), and more networking elements, like GM/BC for timing, and EMS/NMS for the management of the network is used.
- Both CPRI and eCPRI support several topologies for connecting BBU to RF modules. These topologies are Chain, Star, Ring, Load sharing, Trunk Chain, and Dual-Star. Both can be used for various technologies like LTE and NR. Although, due to technical limits, each of these protocols can support specific topologies within a specific technology. For instance, CPRI can support UMTS, GSM, LTE, NR, and multimode technologies in Chain, Star, and Ring topology. But it does not support Dual star for GSM, LTE, UMTS, and NR and Trunk chain for NR & multimode.[29]
- In the same way, eCPRI supports Dual Star topology in multimode technology and LTE, NR, and multimode technologies in Star, intra-board (Single mode) & multimode of Load sharing topology. All other technologies and topologies are not supported by eCPRI.

3. CPRI and eCPRI for 5G Application

- In the 4G that is LTE, the fronthaul network depended on semi-exclusive protocols, such as CPRI and Open Base Station Architecture Initiative (OBSAI).
- Since the 5G requires immensely expanded bandwidth, only the most recent CPRI standard might meet the requisite. Also, if the CPRI protocols are used for the 5G, these protocols will not be cost-effective for 5G, as they use larger spectral bands that are hundreds of MHz and MIMOs. Therefore, it is uncertain if CPRI can provide 5G stability and cost-affectivity or not. Moreover, even if the CPRI is used in the application of 5G, it can only support the advanced standards in a

very limited way, because if they are compared to other protocols, they have limited mainstream packet transport standards. And eCPRI was introduced at first, addressing the shortcomings of CPRI only. So, it is safe to say that having CPRI for 5G is not so cost-effective, might not have the stability, and will have fewer packet network transport standards.

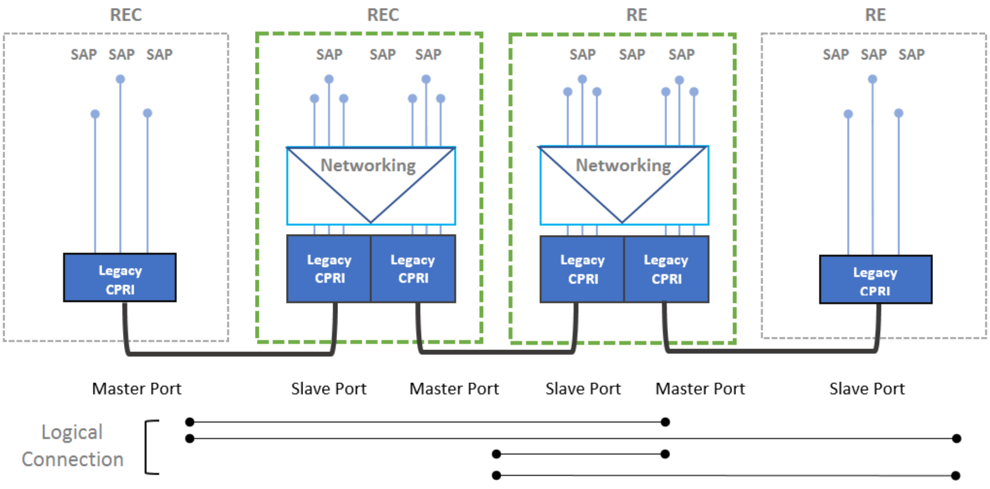


Figure 29. *Structure of CPRI.*

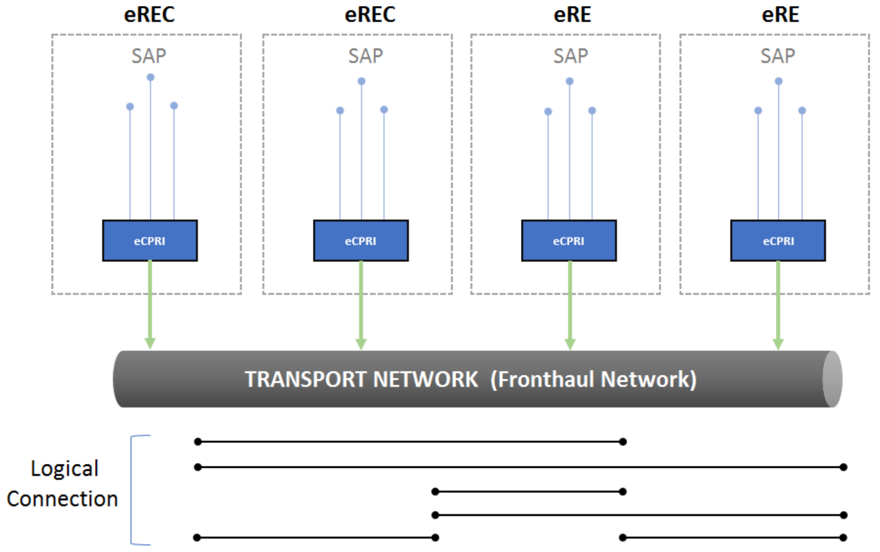


Figure 30. *Structure of eCPRI.*

If the application of 5G with the eCPRI is discussed, the eCPRI helps to reduce the latency of the network and reduces the jitter even for heavy traffic. The eCPRI helps improve the efficiency of 5G fronthaul and uses ten times less bandwidth than the CPRI, or it can be said that eCPRI is tenfold more efficient than the CPRI. In eCPRI, the traffic can be transported on the Ethernet along with other traffic in the same network. Along with all these features, eCPRI has the function of splitting in the PHY layer, which helps keep most of the function in the BBU. Thus, the eCPRI requires fewer transport resources or the radio equipment on the tower and allows acknowledgment of advanced network features without changing the radio equipment. Figure 29 and Figure 30 shows CPRI and eCPRI structure respectively.

4.3 Deployment of eCPRI

It has been established that eCPRI is a fronthaul protocol used to connect the base stations to RRUs in a 5G network, as shown in Figure 32. It allows for more efficient utilization of bandwidth, enabling higher data rates and reducing latency.

In the deployment of eCPRI in a 5G network, the fronthaul links between the Baseband Unit (BBU) and the Remote Radio Head (RRH) are replaced by Ethernet links. The Ethernet-based fronthaul transport enables larger capacity, greater flexibility, and lower latency, which are essential for 5G services such as virtual and augmented reality, autonomous vehicles, and remote surgery.

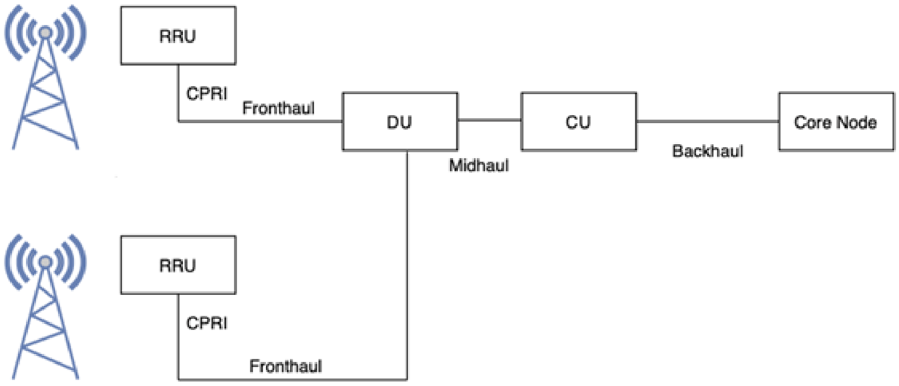


Figure 31. *Fronthaul, midhaul and Backhaul in a 5G network.*

The deployment of eCPRI in the 5G network requires high-speed, low-latency Ethernet connections, such as 10 Gbps or 25 Gbps Ethernet, over fibre-optic or microwave links. The implementation of eCPRI also requires changes in network architecture and equipment, including Ethernet switches, routers, and network interface cards. The deployment of eCPRI in 5G networks enhances the efficiency and performance of fronthaul links, supporting the evolution of 5G services and enabling the full potential of the new network capabilities.

Both distributed deployment and centralized deployment of eCPRI can be achieved. The following is the method of eCPRI deployment in 5G networks.

- Centralized Deployment: In this deployment type, the CU and RRH are located at the same site. This type of deployment requires a high-speed connection between the CU and RRH, such as Ethernet or fibre optic.
- Distributed Deployment: In this deployment type, the CU and RRH are located at different sites. This deployment type requires a high-speed connection between the CU and RRH, typically provided by a mobile fronthaul network.

Necessary Protocols are to be followed while the deployment of eCPRI, such protocols are as follows:

- Ethernet: enhanced CPRI uses Ethernet as a physical layer protocol for transmitting data between the CU and RRH. Ethernet has been used in both centralized and distributed deployment types.
- IEEE 802.1Q: enhanced CPRI uses this standard for tagging and identifying network traffic. According to IEEE 802.1Q virtual LANs (VLANs) can be created and used for separating network traffic.
- UDP/IP: enhanced CPRI uses UDP/IP for transporting control plane messages between the CU and RRH.
- Precision Time Protocol: Precision Time Protocol (PTP) is used in eCPRI to synchronize the timing of the CU and RRH. This is necessary to prevent synchronization issues between different RRHs.
- CPRI: enhanced CPRI is based on the CPRI (Common Public Radio Interface) standard, which is used in 4G networks. The radio interface of the mobile fronthaul network is defined by CPRI, including the physical and protocol layers. Enhanced CPRI builds on these standards to provide enhancements for 5G networks.

The eCPRI enables a substantial decrease of average data rate demands on the fronthaul interface due to multiplexing gain. Bringing more physical layer functionalities to the RU increases the design complexity and form factor while constraining the future-proofs of the hardware due to dependency on 3GPP.

The following are some arguments for why eCPRI deployment could be financially better than CPRI deployment:

- Cost reduction: enhanced CPRI allows for the use of lower-cost Ethernet transport instead of the expensive fibre optic links required for CPRI. This can significantly reduce deployment costs.

- Scalability: enhanced CPRI provides more flexibility in network design and allows for easier scaling, which can reduce costs associated with network upgrades.
- Data compression: enhanced CPRI allows for data compression, which can reduce bandwidth requirements and result in more efficient data transmission.
- Centralized RAN: enhanced CPRI also enables Centralized RAN (CRAN) deployment, which can lead to further cost savings by reducing the number of base station deployments and enabling resource sharing between base stations.
- Reduced power consumption: enhanced CPRI can also reduce power consumption, resulting in lower operating costs.

There are several ways to increase the efficiency and utilization of eCPRI in the CRAN 5G network, including:

1. Network Slicing: This involves segmenting the network to provide dedicated resources for specific services. Network slicing can help increase efficiency and utilization by optimizing resources for specific applications and services.
2. Virtualization: CRAN 5G networks should be virtualized to optimize resource utilization. This will enable the allocation of resources based on demand, thus avoiding wastage of resources.
3. Optimization of Fiber Capacity: Fiber capacity should be optimized to ensure efficient transmission of data, as this is critical to the overall network performance.
4. Use of Machine Learning: Machine learning can be used to optimize resource allocation in CRAN 5G network. This involves analyzing data patterns to identify abnormalities and allocate resources accordingly.
5. Optimization of Radio Resources: Efficient use of radio resources is crucial to the performance of the CRAN 5G network. This can be achieved through innovative technologies such as beamforming, MIMO, and small cell deployment.
6. Implementation of Smart Scheduling: Scheduling algorithms should be implemented to optimize resource allocation and utilization. This involves intelligent distribution of resources based on the demand for these resources.
7. Use of Network Function Virtualization: It can be used to simplify network architecture and reduce the complexity of the network. This involves converting dedicated hardware devices into software running on generic hardware.

In summary, improving the efficiency and utilization of eCPRI in CRAN 5G networks requires implementing advanced technologies such as network slicing, virtualization, machine learning, smart scheduling, and network function virtualization.

5. METHODOLOGY

This methodology chapter contains the methods used in the thesis work. This section will delve into the techniques utilized for setting up the experimental environment and obtaining the test outcomes. Additionally, it will explore potential enhancements that could have been implemented in the FHGW with eCPRI within the context of the CRAN setting.

Initiating the process, the initial stage involved an in-depth exploration of both the operational environment and an infinite feasibility assessment. This step was very important to see if the expected results could happen and if they matched the goals of this research. The second stage revolved around merging the two settings. The pinnacle achievement in this stage was establishing the L3 call, (L3 call = Basic functionality testing) target is to integrate a bit further functionality so that vDU entry criteria are fulfilled. For example, agreed configuration start-up and calls done, different optical cabling variation when sufficient, SW downloads, commissioning, block/unblock in BTS, module level and some small stability. Automation job used when applicable. L3 call integration is part of each new product releasing.

After the environment setup and integration, the third phase entailed a series of tests. These tests aimed to attain the projected throughput while drawing comparisons with the conventional environment. The subsequent goal was to refine the attained throughput, optimizing both rank and overall throughput. To achieve these objectives, exhaustive testing across various parameters was imperative.

5.1 METHOD 1

The initial phase of the thesis comes under consideration. The concept was, researching both CPRI and eCPRI. Firstly, to set up a CRAN system and see the results for that purpose to understand the hardware part. After that, in the second step, need to get the environment ready for testing.

In the testing phase, discussing about setting up the hardware part. In a CRAN environment need to set up FHGW, VDU, VCU to do the testing. It is very important to install the FHGW and connect it to the radio unit.

The process of preparing the FHGW involved a multiple of steps, each essential for the proper setup. Furthermore, it encompassed post-installation actions after establishing the linkage between the FHGW and the radio unit, along with the associated switching aspect. These preparatory activities were undertaken prior to the ultimate implementation of the Cloud server.

This entailed initiating a CentOS installation, a prerequisite for configuring the FHGW, which served as a foundation for subsequent steps. To provide visual clarity, Figure 32 visually represents the network configuration orchestrated for the FHGW installation.

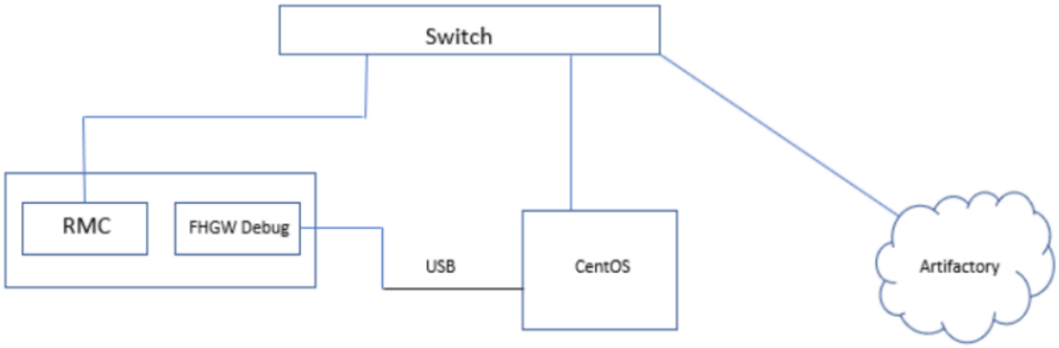


Figure 32. *Configuration of Network for FHGW Installation.*

5.2 METHOD 2

Upon completing the feasibility analysis, the following course of action entails establishing both environments. It begins by initiating the setup of the CRAN ecosystem. Initially, a chassis containing six sleds for the front haul gateway needs to be reconfigured into a solitary sled, as directed by the IP plan of the arrangement. Once the FHGW is deployed, the ensuing task involves the installation of the VDU server within the adjacent sled. A fiber connection is established between these sleds. One sled is designated for power connectivity purposes, while the other accommodates the Baseboard Management Controller (BMC), requiring a connection to be established with the switch configuration linked to the core network.

Once the physical interconnections are established among these components, the subsequent stage entails the installation of the FHGW, which constitutes a very important element of this environment. The installation process of FHGW needs following below mention steps:

- Configuration of a Centos laptop is imperative, aligning its settings in accordance with the appropriate plan.
- Adjustment of the BMC IP address is mandatory, facilitating access to the designated default IP assigned to the FHGW.
- After configuring the BMC IP, the ensuing step is to figure out the accessibility of FHGW.

Once the FHGW is successfully reachable via a ping command, the subsequent measure involves executing the installation procedure. This necessitates the deployment of distinct files within the FHGW.

After establishing the FHGW, the subsequent action involves upgrading the firmware and BIOS version of the FHGW. Following this, the VLAN connections require configuring the switch settings. When this step is completed, the subsequent phase encompasses the installation of the Cloud server. This necessitates the creation of a configuration file, which is subsequently deployed on GitHub. Once the deployment is complete, the process moves on to Jenkins for execution following the file merge.

After the installation of the vDU and vCU, deployment procedures are undertaken, corresponding to the approach applied in the installation of the vDU cloud server. Upon accomplishing all the installations as depicted in Figure 33, it becomes imperative to verify the inability of each IP address and ensure that the environment is primed for use.

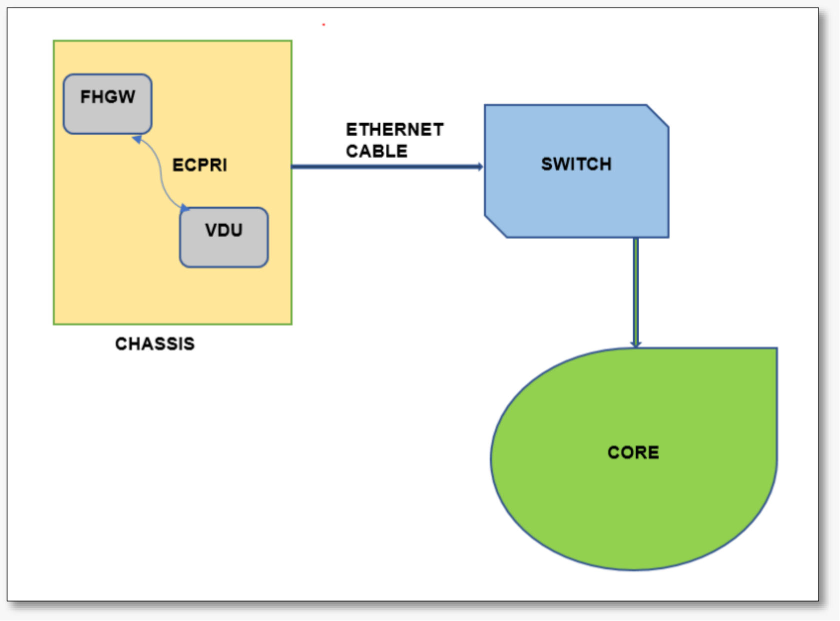


Figure 33. *Preparation Of FHGW Environment for Cloud-Based RAN With eCPRI.*

Once the CRAN setting was arranged, it enabled the establishment of Level 3 (L3). Subsequently, testing methodologies were initiated. All outcomes were realized during the second phase of the methodology.

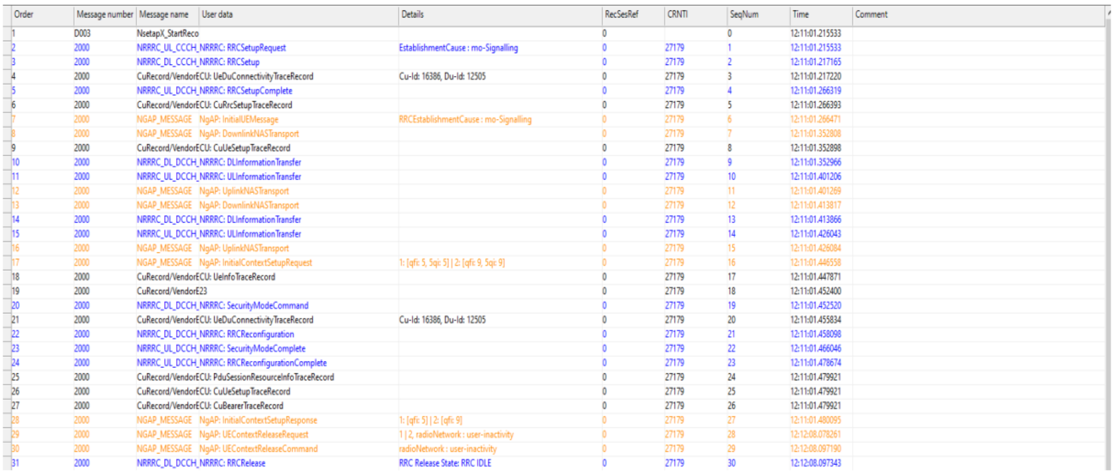
In terms of configuring switches and the core network, the deployment of core and VNF components leveraged GitHub and Jenkins. For the installation of the cloud server, these tools were utilized independently. Prior to integration on GitHub, files were formulated based on the IP plans. Subsequent deployment was executed through Jenkins.

In 5G setup to check the throughput (speed) with eCPRI FHGW having a 100 MHz bandwidth and using 512 QAM, along with either 4x4 or 4x2 closed loop spatial MIMO in this 5G network, makes the data go faster and the connection stronger. In the 4x4 MIMO setup, both the sending and receiving ends have two antennas each, which help to make the connections faster and more reliable so fixing the test line with above mention specification establish a L3 call to check the network availability and get some results.

6. RESULTS

Throughout this thesis my seniors in Nokia Cloud RAN team have been of a great help by providing valuable information regarding this 5G cloud RAN, the basic purpose of this research was to contribute the development of CRAN technology.

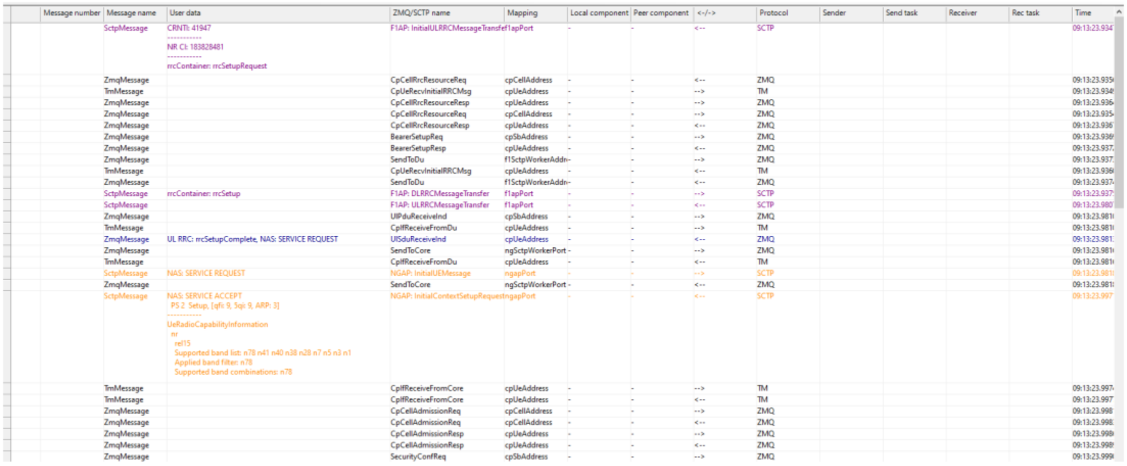
Presented here are the findings that transpired after the formulation of strategies within the methodologies. Following the process of environments, the initial phase necessitated accomplishing L3 call establishment within the designated setting, serving as the fundamental crux of this research undertaking.



Order	Message number	Message name	User data	Details	RecSesRef	CRNTI	SeqNum	Time	Comment
1	D003	NsetapX_StartReco			0		0	12:11:01.215533	
2	2000	NRRRC_UL_CCCH_NRRRC: RRCSetupRequest		EstablishmentCause : mo-Signalling	0	27179	1	12:11:01.215533	
3	2000	NRRRC_DL_CCCH_NRRRC: RRCSetup			0	27179	2	12:11:01.217165	
4	2000	CuRecord/VendorECU: UeDuConnectivityTraceRecord		Cu-Id: 16386, Du-Id: 12505	0	27179	3	12:11:01.217220	
5	2000	NRRRC_UL_DCCH_NRRRC: RRCSetupComplete			0	27179	4	12:11:01.266319	
6	2000	CuRecord/VendorECU: CuRrcSetupTraceRecord			0	27179	5	12:11:01.266393	
7	2000	NGAP_MESSAGE	NgAP: InitialUEMessage	RRCEstablishmentCause : mo-Signalling	0	27179	6	12:11:01.266471	
8	2000	NGAP_MESSAGE	NgAP: DownlinkNASTransport		0	27179	7	12:11:01.352808	
9	2000	CuRecord/VendorECU: CuUeSetupTraceRecord			0	27179	8	12:11:01.352898	
10	2000	NRRRC_DL_DCCH_NRRRC: DLInformationTransfer			0	27179	9	12:11:01.352966	
11	2000	NRRRC_UL_DCCH_NRRRC: ULInformationTransfer			0	27179	10	12:11:01.401206	
12	2000	NGAP_MESSAGE	NgAP: UplinkNASTransport		0	27179	11	12:11:01.401269	
13	2000	NGAP_MESSAGE	NgAP: DownlinkNASTransport		0	27179	12	12:11:01.413817	
14	2000	NRRRC_DL_DCCH_NRRRC: DLInformationTransfer			0	27179	13	12:11:01.413866	
15	2000	NRRRC_UL_DCCH_NRRRC: ULInformationTransfer			0	27179	14	12:11:01.426043	
16	2000	NGAP_MESSAGE	NgAP: UplinkNASTransport		0	27179	15	12:11:01.426084	
17	2000	NGAP_MESSAGE	NgAP: InitialContextSetupRequest	1: [qfi: 5, 5qi: 5] | 2: [qfi: 9, 5qi: 9]	0	27179	16	12:11:01.446558	
18	2000	CuRecord/VendorECU: UeInfoTraceRecord			0	27179	17	12:11:01.447871	
19	2000	CuRecord/VendorE23			0	27179	18	12:11:01.452400	
20	2000	NRRRC_DL_DCCH_NRRRC: SecurityModeCommand			0	27179	19	12:11:01.452520	
21	2000	CuRecord/VendorECU: UeDuConnectivityTraceRecord		Cu-Id: 16386, Du-Id: 12505	0	27179	20	12:11:01.455834	
22	2000	NRRRC_DL_DCCH_NRRRC: RRCReconfiguration			0	27179	21	12:11:01.458098	
23	2000	NRRRC_UL_DCCH_NRRRC: SecurityModeComplete			0	27179	22	12:11:01.466046	
24	2000	NRRRC_UL_DCCH_NRRRC: RRCReconfigurationComplete			0	27179	23	12:11:01.478674	
25	2000	CuRecord/VendorECU: PduSessionResourceInfoTraceRecord			0	27179	24	12:11:01.479921	
26	2000	CuRecord/VendorECU: CuUeSetupTraceRecord			0	27179	25	12:11:01.479921	
27	2000	CuRecord/VendorECU: CuBearerTraceRecord			0	27179	26	12:11:01.479921	
28	2000	NGAP_MESSAGE	NgAP: InitialContextSetupResponse	1: [qfi: 5] | 2: [qfi: 9]	0	27179	27	12:11:01.480095	
29	2000	NGAP_MESSAGE	NgAP: UEContextReleaseRequest	1 | 2, radioNetwork : user-inactivity	0	27179	28	12:12:08.078261	
30	2000	NGAP_MESSAGE	NgAP: UEContextReleaseCommand	radioNetwork : user-inactivity	0	27179	29	12:12:08.097190	
31	2000	NRRRC_DL_DCCH_NRRRC: RRCRelease		RRC Release State: RRC IDLE	0	27179	30	12:12:08.097343	

Figure 34. *DCAP L3 call establishment.*

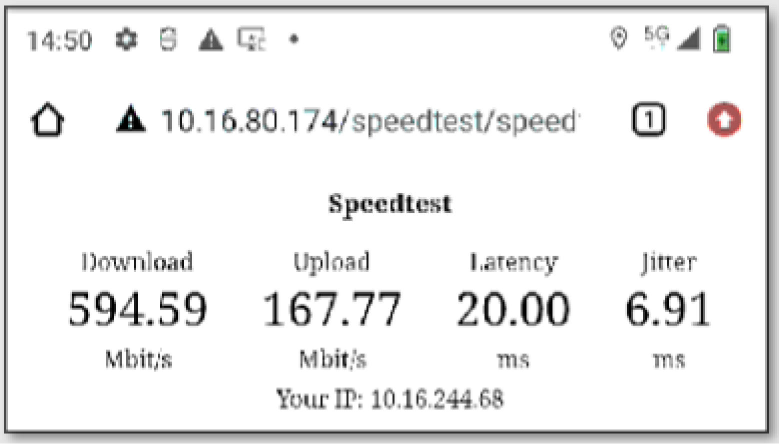
Illustrated in Figure 34 is the L3 signal communication, displaying IDs of both the Control unit and the distributed units. The figure provides a visual representation of all the L3 messages. In Figure 35, accompanying the signal communication, all the protocols employed in setting up the L3 conversation are apparent.



	Message number	Message name	User data	ZMQ/SCTP name	Mapping	Local component	Peer component	<-/->	Protocol	Sender	Send task	Receiver	Rec task	Time
		SctpMessage	CRNTI: 41947 ----------- NR CI: 183828481 ----------- rrcContainer: rrcSetupRequest	F1AP: InitialULRRCMessageTransfe	f1apPort	-	-	<--	SCTP					09:13:23.934
		ZmqMessage		CpCellRrcResourceReq	cpCellAddress	-	-	<--	ZMQ					09:13:23.935
		TmMessage		CpUeRecvInitialRRCMsg	cpUeAddress	-	-	-->	TM					09:13:23.934
		ZmqMessage		CpCellRrcResourceResp	cpUeAddress	-	-	-->	ZMQ					09:13:23.936
		ZmqMessage		CpCellRrcResourceReq	cpCellAddress	-	-	-->	ZMQ					09:13:23.935
		ZmqMessage		CpCellRrcResourceResp	cpUeAddress	-	-	<--	ZMQ					09:13:23.936
		ZmqMessage		BearerSetupReq	cpSbAddress	-	-	-->	ZMQ					09:13:23.936
		ZmqMessage		BearerSetupResp	cpUeAddress	-	-	<--	ZMQ					09:13:23.937
		ZmqMessage		SendToDu	f1SctpWorkerAddr	-	-	-->	ZMQ					09:13:23.937
		TmMessage		CpUeRecvInitialRRCMsg	cpUeAddress	-	-	<--	TM					09:13:23.936
		ZmqMessage		SendToDu	f1SctpWorkerAddr	-	-	<--	ZMQ					09:13:23.937
		SctpMessage	rrcContainer: rrcSetup	F1AP: DLRRCMessageTransfer	f1apPort	-	-	-->	SCTP					09:13:23.937
		SctpMessage		F1AP: ULRRCMessageTransfer	f1apPort	-	-	<--	SCTP					09:13:23.980
		ZmqMessage		UlPduReceiveInd	cpSbAddress	-	-	-->	ZMQ					09:13:23.981
		TmMessage		CpIfReceiveFromDu	cpUeAddress	-	-	-->	TM					09:13:23.981
		ZmqMessage	UL RRC: rrcSetupComplete, NAS: SERVICE REQUEST	UlSduReceiveInd	cpUeAddress	-	-	<--	ZMQ					09:13:23.981
		ZmqMessage		SendToCore	ngSctpWorkerPort	-	-	-->	ZMQ					09:13:23.981
		TmMessage		CpIfReceiveFromDu	cpUeAddress	-	-	<--	TM					09:13:23.981
		SctpMessage	NAS: SERVICE REQUEST	NGAP: InitialUEMessage	ngapPort	-	-	-->	SCTP					09:13:23.981
		ZmqMessage		SendToCore	ngSctpWorkerPort	-	-	<--	ZMQ					09:13:23.981
		SctpMessage	NAS: SERVICE ACCEPT PS 2 Setup, [qfi: 9, 5qi: 9, ARP: 3] ----------- UeRadioCapabilityInformation nr rel15 Supported band list: n78 n41 n40 n38 n28 n7 n5 n3 n1 Applied band filter: n78 Supported band combinations: n78	NGAP: InitialContextSetupRequest	ngapPort	-	-	<--	SCTP					09:13:23.997
		TmMessage		CpIfReceiveFromCore	cpUeAddress	-	-	-->	TM					09:13:23.997
		TmMessage		CpIfReceiveFromCore	cpUeAddress	-	-	<--	TM					09:13:23.997
		ZmqMessage		CpCellAdmissionReq	cpCellAddress	-	-	-->	ZMQ					09:13:23.998
		ZmqMessage		CpCellAdmissionReq	cpCellAddress	-	-	<--	ZMQ					09:13:23.998
		ZmqMessage		CpCellAdmissionResp	cpUeAddress	-	-	-->	ZMQ					09:13:23.998
		ZmqMessage		CpCellAdmissionResp	cpUeAddress	-	-	<--	ZMQ					09:13:23.998
		ZmqMessage		SecurityConfReq	cpSbAddress	-	-	-->	ZMQ					09:13:23.999

Figure 35. *L3 call and messages establishment procedure.*

Following the creation of the setting, the subsequent phase involved evaluating the downlink and uplink capacity or throughput was initially not so good to improve the throughput results substantial efforts were done to rectifying this situation and enhancing the outcomes. This involved a complete troubleshooting process aimed to get some reasonable results. It is important to note that the positions of the antennas remained unchanged throughout this analysis, and the data was collected accordingly.



Speedtest

Download 594.59 Mbit/s

Upload 167.77 Mbit/s

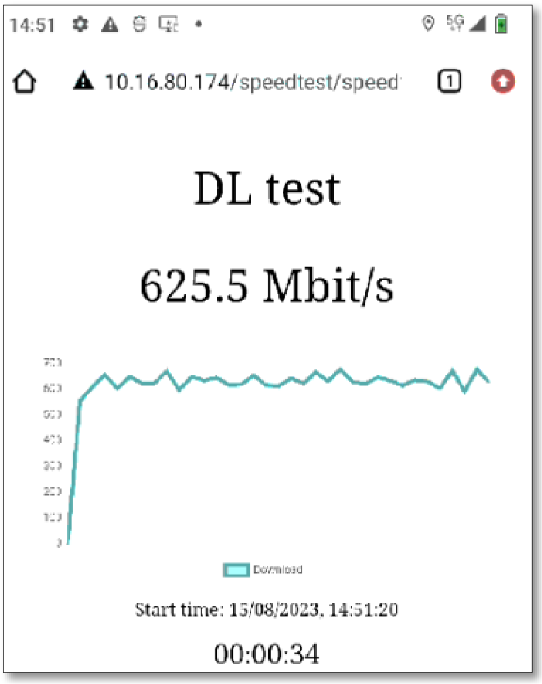
Latency 20.00 ms

Jitter 6.91 ms

Your IP: 10.16.244.68

Figure 36. *Initial throughput chart.*

In Figure 36, the initial approach that was previously examined, demonstrating outcomes gathered in the field. With this 5G network setup expecting to achieve download speed above than 600 Mbit/s but clearly, there is a noticeable very low speed in both download and upload as expecting much more with 5G. Following investigation and adjustments to the configuration, all of this was achieved without altering the antenna locations. The subsequent findings display significant enhancements of throughput rates in uplink and downlink speed.



DL test

625.5 Mbit/s

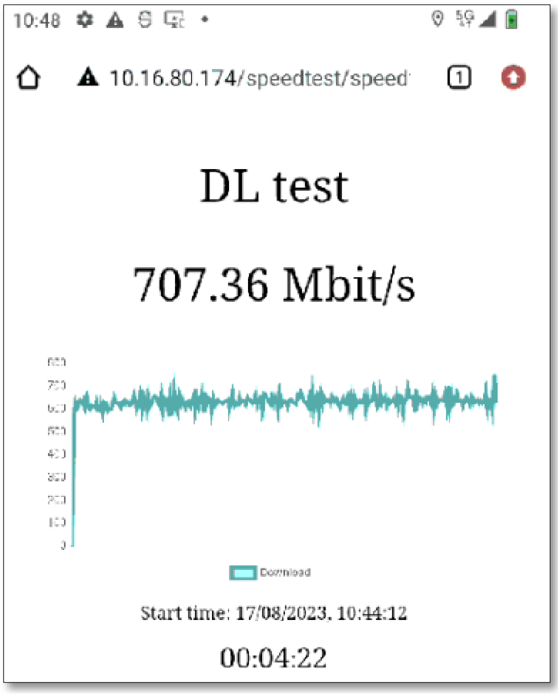
Start time: 15/08/2023, 14:51:20

00:00:34

Figure 37. *First Downlink Speed.*

After modifying several parameters in the Site configuration file (SCF) a noticeable improvement can be observed in the Downlink data transmission rate, as depicted in Figure 37.

SCF consists of group of parameters that could be set by system which cannot be changed also some reference parameters so with the help of that SCF gained the good throughput results.



DL test

707.36 Mbit/s

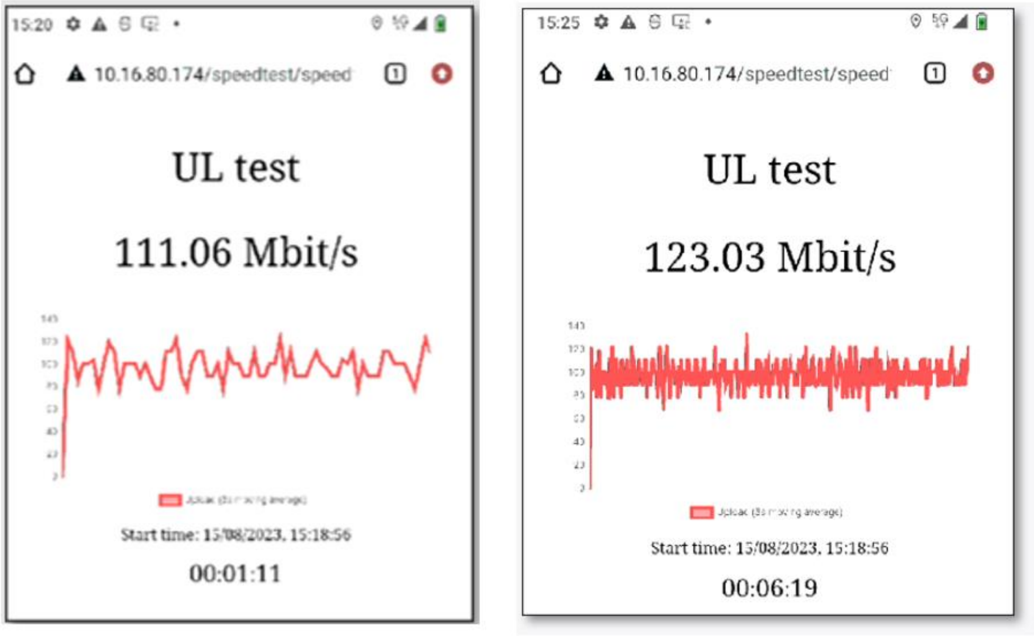
Start time: 17/08/2023, 10:44:12

00:04:22

Figure 38. *Second Downlink Speed.*

It can be seen in Figure 38, the peak download speed of 707 Mbit/s which is comparatively very good with respect to initial downlink throughput which was 594.5 Mbit/s.

From the below Figure 39, a clear pattern emerges: the uplink throughput speeds rapidly increase following the implementation of configuration adjustments and the completion of troubleshooting efforts.



UL test

111.06 Mbit/s

Start time: 15/08/2023, 15:18:56

00:01:11

UL test

123.03 Mbit/s

Start time: 15/08/2023, 15:18:56

00:06:19

Figure 39. *First (left) and second (right) Uplink speed.*

Successfully achieved the good speed outlined in the thesis, aiming for a minimum of 700 Mbps and surpassing 700 Mbps in downlink throughput. Among the pivotal components of the thesis, Figure 39 stands out, demonstrating a pronounced increase in speed. This rise aligns with the objective of the thesis, realized through the application of FHGW with eCPRI configuration. Moving to Figure 39, a noticeable enhancement in uplink speed.

The findings encompass the outcomes extracted throughout the entirety of the thesis research. In the concluding section, there is a deliberation on the noteworthy augmentation in the pace of throughput, accompanied by a discourse on prospective objectives.

7. CONCLUSIONS

In conclusion, CRAN presents a range of benefits over traditional RAN structures. These advantages encompass enhanced network scalability, optimized resource utilization, reduced equipment expenditures, and simplified maintenance and upgrades. By centralizing the processing of baseband functions and enabling resource sharing across numerous cellular sites, CRAN streamlines network administration, curtails hardware outlays, and elevates overall network efficiency. Consequently, CRAN is progressively gaining favour among mobile network operators seeking to amplify network capacity and curtail operational expenses. Moreover, in proximity scenarios, there exists a higher probability that the device can employ advanced modulation techniques like 64-QAM. This results in the transmission of a greater number of symbols, heightening overall throughput due to a stronger and more dependable signal, and decreased interference. CRAN architecture provides a flexible and scalable network design that allows for the efficient management of network resources, better traffic regulation, and cost-effectiveness. Unlike traditional RAN, CRAN architecture centralizes baseband processing and separates it from the remote radio head. This allows for the deployment of more radios with simplified installation since the baseband processing can be centralized in a data center. Overall, CRAN architecture enables network operators to have better control over the network while making it more efficient, cost-effective, and scalable. As a result, it is seen as significant innovation and an essential component in the establishment and development of 5G networks worldwide.

When working with hardware to measure eCPRI performance, in the form of downlink, uplink speed there can be some measurement errors due to inaccuracies in the instruments or the calibration process. It is very important to ensure that measurement tools are properly calibrated and regularly maintained and some factors like network congestion, signal interference, and variations in signal strength can affect the performance of test results.

With a limited study and research of all the above factors, it was concluded that eCPRI Interface is a next generation FHGW, and it offers more efficient use of network resources, higher bandwidth capacity, and lower latency than CPRI. It is designed as an open, common interface standard that supports Ethernet-based fronthaul networks. Moreover, eCPRI allows the centralized or distributed nature of the radio transmission process.

Comparatively, eCPRI is considered a better option than CPRI due to its increased bandwidth capacity, improved use of network resources, and lower latency, making it possible to handle network slicing and centralized baseband processing. For applications that require ultra-low latency and low-jitter performance, eCPRI should be preferred over CPRI. It has more advanced features than CPRI, which includes compression, traffic aggregation, and distributed processing, which reduce the overall bandwidth requirements. While CPRI has been widely used in traditional cell site architectures and provides a reliable interface between the baseband and the radio unit, eCPRI offers more flexibility and scalability in designing wireless networks while providing better QoS.

Anticipated Subsequent investigations into CRAN are expected to concentrate on enhancing the efficiency and capability of the technology, along with formulating fresh applications and usage scenarios. Pioneering resource management and allocation algorithms, alongside exploration into innovative network frameworks and configurations, constitute pivotal research domains worth pursuing. As the adoption of CRAN continues to rise, investigations might delve into comprehending the technology's impact on network security, privacy, and reliability. Additionally, examination of novel business strategies and revenue streams for mobile network operators could assume prominence in research endeavours.

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