Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering
Communication Engineering Graduate Program

Comparative Analysis of Fronthaul Delay in 5G C-RAN: The Case of Ethio Telecom Legehar Area

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Addis Ababa, Ethiopia

Abstract

This thesis investigates fronthaul delay in 5G Centralized-Radio Access Network (C-RAN) architecture, focusing on Ethio Telecom's Legehar area. Fronthaul (FH) is the communication link between the Radio Unit (RU) and Distributed Unit (DU). This research compares D-RAN and C-RAN architecture to evaluate their delay performance.

The increasing demand for low latency has emphasized the need to analyze the fronthaul delays in diverse scenarios, including Financial hubs, major event venues such as Stadium, and Africa Union (AU) summits. C-RAN is a promising solution for meeting the growing demand for high-speed, low-latency, and reliable wireless connectivity. Legehar and its surroundings are key areas where delay affects users' demands. The impact of delay on FH was demonstrated by comparing and analyzing various network architectures and FH configurations.

Simulation and analytical techniques were used to analyze the delay characteristics. The findings demonstrate that the C-RAN exhibits superior delay performance under specific conditions, offering insights for optimizing 5G deployments. The simulation results show that the eCPRI protocol performed better than the current Ethio Telecom used, known as CPRI. Because the FH data rate impacts delay, CPRI uses the maximum data rate of 24.33 Gbps. The delay for 24.33 Gbps is 0.493 $\mu s.$ eCPRI at 50 Gbps rate can achieve a delay of 0.24 μs. Additionally, there is a user plane delay that achieved to 0.48 μs by dividing plane.

Key Words: 5G Networks, eCPRI, C-RAN, D-RAN, NR, and FH delay

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List of Symbols

Symbol	Description
C_{link}	Link capacity (Gbps)
C_{proc}	Processing capacity (Gbps)
d	Distance between DU and RU (km)
Δf	Subcarrier spacing (KHz)
τ_{fh}	Fronthaul delay (μs)
τ_{proc}	Processing delay (μs)
τ_p	Propagation delay (μs)
τ_{tx}	Transmission delay (μs)
τ_{final}	Final delay
τ_{init}	Initial delay
τ_{total}	Total delay
L	packet size (kb)
M	Mesaage size (kb)
R	Data rate (Gbps)
R_{line}	Line rate (Gbps)
R_t	Transmission rate (Gbps)
T_s	Symbol duration
v	Speed of signal in medium (m/s)

List of Abbreviations

2G Second Generation

3G Third Generation

4G Fourth Generation

5G Fifth Generation

3GPP Third Generation Partnership Project

ACK Acknowledgement

ATN Any Transport Network

AU Africa Union

BBU Baseband Unit

BS Base Station

BTS Base Transceiver Station

CoMP Coordinated MultiPoint

CP Control Plane

CU Centralized Unit

C-RAN Centralized-Radio Access Network

CPRI Common Public Radio Interface

DU Distributed Unit

eCPRI enhanced CPRI

eREC enhanced REC

FH Fronthaul

FEC Forward Error Correction

FFT Fast Fourier Transform

ARQ Automatic Repeat reQuest

HARQ Hybrid ARQ

iFFT inverse FFT

IP Internet Protocol

IQ In-phase and Quadrature

ISI Inter Symbol Interference

IoT Internet of Things

LDPC Low-Density Parity-Check

LTE Long-Term Evolution

MAC Medium Access Control

MIMO Multiple Input Multiple Output

NACK Negative ACK

NR New Radio

ODN Optical Distribution Network

OFDM Orthogonal Frequency Division Multiplexing

RE Resource Element

REC Radio Equipment Control

RRH Remote Radio Head

RLC Radio Link Control

PDCP Packet Data Convergence Protocol

PDU Protocol data unit

PHY Physical Layer

RE Resource Element

RRC Radio Resource Control

RRU Radio Remote Unit

RU Radio Unit

SA Standalone

SCS Subcarrier Spacing

SDAP Service Data Adaptation Protocol

TR Technical Report

TS Technical Specification

T-RAN Traditional-RAN

UE User Equipment

UP User Plane

uRLLC ultra-Reliable Low-Latency Communication

Chapter 1

Introduction

1.1 Background

In the evolving landscape of Fifth Generation (5G) network architectures, C-RAN has become central due to its promise of reducing operational costs, improving network performance, and facilitating centralized resource management. The fronthaul, which connects Remote Radio Head (RRH)s to the centralized Baseband Unit (BBU)s, plays a crucial role in determining the effectiveness of C-RAN, particularly in terms of latency, which is vital for meeting the strict requirements of 5G technologies like ultra-Reliable Low-Latency Communication (uRLLC)s.

One difference of 5G compared to earlier mobile communication systems is that it is expected to address a much broader range of applications and use cases[1]. Recently, C-RANs have been proposed, which are enhancements of classical RAN architectures through cloudification and virtualization techniques to comply with the requirements of envisioned 5G mobile networks[2]. In a C-RAN system, the baseband processing units are centralized in a data center, while the remote radio units are distributed at the cell sites. The Fronthaul network connects the remote radio units to the centralized BBUs.

It employs Orthogonal Frequency Division Multiplexing (OFDM), a technique that modulates digital signals across various channels to minimize interference. The primary objective of 5G is to significantly enhance transmission speeds, with a target of up to 25 Gbps. Additionally, it aims to reduce latency and improve the overall flexibility of wireless services. Fronthaul latency is a critical factor in determining the overall performance of a C-RAN system. It refers to the time it takes for a signal to travel from the remote radio unit to the centralized BBU.

Different Fronthaul technologies, such as Ethernet, fiber optic, and wireless, have different delay characteristics that can impact the latency and throughput of the system. C-RAN aims to reduce capital costs, enhance energy efficiency, and support advanced capacity and coverage by leveraging centralized processing. One of the critical aspects of C-RAN is the FH traffic delay.

In the case of Ethio Telecom's 5G network, the bandwidth is set at 100 MHz. The frequency band utilized is N78, which corresponds to the New Radio (NR) operating band. The uplink and downlink frequency bands range from 3.4 GHz to 3.5 GHz. Two main frequency classification categories exist, each with a corresponding frequency range. FR1 (Frequency Range 1) refers to sub-7 GHz frequencies, covering 410 to 7.125 GHz. FR2 (Frequency Range 2) covers millimeter-wave (mmWave) frequencies, specifically from 24.25 GHz to 52.6 GHz.

The C-RAN architecture presented by China Mobile introduces the idea of cloud computing-based processing of baseband signals on cellular networks. Experiments testing the C-RAN framework reveal that significant savings in both operational and capital expenditures can be achieved[3]. However, the focus of this research is on reducing operational time and cost. i.e., for each AAU, we go to the site and identify the problem. However, in the case of C-RAN, we can troubleshoot from one DU for several AAUs.

Ultra reliable low latency is a service category designed to meet delay-sensitivity services such as the tactile internet, vehicular-to-vehicular communication, autonomous driving, and remote control [4]. For the rollout of the radio access network, Ethio Telecom aims to achieve an average latency of less than 30 ms. The protocol employed for communication between the BBU and the Radio Remote Unit (RRU) is the Common Public Radio Interface (CPRI). Furthermore, the connection between the BBU and RRU is established using fiber optic technology.

The advancements in optimizing Fronthaul delay in 5G C-RAN have significantly contributed to the enhancement of overall network performance and user experience. By reducing latency, operators can provide faster and more reliable services to their customers, enabling applications that require real-time responsiveness, such as autonomous vehicles, remote surgery, and virtual reality. Motivation discusses why this research is worthwhile.

1.2 Motivation

Ethio Telecom Legehar Area: This specific area was chosen as a case study due to its unique challenges and opportunities in deploying 5G infrastructure. Urban environments like Legehar present complex scenarios with high user density, varied traffic patterns, and existing infrastructure that must be integrated with new centralized 5G deployments.

Fronthaul Delay: The latency introduced by the fronthaul link can significantly impact the overall performance of 5G networks. Delays in fronthaul are influenced by the distance between the RRHs and BBUs, the medium used for transmission is optical fiber or free space in wireless, and the capacity and congestion of the fronthaul network.

Need for Analysis: There is a necessity to understand how these factors play out in real-world scenarios, particularly in regions like Ethiopia, where infrastructure development and technological adoption rates can vary significantly from those in more developed countries.

Although the promise of improved connection and service quality is what motivates the deployment of 5G networks in highly populated places like legehar, overcoming the latency bottleneck in the fronthaul section of the C-RAN is a significant challenge.

1.3 Statement of the Problem

With the advent of 5G technology, there is a pressing need to analyze and compare FH solutions. Fronthaul, the segment of the network that connects the DU to the RU in centralized RAN system, has become increasingly critical with 5G due to its demands for lower latency, higher data rate, and greater network capacity.

The FH link is more sensitive to latency than other parts of the network. Because it carries real-time, unprocessed radio signals that require immediate processing to ensure that the data can be quickly transformed, decoded, and made ready for transmission through the midhaul to the core network or to be sent back over the air to user devices. Any delay in this process can lead to increased latency, which in turn can degrade the quality of service, particularly for applications demanding ultra-low latency like video streaming, online transactions, and online gaming.

There is a clear worldwide pattern in the increment of population around Metropolitan areas. Such dense metropolitan areas are responsible for the majority of traffic growth and network congestion. To satisfy the demand, Ethio Telecom has to implement better RAN architecture with a minimal-delay FH network and flexible FH RAN. This thesis aims to enhance the aforementioned issues.

Technologies with minimal latency requirements have been prevailing in this area, dramatically altering how we interact with digital systems. Legehar and its surrounding areas have a large number of business enterprises and large financial headquarters, The AU summit, Public holidays, Parking lots, Luxury apartments, and a stadium are found in this area. Since all Ethiopian financial headquarters are located in this area, intra-transaction with sub-branch and inter-transaction or within national bank needs fractions of microsecond delay.

1.4 Literature Review

The C-RAN scheme comes into the scene to reduce the complexity of the base stations, enabling the sharing of signal processing capacity by several antennas. Various papers have been written on minimal-latency FH C-RAN. 5G cellular systems aim to achieve very high data rates (100x of 4G) and low latency by exploiting advanced RAN solutions[5]. The expected 1000x increase of mobile data traffic in 5G compared to that of Long-Term Evolution (LTE) release 8 implies the utilization of new radio access technology, such as small cells, Coordinated MultiPoint (CoMP), massive Multiple Input Multiple Output (MIMO), and Carrier aggregation.

Since it is not possible to satisfy these relentless changes with a small modification of current radio access technology, the Third Generation Partnership Project (3GPP) has defined a new air interface called NR access technology. The underlying principle of the NR access technology is to abandon backward compatibility and add entirely new features and technologies to provide a customized connection to any device from sensor to vehicle and smartphone[4]. 3GPP has defined that not every protocol layer should reside in a fixed virtual function but should be given the freedom to reside in a virtual function that is more supportive of the service requirements.

High-functional split options at the FH, such as split option 2, will not be practical because the complexity of the RUs will be higher, and the statistical multiplexing gain will be reduced. As 5G deployment is based on small-cell architecture and because each of the Standalone (SA) RUs works relatively as a full base station, there will be a need for frequent handovers.

This will degrade the latency performance and greatly increase the control messaging to handle the frequent handover procedure[6], the most accepted candidate functional split option for FH is split Option 7, which can reduce the FH bandwidth requirement and keep the RU quite simple. Higher functional split options can be used to facilitate lower latency applications by placing more functions at the RU.

By distributing protocol stacks between different components, a near-perfect FH between BBUs could be achieved. A near-perfect FH means that it would virtually introduce no latency, speed loss, or reduced bandwidth to the traffic it was carrying. According to [7] to achieve a reduction in the time to transmit latency, the symbol period and/or the number of symbols in a packet need to be reduced. By reducing the symbol period, the time taken for each symbol to be transmitted is shorted and this directly influences the transmission delay.

Alfadhli et al. propose that by reducing the number of symbols per packet, the amount of data to be processed and transmitted per unit of time is decreased, which contributes to a reduction of overall delay[7]. In many indoor scenarios, and also when a high-frequency band millimeter wave is used, the cell radius would be small, and so will be channel delay spread in this case, we can reduce the symbol period by controlling the Subcarrier Spacing (SCS) (e.g. 15, 30, and 60 KHz) without affecting the system performance.

In addition to the capacity requirement, there is a stringent requirement for the latency in the 5G FH network as the majority of machine-to-machine and mobile applications supported by 5G are high delay sensitive[8]. For example, applications such as Tactile Internet will require a tolerant margin of 1 ms for end-to-end communication.

The Physical Layer (PHY) split architecture, lower-layer physical functions like modulation and FFT are moved to RRH, reducing the fronthaul bandwidth significantly while maintaining a balance between centralization and cost[8]. To achieve such a low latency, not only 5G technology but also FH technology and architecture should also be designed carefully. Since radio signals are centrally processed at the BBU, the FH network needs to transport the signals within the required time frame to be processed at the BBU without any losses.

The network Ethernet-based FH network topology, even on a large network scale, and focus on reconfigurable FH technology for C-RAN to meet the scalability and flexibility demands of modern networks[5]. It emphasizes using Ethernet-based fronthaul as a cost-effective alternative to CPRI for handling variable traffic loads. The paper also highlights challenges like latency and synchronization while suggesting potential solutions to meet 5G performance needs.

In order to obtain high statistical multiplexing gains and significant overhead efficiency, the future fronthaul needs to treat the newly exposed traffic flows separately, applying mapping on a per-flow basis based on their respective traffic generation characteristics (large data rate or channel condition differences between users)[9].

Different mapping is also required between user- and control-plane flows. Such an approach is efficient but will lead to design complications in multi-operator/multi-user slicing scenarios so must be taken into account in future research. Potential alternative methods such as efficient aggregation of flows exist, but these may complicate slice isolation and class-of-service differentiation[9].

Moreover, [6] stated in the research that the specification gives recommendations for the transport of the user plane data over Ethernet and Internet Protocol (IP). Added every enhanced CPRI (eCPRI) packet consists of a common header of 4 bytes'. The header is common for all eCPRI packets[6]. It contains a bunch of useful information such as the protocol version, a flag to mark concatenated eCPRI packets, a type field, and 2 bytes to denote the payload size. To assess and enhance the latency performance of 5G FH C-RAN, various analysis methods are employed.

Currently, the eCPRI-based Ethernet networks are gaining the attention of network operators and telecom vendors due to their minimal-cost and reconfigurability features, but achieving the required end-to-end latency is still a challenging issue that requires further exploration. The end-to-end latency in such networks is the result of indeterministic and deterministic delays[2].

Processing delay is both indeterministic and deterministic in some condition, and depends on the processing speed of the switch. It is the amount of time the switch needs to process a packet completely for routing. Transmission delay is a static value and depends on the packet sizes and capacity of the link[10].

1.5 Objective

1.5.1 General Objective

The goal of this thesis is to Compare and Analyze Fronthaul Delay in 5G C-RAN, The Case of Ethio Telecom Legehar Area.

1.5.2 Specific Objective

The specific objectives of this thesis are:

- To lower the FH delay in C-RAN.
- To assess the performance of the C-RAN architecture instead of the D-RAN.
- Comparison of D-RAN vs. C-RAN in terms of reducing FH delay.
- To assess and examine the best RAN types for the Legehar and its environments.
- To describe the importance of C-RAN architecture for Legehar and current trends in this area.
- To examine and contrast various PHY protocol stacks with regards to FH delay.
- To describe how split options and sub-PHY parameters affect delays in FH.

1.6 Scope

The thesis focuses on comparing and analyzing 5G fronthaul C-RAN delays using various fronthaul configurations, such as protocol-based and plane-based split methods. This thesis focuses solely on transmission delay and performance metrics processing, and its analysis and comparison are based solely on simulation rather than real-time data collected from operational networks. The Legehar area of the Ethio Telecom network is the specific focus of the study.

This thesis only addressed a small portion of PHY; many parameters are not detailed. Furthermore, just a portion of the downlink is covered and the uplink path is not mentioned because the topic is too broad to summarize under this topic. Some vast and sophisticated portions, not discussed in C-RAN, fronthaul include Radio Link Control (RLC) and Medium Access Control (MAC). If not in the Centralized Unit (CU), RLC would be placed in DU depending on the split.

The objective was to examine and contrast FH configurations based on delay measures, as these configurations have a direct impact on processing and transmission delays. However, queuing delays can be influenced by many variables outside of the FH setup such as core network load or user behavior, which were beyond the study's scope and future studies could extend this work by incorporating queuing delay into analysis.

Because the Thesis focus is restricted to the Legehar area, propagation delay is also not included in this study. Because it measures how long it takes for the signal to reach its destination from its source over a medium or free space, the propagation delay is directly correlated with the distance.

$$\tau_p = \frac{d}{v}$$

Thus, this kind of delay metric works better for a wide geographic area, and it can be incorporated into the future study.

1.7 Significance of the Studies

- **Localized Network Design**: The emphasis on the Legehar area can yield localized insights for Ethio Telecom, which can be a guide for other urban areas of Addis Ababa or elsewhere.

- **Fronthaul Split Evaluation**: Evaluating the impact of different functional splits on fronthaul delay helps to choose the right balance between centralization for cost and management benefits and the reduction in distribution latency. The delay options for various functional splits vary, as does the cost of additional system flaws.

- **Optimization of 5G Networks**: We can distribute the radio parts and centralize the distributed unit into a single room a centralized radio access network. This makes it simple to intelligently optimize services for areas with a high volume of users rather than those with fewer users. In wireless communications, beamforming is a technique used when traffic moves towards areas with more users.

- **For Academic Contribution**: The study adds to the academic body of knowledge on 5G C-RAN fronthaul analysis and comparison, offering a case study that can be referenced for further research or educational purposes.

- **Future Network Planning**: Understanding current limitations and capabilities of fronthaul in 5G C-RAN can guide future networks planning, not just for Ethio Telecom but for Safaricom Ethiopia when want to deploy 5G networks for Legehar and other urban areas.

Chapter 2

Overview of C-RAN and 5G Fronthaul

C-RAN and 5G Fronthaul are two key technologies that are revolutionizing the way mobile networks are designed and operated. C-RAN is a network architecture that centralizes the processing and management of radio access network functions in a cloud-based data center. This allows for more efficient resource allocation, improved scalability, and easier maintenance of the network.

By separating the baseband processing from the radio units, C-RAN enables operators to deploy more flexible and cost-effective network solutions. 5G FH, on the other hand, refers to the high-speed, low-latency connection between the centralized BBUs in the C-RAN architecture and the distributed remote radio units at the cell sites. This connection is crucial for enabling the high data rates, low latency, and massive connectivity that are key features of 5G networks.

FH networks must be able to support the high bandwidth and low latency requirements of 5G applications, such as virtual reality, autonomous vehicles, and industrial automation. Together, C-RAN and 5G FH are driving the evolution of mobile networks toward more efficient, flexible, and scalable architectures that can support the growing demand for high-speed, low-latency connectivity[1]. These technologies are expected to play a key role in enabling the full potential of 5G networks and unlocking new opportunities for innovation and growth in the mobile industry.

2.1 RAN Categories

2.1.1 Traditional RAN

Traditional-RAN (T-RAN) is also known as classic RAN. In T-RAN, each base station Base Transceiver Station (BTS) in Second Generation (2G), NodeB in Third Generation (3G), or eNodeB in Fourth Generation (4G) is a standalone entity with all radio functions (including baseband processing, RF, and antenna) integrated into one physical unit. The T-RAN deployment starts with a D-RAN architecture where BBUs are distributed, and a BBU and RRU pair always sits at the same cell site[12].

T-RAN used to associate a Base Station (BS) to a UE on the basis of received signal strength from various BSs(the dominated one selected). This sort of BS selection suffers from the fact that the interfering power received by the cell edge users is usually affected by severe inter-cell interference. C-RAN has shifted towards UE UE-centric approach, which uses several BSs to reduce interference from the other cells [16].

2.1.2 Standalone vs Non-Standalone

Standalone RAN: Operates independently of 4G LTE, utilizing a complete 5G core and RAN.

Non-Standalone RAN: Uses the existing 4G LTE infrastructure for control functions while adding 5G NR for increased data capacity and speed. The non-standalone operation was specified in the early timing of Release 15. Standalone-specific functionality were specified in the later timing of Release 15 to keep functional commonalities between non-standalone and standalone operations as much as possible[11]. In early deployment, this one is very suitable because the spectrum license can take time.

2.1.3 The open-RAN

The O-RAN concept encompasses various technologies that telecom operators anticipate will disrupt vendor lock-in and result in substantial cost reductions in both capital expenditure and operational expenditure for their radio access networks. O-RAN networks can be built with multi-vendor, interoperable components, and can be programmatically optimized through a centralized abstraction layer and data-driven closed-loop control[14].

Vendor lock-in occurs when an operator is compelled to continuously bring in equipment and services from a specific vendor due to the lack of compatibility with other vendors' offerings within the operator's existing architecture. By embracing open RAN, operators gain the flexibility to utilize different vendors for both baseband units and radio units, fostering a more diverse and competitive ecosystem.

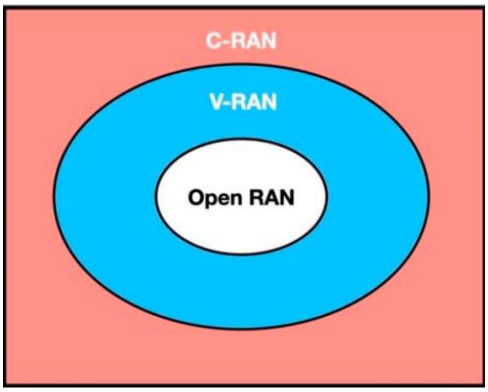


Figure 2.1: RAN types

2.1.4 Virtual RAN

Also known as vRAN, virtualizes the baseband units to enable the use of generic hardware. In vRAN, the functionality is no longer tied to dedicated hardware but is instead implemented through software. This flexibility allows operators to opt for non-branded hardware, commonly known as white boxes. Virtual RAN facilitates the use of software and hardware from various vendors, offering a more versatile and customizable solution.

2.1.5 C-RAN

In centralized RAN or Cloud RAN, the baseband functionality is consolidated over a reduced number of sites, or in the cloud.

Characteristics

Centralized Processing: Baseband processing is centralized, allowing for better resource utilization, easier upgrades, and maintenance.

Scalability: Easier to scale since adding capacity can be as simple as increasing the processing power in the data center.

Fronthaul Challenges: Requires a high-capacity, low-latency fronthaul network.

2.1.6 D-RAN

D-RAN is somewhat of a middle ground between Traditional RAN and C-RAN, but the core concept is still distributing the radio functions closer to the user equipment for better performance. In D-RAN topology, the base station is self-contained, and the requirement on fronthaul is quite limited[12].

Characteristics

Partial Centralization: Some functions might be centralized for better coordination, but most processing remains at the cell site.

Flexibility: Allows for some level of resource sharing and control centralization without the full infrastructure overhaul needed for C-RAN.

Figure 2.2: Ethio-Telecom 5G active antenna unit

2.2 C-RAN Architecture

C-RAN architecture, also known as Centralized Radio Access Network architecture, is a network design approach that revolutionizes the way wireless networks are structured and managed. Traditionally, in a distributed radio access network (D-RAN), each RRH has its own BBU located at the cell site. However, C-RAN takes a different approach by centralizing the baseband processing of multiple RRHs in a centralized location.

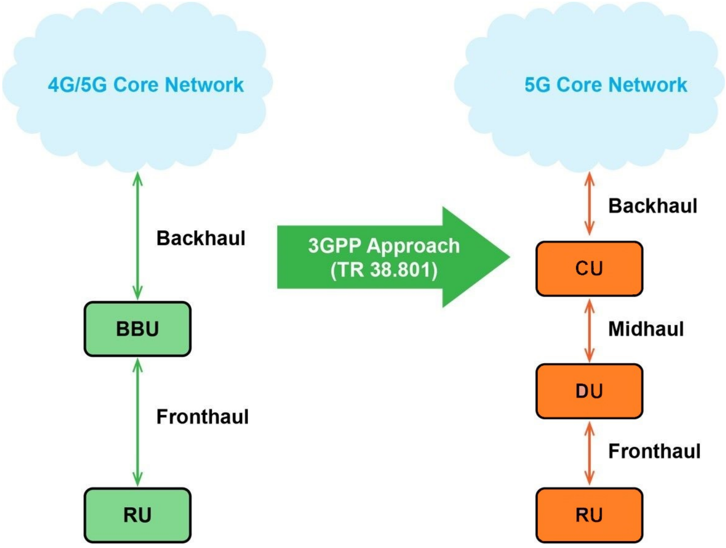


Figure 2.3: C-RAN Architecture

One of the key advantages of C-RAN architecture is improved resource allocation. With the baseband processing centralized, resources can be allocated dynamically and efficiently based on the network's needs. This allows for better utilization of network resources, resulting in improved network performance and capacity. Another significant benefit of C-RAN is reduced power consumption. By consolidating the baseband processing in a centralized location, the need for individual BBUs at each cell site is eliminated. This leads to significant energy savings, as the centralized processing unit can be optimized for power efficiency.

Additionally, the reduced power consumption also translates to lower operational costs for network operators. Scalability is another advantage offered by C-RAN architecture. As the demand for wireless connectivity continues to grow, C-RAN provides a flexible and scalable solution. With the centralized processing unit, additional RRHs can be easily added to the network without the need for extensive infrastructure upgrades. This scalability ensures that the network can adapt to the increasing demands of users and applications. Furthermore, C-RAN enables more efficient network management and optimization.

With the baseband processing centralized, network operators have greater control and visibility over the entire network. This allows for more effective monitoring, troubleshooting, and optimization of network performance. Additionally, C-RAN architecture enables the implementation of advanced network management techniques, such as virtualization and software-defined networking, further enhancing network efficiency and flexibility.

The increasing demand for high-speed and reliable wireless connectivity is driving the popularity of C-RAN architecture in the telecommunications industry. With its ability to improve resource allocation, reduce power consumption, enhance scalability, and enable efficient network management, C-RAN is seen as a promising solution for meeting the evolving needs of wireless networks. As technology continues to advance, C-RAN architecture is expected to play a crucial role in enabling the deployment of 5G networks and supporting the future growth of wireless communications.

2.3 5G Fronthaul

Fifth-generation FH technology, also known as 5G FH, is an advanced communication technology that enables the seamless transmission of data between the central processing unit and the RU in a wireless network. It is a crucial component of 5G networks, which are designed to provide ultra-high-speed, low-latency, and reliable connectivity.

One of the key features of 5th-generation FH technology is its ability to support massive data traffic. With the increasing demand for high-bandwidth applications such as video streaming, virtual reality, and Internet of Things (IoT) devices, 5G FH ensures that the network can handle massive data volumes without any degradation in performance.

In C-RAN, the centrally located BBU pool controls the radio signals of its hundreds or even thousands of RRHs that are connected via the fronthaul network. The optical network is naturally the best candidate for the 5G fronthauling due to its inherent capabilities such as low latency, high capacity, and scalability[8].

With the introduction of 5G, the development of architectures, technologies, interfaces, and networks for the fronthaul has gained significant attention from both academia and industry. For example, Authors in [2,3,5,6,8,9,10] talked about how 5G implementations can employ Ethernet frames for fronthaul systems.

Furthermore, 5G FH technology supports advanced beamforming techniques, which enhance the network's coverage and capacity. Beamforming allows the network to focus its signal towards specific users or areas, improving signal strength and reducing interference. This capability is particularly beneficial in dense urban environments or areas with high user concentrations.

In General, 5th generation Fronthaul technology is a critical component of 5G networks, providing high-speed, low latency, and reliable connectivity. Its ability to handle massive data traffic, support network slicing, and enable advanced beamforming techniques makes it a key enabler for a wide range of applications and industries in the era of the IoT and digital transformation.

2.4 C-RAN Protocol Stack

From the perspective of the network layer and going down the protocol stack towards the Physical Layer, we find the following operations [6]. Firstly, the PDCP process receives the so-called Radio Bearers, in short, bearers. Then, the RLC stage takes over and performs the segmentation and flow control operations for the upper layers. Next, the MAC layer multiplexes and demultiplexes data of different bearers. Finally, the RLC data is organized into transport blocks that will be delivered to the PHY[6].

Additionally, the C-RAN protocol stack may also include higher layers such as the transport layer, which ensures reliable delivery of data between the centralized BBU and the distributed RUs, and the application layer, which includes protocols for specific services such as voice calls or video streaming. Overall, the C-RAN protocol stack plays a crucial role in enabling efficient communication between the centralized BBU and the distributed RUs in a C-RAN architecture, ultimately improving network performance and scalability.

5G Protocol Layers	
Protocol Layer	Responsible for
PHY	Mapping transport channels to physical channels
	5G frame structures
	Beamforming
	5G channel coding
	PHY retransmission handling
	Power control
	Power sharing with dual connectivity
	Timing advance
MAC	Allocating data transfers towards upper layers
	Allocating radio resources towards upper layers
	Mapping between logical and transport channels
	Scheduling information reporting error correction through HARQ
	Channel prioritisation
RLC	Transfer of upper layer PDUs
	Concatenation, segmentation and reassemble of RLC
	Protocol error detection and recovery
	RLC re-establishment
PDCP	Transfer of upper layer PDUs
	Transferring user and control plane data
	Routing or duplicating split bearers
	Activating and deactivating PDCP duplication
	Re-ordering and in order delivery

Table 2.1: 5G protocol layer

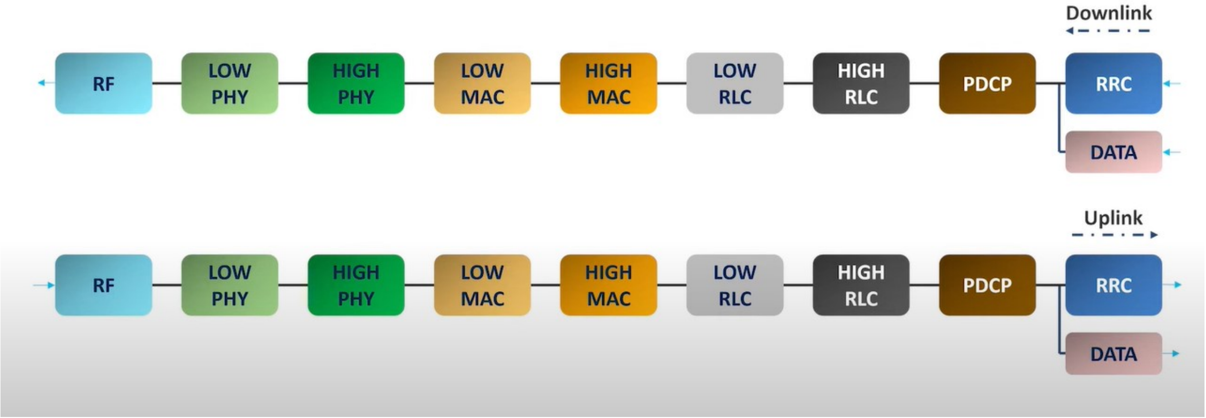


Figure 2.4: 5G C-RAN protocol stack

2.5 5G C-RAN Functional Splits

Splittingg the 5G NR functional split is to divide it into two main layers: the Control Plane (CP) and the User Plane (UP). The control plane is responsible for managing the signaling and control functions of the network, while the UP is responsible for handling the actual data transmission. Separation of control and user plane functions is ongoing, which allows for separate scaling of the user plane and control plane[1].

2.5.1 Control Plane split

The CP functions are primarily handled by access and mobility management function, session management function of the core part, and DU-CP for the RAN part. Because of the inherent characteristics of the network, control plane processing delays are greater than user plane processing delays, even though control plane traffic usually uses a lot less bandwidth than user plane data.

2.5.2 User Plane split

The user plane deals with the data that the user actually sends or receives, like internet traffic, voice calls, and video streaming. The UP demands high bandwidth due to the volume of data traffic. This has a direct effect on high-capacity links like fiber optics and fronthaul design.

For upper layer processing, DU-UP can be divided between the distributed unit and user plane, which minimizes the amount of data that must travel over the fronthaul.

The envisioned user plane end-to-end latency for 5G varies depending on the type of application[6]. DU can handle the higher layers of the user plane, like Packet Data Convergence Protocol (PDCP) and part of RLC, to reduce the load on the fronthaul by processing data closer to where it is needed. While RU could handle lower-layer functions of the user plane, particularly in splits where more PHY or MAC functions are pushed to the edge.

2.6 Option for splitting the 5G NR protocol stack

The 5G NR protocol stack can be split into various options, each defining how processing is distributed between CU, DU, and RU. But for this thesis purpose and scope, DU and RU are considered.

Option 7 (PHY): The Author [6] wrote that 3GPP specifies three different subdivisions of this split. Split option 7-1 (Low-PHY), where the up to FFT operation is kept in the remote unit, including the processing of the cyclic prefix. This eliminates some overhead information, lowering the fronthaul requirements. Split option 7-2, additionally keeps the precoding and the resource mapper at the remote unit (RU/RRH). Finally, split option 7-3 further includes more operations at the DU. Specifically, the layer mapping, modulation and demodulation, and scrambling/descrambling are now situated there. As a result, less data needs to be transmitted over the fronthaul. PHY protocol stacks are not immediately affected by the remaining options.

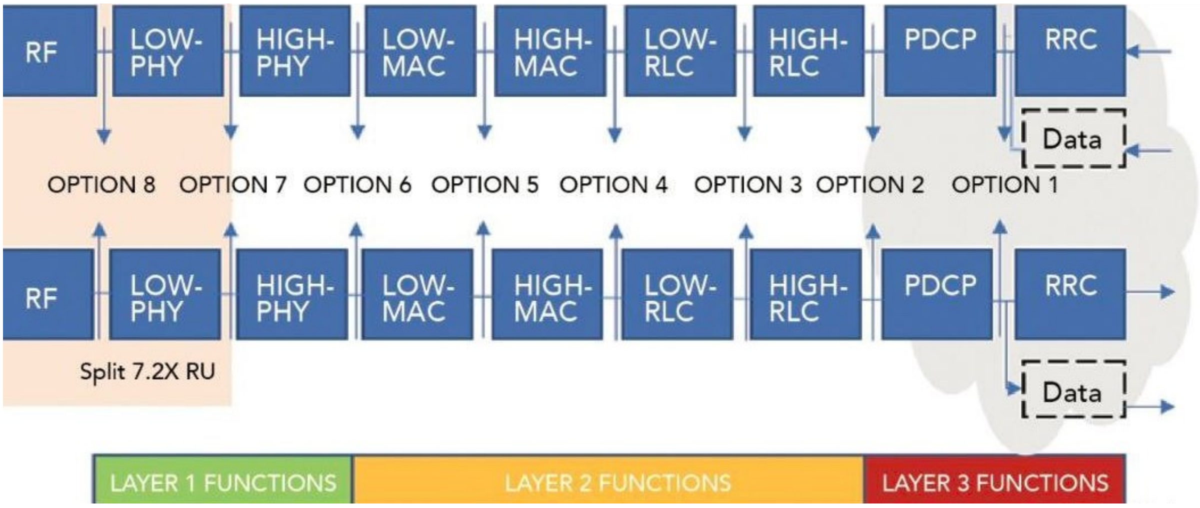


Figure 2.5: Splitting the 5G NR protocol stack and Protocol layer

Chapter 3

Physical Layer Impact on Fronthaul Network

The physical layer of the FH network plays a crucial role in determining the delay experienced by data packets as they travel from the BBU to the RRH in a C-RAN architecture. The PHY encompasses the physical transmission medium, such as fiber optic cables or wireless links, as well as the hardware components like transceivers and antennas.

The choice of the physical transmission medium can significantly impact the delay in the FH network. Fiber optic cables offer high bandwidth and low latency, making them ideal for carrying large amounts of data quickly and efficiently. In contrast, wireless links may introduce more latency due to factors such as interference, signal attenuation, and packet loss. Furthermore, the quality of the hardware components used in the PHY can also affect the delay in the Fronthaul network.

High-quality transceivers and antennas can ensure reliable and fast data transmission, while lower-quality components may introduce errors or delays in the communication process. Overall, the PHY of the FH network plays a critical role in determining the delay experienced by data packets, and careful consideration of the transmission medium and hardware components is essential to minimize latency and ensure optimal network performance.

3.1 Functional Split Option

The functional split option focuses on dividing the PHY of the 5G NR stack between the DU and the RU. Option 7 is also referred to as intra-PHY split, as the Authors [13] noted in their research. due to the fact that choice 7 can be further divided.
7.1 Allocates specific PHY functionality between RU and DU.
7.2 Provides an alternative way to divide PHY tasks.
7.3 Vendor specific (e.g., precoding). Use case is for advanced MIMO/CoMP.

3.1.1 Split Option 7.1

In this scenario, PHY is divided into High-PHY and Low-PHY, with specific functionality allocated between DU and RU. This split optimizes latency across FH by adding redundancy to data. This occurs at the interface between iFFT/FFT and the rest of the physical functions.
Latency Characteristics: The RU handles FFT/iFFT, which is computationally intensive but fast when implemented in hardware. The DU sends frequency-domain data, reducing processing delay compared to raw time-domain samples.
Pros for latency: Offloads FFT/iFFT to the RU, reducing DU processing time.
Frequency-domain data transmission is efficient, avoiding excessive buffering.
Cons: Slightly higher latency than 7.2 due to more data being sent (frequency-domain I/Q), which could introduce minor transport delays over longer fronthaul distances.

3.1.2 Split Option 7.2

Latency Characteristics: The DU performs modulation and resource mapping, sending pre-modulated data (e.g.,coded bits) to the RU, which then handles FFT/iFFT and RF functions. Less data is transmitted over the fronthaul compared to 7.1, reducing processing and transport latency. Modulation in the DU can be optimized for speed, while the RU's task (FFT/iFFT) are hardware-accelerated. Because of its flexibility and lower fronthaul load, this approach is suitable for low latency.

3.1.3 Split Option 7.3

Latency Characteristics: Designed for advanced features like CoMP or massive MIMO, often splitting some precoding or beamforming to the RU. Latency depends on the specific implementation- moving precoding to the RU can reduce DU processing time but may increase RU complexity and delay if not optimized. This type of option is used for industrial automation with MIMO, but not much in telecom operators like Ethio Telecom and the Legehar area, where there is no industry.

3.2 Functional Components

The physical layer in 5G NR is composed of several functional components that collectively handle the transmission and reception of data over the air interface. Here are the PHY functional components:

3.2.1 Encoding

Encoding typically refers to the process of converting digital data into a format suitable for transmission over radio waves. Adds redundancy to the data to protect against transmission errors(Low-Density Parity-Check (LDPC) for data channels, polar codes for control channels) Encoding in fronthaul occurs primarily at the PHY for In-phase and Quadrature (IQ) data compression and at the data link layer for framing and error checking. Delays depend on the complexity of encoding at each layer and the amount of data being compressed.

Authors [10] cite in their research that the CPRI protocol in LTE uses an 8B/10B encoding scheme for a data rate of 2.457 Gbps. In their research, CPRI can impose restrictions on delay and data rate in fronthaul. The encoding capacity rises with the data rate; for example, eCPRI now employs 64B/66B encoding, which has lower overhead. Fronthaul latency is reduced when data throughput increases because transmission and processing delays are reduced with less encoding overhead.

3.2.2 Scrambling

During transmission, data are scrambled using a specific algorithm or technique randomizing the bit sequence to reduce the impact of interference and improve security) to make it unintelligible to unauthorized users or to provide error detection and correction capabilities. Scrambling is often used to enhance security, improve signal quality, or optimize bandwidth utilization. Reference [6] explains in his research that scrambling, descrambling are done in the DU split option 7-3. Descrambling is reversing this process at the receiver.

3.2.3 Modulation

Modulation is used to encode information onto a carrier signal for efficient transmission over a channel. Adaptation modulation dynamically adjusts the modulation scheme based on real-time channel conditions. Converts bits into suitable symbols for transmission (QPSK, 16QAM, 64QAM, 256QAM). In [15], the authors analyze how modulation and a number of physical resource blocks affect fronthaul delay in 5G, and queuing and switching delay are also discussed here which is not important here. Demodulation Converts received symbols back to into bits.

3.2.4 Layer Mapping

Refers to the process of mapping different logical layers of communication onto physical resources within the radio access network. This includes mapping higher-layer Protocol data unit (PDU)s onto lower-layer transport channels for transmission over the air interface. Layer mapping involves various functions such as segmentation, concatenation, and mapping of data onto appropriate radio bearers and physical channels.

A part of PHY processing within DU and is involved in mapping codewords to the layer. Codewords represent transport blocks of user data. Layers correspond to logical data streams that are transmitted over antenna ports. Handling MIMO streams, i.e., 5G supports massive MIMO with hundreds of antenna elements. Each user may be assigned to multiple transmission layers for spatial multiplexing, diversity, or beamforming. Signaling delays due to reconfiguration of layers scheduling of resources, and retransmission delay.

3.2.5 Resource Element Mapping

The process of assigning data symbols to specific subcarriers (frequency domain) and time slots (time domain) in the transmission frame. Assign the modulated symbols to specific time-frequency resources within the resource grid. The mapping of data symbols to resource elements is typically performed based on the system's scheduling algorithm, the modulation scheme, channel conditions and the quality of service requirements.

Fronthaul Consideration

a. Compression: IQ compression, b. Timing Alignment by ensuring REs are delivered to RU, and c. Synchronization: Maintains accurate time-domain synchronization for REs placement. Symbol duration is inversely proportional to the SCS.

$$T_{\text{s}} = \frac{1}{\Delta f}$$

$$T_{\text{s,tot}} = T_{\text{s}} + T_{\text{cyclic prefix}}$$

Relationship between symbol duration and FH delay

In 5G, Fronthaul delay must ensure that REs mapped to OFDM symbols arrive for in time for: Symbol-level synchronization: between DU and RU. Guard Intervals(Cyclic Prefix): To be preserved to prevent Inter Symbol Interference (ISI). For symbol n of a slot, Symbol duration can be expressed as, fronthaul budget $<$ total Symbol duration. If fronthaul delay exceeds the symbol duration, it may result in Resource Element (RE) misalignment, overlapping or dropped symbols, and performance degradation due to ISI.

$$\text{Longer symbol duration } \rightarrow \text{ Lower SCS } \rightarrow \text{ More fronthaul delay tolerance.}$$

$$\text{Shorter symbol duration } \rightarrow \text{ higher SCS } \rightarrow \text{ less fronthaul delay tolerance.}$$

If Fronthaul delays larger than total symbol duration, Symbols overlap and cause the frame dropped. For Legehar scenario we use SCS of 15 KHz and 30 KHz.

$$T_s = \frac{1}{15\ KHz} \approx 66.67\,\mu\text{s}$$

$$T_s = \frac{1}{30\ KHz} \approx 33.33\,\mu\text{s}$$

3.2.6 Channel Estimation

Impact on reference signals

Reference signals for channel estimation must be timely and synchronized, and use known reference signals to estimate the channel characteristics for coherent demodulation. If the FH delay exceeds the symbol duration, the reference signal used for channel estimation may arrive late, causing misalignment estimation. In reference [4], the processing delay in PHY is the time to perform the encoding and decoding, and channel estimation in the initial transmission. In [6,14,15], the channel estimation for the PHY split is used in order to reduce fronthaul latency.

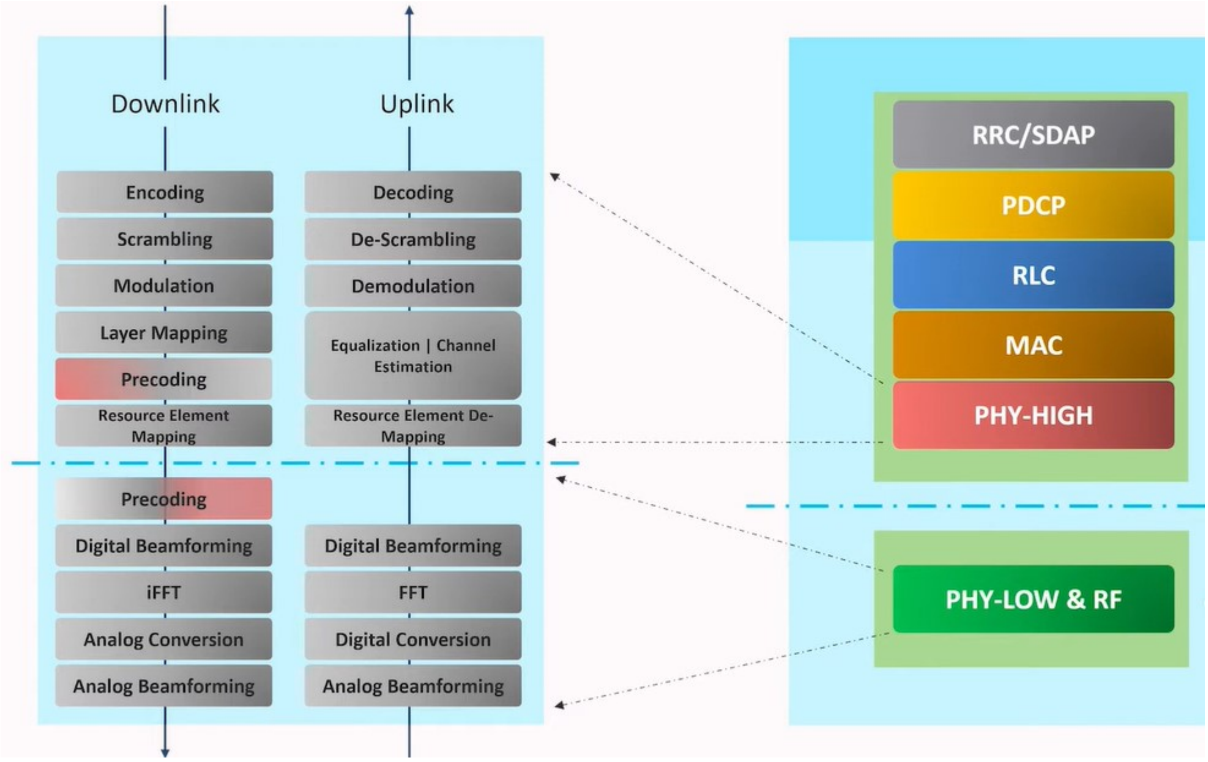


Figure 3.1: Physical Layer components

3.2.7 Multiple Input Multiple Output

Precoding: Adjusts the signal before transmission to optimize for the channel conditions or to direct beams. Precoding can be done at both High-PHY and Low-PHY. At High-PHY, logical or user-level precoding is used to prepare data streams for multiple users or logical channels in the frequency domain, before mapped to physical antennas, and supports multi-user MIMO, where data streams are transmitted to multiple users simultaneously on the same time-frequency resources. Implements spatial multiplexing at the logical level to efficiently utilize resources. At Low-PHY, precoding happens at the antenna port level, in the time or symbol domain, after the data is mapped to REs and modulated into IQ samples, and enables beamforming, where the signal is directed toward specific users or coverage areas.

How precoding affects FH delay

At DU, FH transports IQ samples for individual antennas, and DU adds processing delay because high-PHY precoding involves tasks like spatial multiplexing or resource mapping. At RU real-time precoding introduces processing delay within RU but reduces overall FH delay if less data is sent over the link, and if RU has sufficient computational resources, FH delay becomes less critical.

Beamforming: It involves utilizing signal processing techniques to adjust the phase and amplitude of signals transmitted or received by multiple antenna elements. Focuses the signal in specific directions to increase signal strength or reduce interference.

Spatial Multiplexing: Sends multiple data streams simultaneously over different antennae.

3.2.8 Orthogonal Frequency Division Multiplexing

Inverse Fast Fourier Transform: The inverse FFT (iFFT) is the inverse operation of Fast Fourier Transform (FFT) and is used to convert a Frequency-domain representation back to the time-domain for transmission.

Fast Fourier Transform: At the receiver, transforms the time-domain signal back to the frequency domain.

3.2.9 Power Control

Control Information

The data flow in power control needs to flow from the DU to RU over the fronthaul and this can be as follows:

Uplink power Control:

Adjusts the transmission power of user devices to balance between signal quality and interference.

i.e. commands to User Equipment (UE)s to adjust their transmit power based on measurements and algorithms at the network side.

Downlink power Control: Adjustments to the power of signals transmitted by the RU, potentially based on feedback from UEs or network conditions.

Coordination: In C-RAN, where multiple cells might share resources, coordinating power control across different RUs to optimize network performance while minimizing interference can be complex.

Scalability: As networks grow, managing power control over a centralized infrastructure must scale to handle more UEs and cells without degrading service quality.

3.2.10 Hybrid Automatic Repeat reQuest

Power control directly impacts HARQ efficiency; too low power might result in more retransmissions, while too high might waste energy and cause interference. HARQ is a method used to improve the reliability of data transmission. Hybrid ARQ (HARQ) combines Forward Error Correction (FEC) with Automatic Repeat reQuest (ARQ) to detect and correct errors in received data. In C-RAN fronthaul HARQ processing is the part of DU due to its need for low-latency feedback. The HARQ feedback(Acknowledgement (ACK)/Negative ACK (NACK)) travels back from UE through the RU to the DU, where the retransmission decision is made. This feedback loop is managed over the FH to ensure low latency to maintain the effectiveness of HARQ.

3.2.11 Waveform Generation

Waveform generation involves creating the actual radio signal from digital data. This includes processes like modulation, OFDM symbol construction, cyclic prefix addition, and digital-to-analog conversion. In C-RAN fronthaul waveform generation occurs at the lowest level of the PHY and is thus closely associated with the RU. In some functional split Option 7, waveform generation might be split be option 7.1 or 7.2. The FH transports the data necessary for waveform generation, either in the form of coded bits, modulated symbols, or IQ samples, depending on the centralized the PHY functions are.

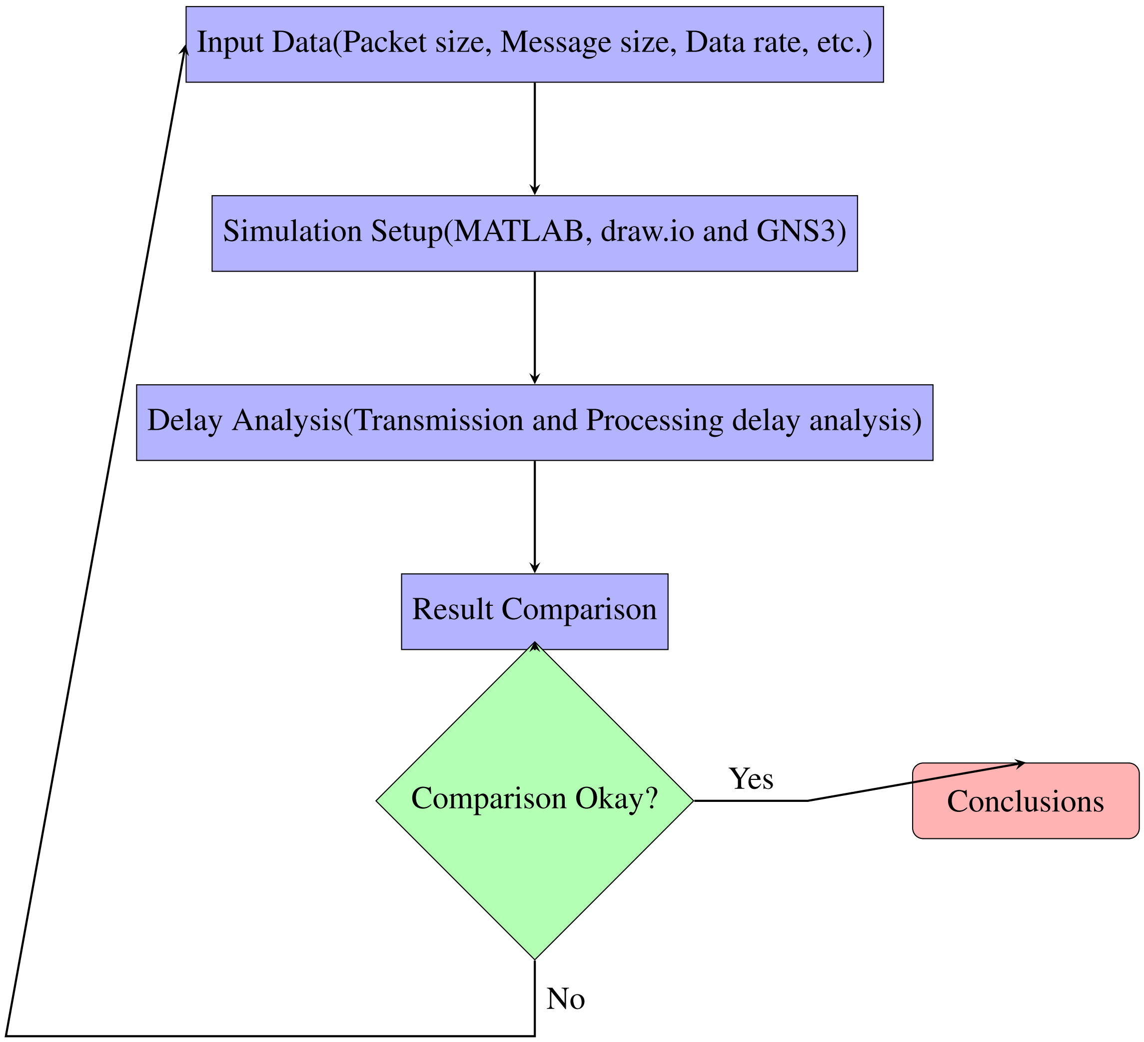
Chapter 4

Methodology

The majority of the source data utilized in this methodology and Chapter 5 is found in the Third Generation Partnership Project Standards release. The 3GPP reports and specifications serve as the basis for the calculations and data used. I provide information from Ethio Telecom's has and can offer on behalf of the RAN rollout team and the RAN operation and maintenance department in particular, but they do not have authorization to reveal specifics such as latency and delay.

This is why 3GPP Technical Report (TR)s 38.801 and 3GPP Technical Specification (TS) 38.211 are used as the source of input data for this thesis. 3GPP TR 38.801 study on New Radio Access Technology; Radio Access Architecture and Interfaces. The Technical Reports study the architecture and interface requirements for 5G NR systems. It covers fronthaul interfaces(CPRI, eCPRI), latency, data rates, and other aspects necessary for network design.

This methodology is based on different approaches, including delay analysis, system parameters, and system models. System parameters include packet size, message size, data rate, transmission capacity, processing rate, and other important variables, values, and settings that define the behavior, performance, and configuration of the system under analysis and comparison. The system model illustrates a mathematical or logical model that we employed for our thesis. GNS3 and draw.io are used to graphically sketch the thesis diagram, and MATLAB is utilized to simulate the system parameters. Changing specific parameters alters the fronthaul delay within a range of input values, according to an analysis of the delay based on the parameters provided.



4.1 System Parameters

In this specific thesis, comparison and analysis are done by two major approaches.

- Protocol approach
- Plane-based split option approach

4.1.1 Protocol Approach

CPRI, which specifies a straightforward synchronous protocol to map user data that will eventually be modulated and transmitted to RU, is a well-known FH protocol. The improved CPRI, or eCPRI, serves as the interface between the low PHY and high PHY protocol. In this approach, the processing and transmission delay of eCPRI and CPRI is compared and analyzed with their input parameters, like CPRI data rate, eCPRI data rate, packet sizes, message sizes, processing, and transmitting capacity are input values that alter the delay.

In urban areas like Legehar, with massive MIMO (64T64R antennas), the maximum data rate used for fronthaul is not efficient with 24.3 Gbps. Therefore, eCPRI is preferred in 5G as it is more efficient, scalable, and flexible transport, reducing the bandwidth by transmitting only user data instead of a digitized radio frequency signal.

4.1.2 Key differences between CPRI and eCPRI

CPRI and eCPRI Comparison	
CPRI	**eCPRI**
Single P2P interface	Multiple P2P interface
Has master and slave port	Master and slave ports classification at the physical level
Depends on radio equipment and Radio Equipment Control (REC) functions	Depends on enhanced RE and enhanced REC (eREC) functions
Does not rely on standard transport protocols	Does not dictate the specific details of transport layer
Limited coverage for 5G	Special coverage for 5G networking
Demands more bandwidth than eCPRI	Demands more bandwidth than CPRI
Multi-scheduling	Best synch capabilities

Table 4.1: Comparison of CPRI and eCPRI Protocols

Through a serial link, CPRI transmits continuous streams of digital radio frequency data (IQ) and eCPRI Sends only essential data (user, control, synchronization) in packetized form over Ethernet. CPRI transport type is synchronous, constant bit rate while eCPRI is asynchronous, packet-switched network (Ethernet/IP).

4.1.3 Plane Split Based Approach

5G C-RAN Architecture handles higher-layer protocols like the Service Data Adaptation Protocol (SDAP), PDCP, and Radio Resource Control (RRC). The CU can be further split into CU-CP and CU-UP for control and user data separation and DU handles medium and some lower-layer processing, including RLC, Part of the MAC layer, and potentially some of the PHY functions. RU Manages the lowest layer PHY functions, interfacing directly with the antennas.

Processing and transmission delays are thereby shortened by dividing the control plane and user plane to a specific function rather than processing and transmitting at the same level. The user technique to minimizing the fronthaul latency is nearly ideal when the higher layer PHY is offloaded to the lower layer PHY without causing system instability.

Control Plane: Responsible for network control signaling, including RRC signaling for connection setup, mobility management, and other control functions. In a plane-based split, the control plane functions can be centralized to a greater extent to allow for coordinated network management.

User Plane: Handles the actual data traffic, both uplink (from UE to network) and downlink (from network to UE). U-plane is critical for performance metrics like throughput and latency, directly affecting fronthaul delay. This study explores how separating these planes impacts fronthaul delay. For example, centralizing the CP reduces signaling overhead on the fronthaul, potentially reducing the delay for control messages.

4.2 System Model

Network Model: Centralizing the BBU in a single room and dispersing the AAU for Legehar and its surroundings. Dynamic user traffic is present in Legehar and its surroundings, including religious gatherings, special events held at the Stadium and Meskel Square, AU summits, and variations in daytime and nighttime traffic. The network model is sketched by two approaches for clarity of this thesis. The first approach is sketching the network model on GNS3 by assuming the router (Cisco 7200 model) as DU, Ethernet Switch as splitter, or ODN as transport network, and VPCS as AAU. This means the router function is not equivalent to

DU, and neither are Switches and AAU.

It is chosen for simplicity to visualize the network model. For three DUs, assigning three different networks, and also assigning an IP address for each AAU. The 3 DU have no redundant connections instead, one DU communicates with its AAU. The site names are randomly selected based on their proximity to the target customer. For the Stadium and Meskel Square, one site is not fully covered at the critical issue and assumed to more than one sites.

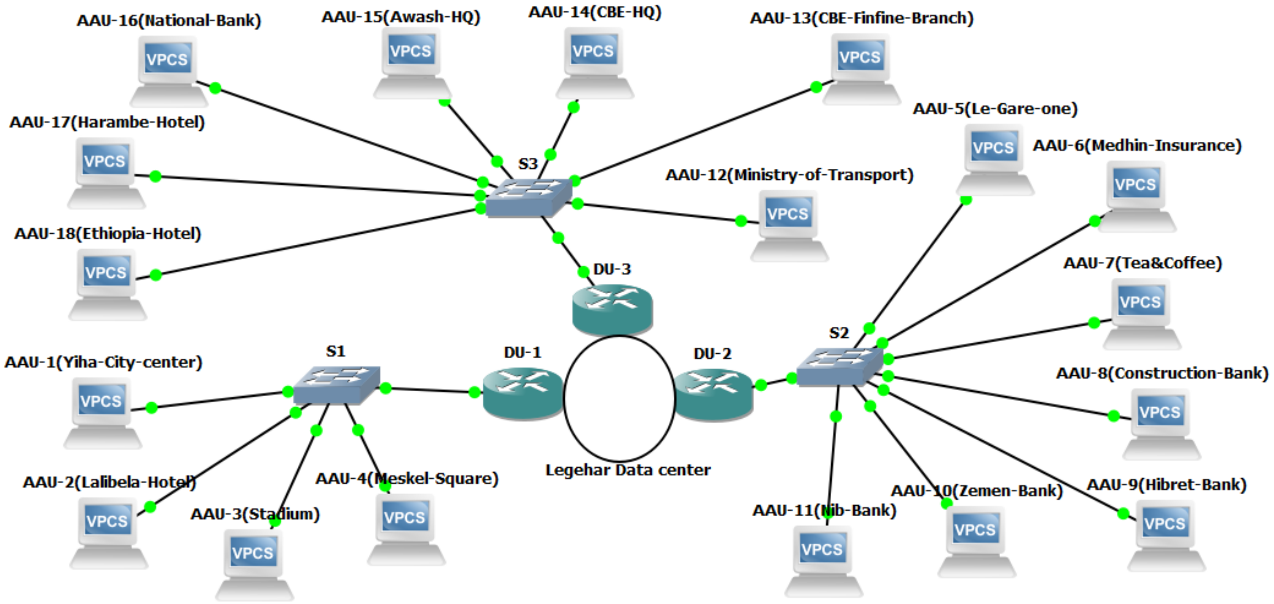


Figure 4.1: GNS3 based C-RAN modelling

The current Ethio Telecom used network model is shown in the figure below, where the core switch or access switch group handles traffic from Any Transport Network (ATN) that are put with BBU in the same room. Fiber from the access switch terminates at ATN through an Optical Distribution Network (ODN) and patch panel. BBU is directly connected to the backhaul or ATN. One ATN can connect with different BBUs depending on the ATN capacity and the available port on it.

In GNS3, drawing a connection is simple and clear, but the network element used is not the actual device, and it's only for a demo. In case of a draw.io sketch, it is more closely approached to real equipment than the previous model by demonstrating the D-RAN and C-RAN separately.

For the C-RAN case, all the backhaul and midhaul are located in the data center, whereas part of FH can be put into the data center or in any vicinity to RU to decrease the FH delay. One or several DU can be put in a DU hotel and distribute the RU to the sites. As the model is designed based on draw.io, all sites are not on a roof like the new Ethiopian commercial bank, Nib Bank, and Zemen Bank. They are provided the coverage indoors by distributing pico antennas to the floors.

Tools used for simulation: MATLAB was utilized as the primary tool for this simulation output, draw.io, and GNS3 were used to sketch the network model as shown in the above diagrams.

Delay Model: Specifically for fronthaul, this thesis models the processing delay and transmission delay at RU and DU.

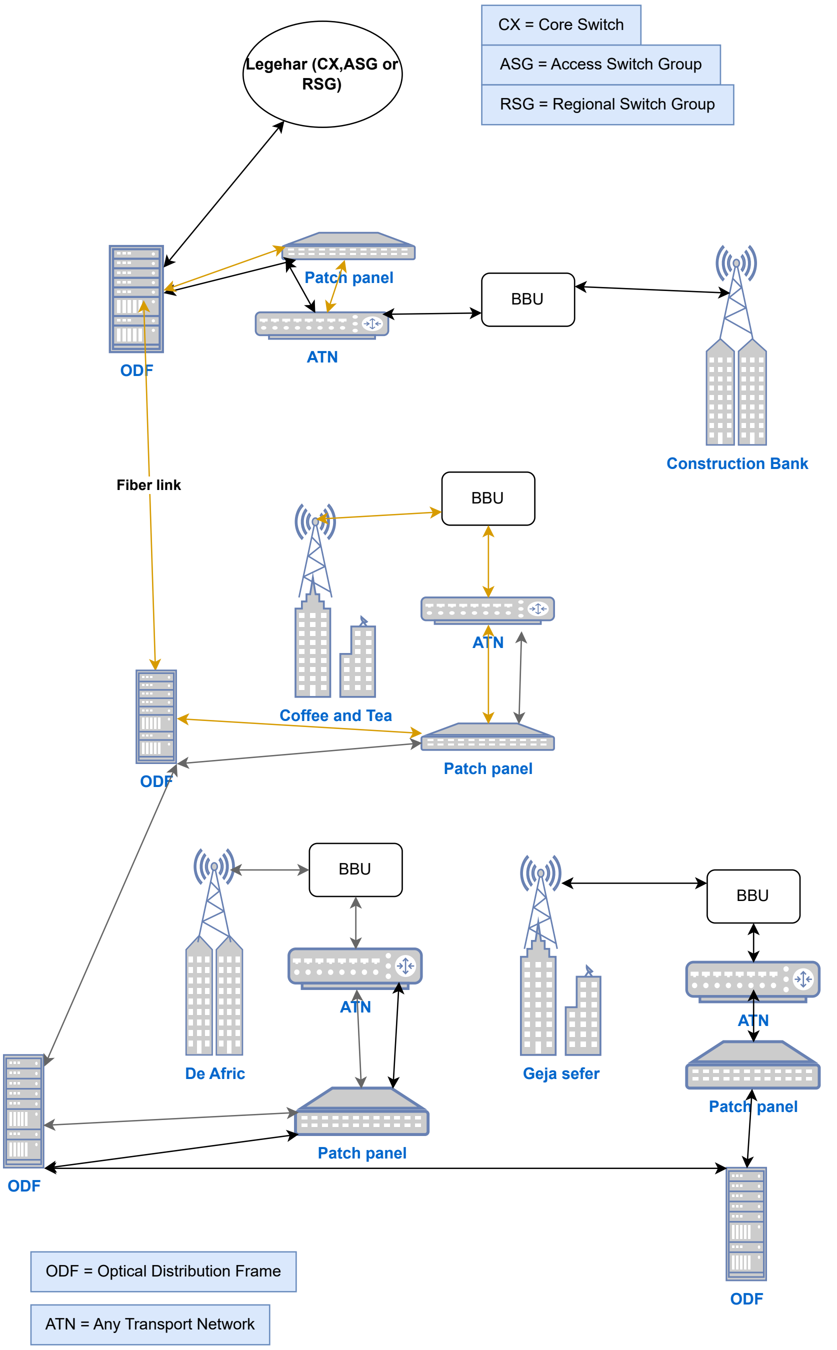


Figure 4.2: D-RAN network model for existing Ethio Telecom network

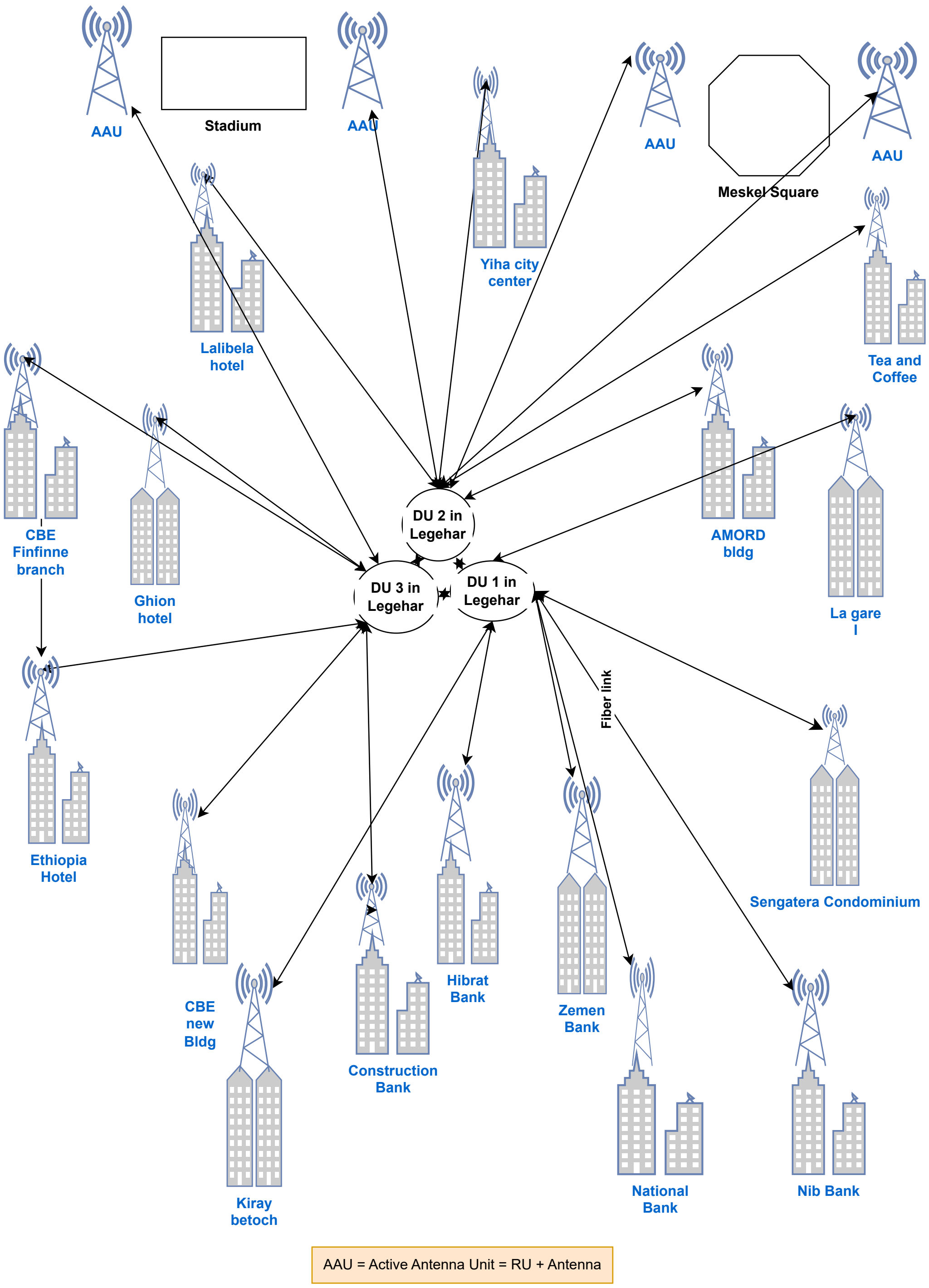


Figure 4.3: C-RAN with centralized DU in data center and distributed RU

4.3 Delay Analysis

4.3.1 CPRI and eCPRI Processing delay analysis

eCPRI employs a dynamic data rate, while CPRI uses a fixed data rate regardless of how much traffic there is. Once assigned, services are always available unless they are switched to another choice. The available traffic determines how much bandwidth is allotted in eCPRI.

CPRI line rate	
Option	**Line Rate**
Option 1	0.6144 Gbps
Option 2	1.2288 Gbps
Option 3	2.4576 Gbps
Option 4	3.0720 Gbps
Option 5	4.9152 Gbps
Option 6	6.1440 Gbps
Option 7	9.8304 Gbps
Option 8	10.1376 Gbps
Option 9	12.1651 Gbps
Option 10	24.3302 Gbps

Table 4.2: CPRI data rate with respective Option

$$\text{DU } \tau_{\text{proc}} = \frac{L}{CPRI\ R}$$

$$\tau_{\text{total}} = \tau_{\text{proc}} + \tau_{tx}$$

Option 8	
CPRI R_{line}	10.1376 Gbps
C_{link}	25 Gbps
τ_{fh}	$1.184\ \mu s$
Option 9	
CPRI R_{line}	12.1651 Gbps
C_{link}	25 Gbps
L	12 kb
τ_{fh}	$0.986\ \mu s$
Option 10	
CPRI R_{line}	24.3302 Gbps
C_{link}	25 Gbps
L	12 kb
τ_{fh}	$0.493\ \mu s$
eCPRI	
eCPRI R_{line}	50 Gbps
C_{link}	50 Gbps
L	12 kb
τ_{fh}	$0.24\ \mu s$
eCPRI	
eCPRI R_{line}	70 Gbps
C_{link}	100 Gbps
L	12 kb
τ_{fh}	$0.1714\ \mu s$

Table 4.3: CPRI and eCPRI processing delay estimation’

4.3.2 Plane-based split Option Analysis

In this portion, splitting the CP and UP can significantly reduce the delay. DU handles control plane functions, while the RU handles user plane functions. User plane carries the network user traffic while the control plane carriess signaling traffic. There is no need for a separate study of the CP and UP delays for same plane since the control and user planes are regarded as one physical entity. However, in order to have a separate plane split, we must have a control plane and a user plane with their parameters.

Simulation Parameter	
User Plane	**Control Plane**
UP M	CP L
UP R_t	CP R
UP τ_{proc}	CP τ_{proc}
UP τ_{tx}	CP τ_{tx}
UP C_{proc}	CP C_{proc}

Table 4.4: The plane split simulation Parameter

For same plane delay analysis

$$\text{UP } \tau_{tx} = \frac{\text{UP M}}{\text{UP } R_t}$$

$$\text{UP } \tau_{\text{proc}} = \frac{\text{L}}{\text{UP } C_{proc}}$$

$$\text{UP } \tau_{\text{total}} = \text{UP } \tau_{\text{proc}} + \text{UP } \tau_{tx}$$

$$\text{CP } \tau_{tx} = \frac{\text{CP } M}{\text{CP } R_t}$$

$$\text{CP } \tau_{\text{proc}} = \frac{\text{CP } L}{\text{CP } C_{proc}}$$

$$\text{CP } \tau_{\text{total}} = \text{CP } \tau_{\text{proc}} + \text{CP } \tau_{tx}$$

$$\text{UP } \tau_{\text{proc}} = \frac{1.2 \times 10^{4}}{10.1376 \times 10^{9}} = 1.18\,\mu s$$

$$\text{UP } \tau_{tx} = \frac{1.2 \times 10^{4}}{25 \times 10^{9}} = 0.48\,\mu s$$

$$\text{UP } \tau_{\text{total}} = 1.66\,\mu s$$

$$\text{CP } \tau_{\text{proc}} = \frac{1.024 \times 10^{3}}{1 \times 10^{9}} = 1.02\,\mu s$$

$$\text{CP } \tau_{tx} = \frac{1.024 \times 10^{4}}{1.4 \times 10^{9}} = 0.73\,\mu s$$

$$\text{CP } \tau_{\text{total}} = 1.76\,\mu s$$

$$\tau_{\text{total}} = 1.66 + 1.76 = 3.42\,\mu s$$

Some parameters are ignored since they are fixed across the table and appear frequently. For example, the packet and message sizes are altered or ignored in order to minimize redundancy.

$$\text{UP } \tau_{\text{proc}} = \frac{1.2 \times 10^4}{49 \times 10^9} = 0.24\,\mu s$$

$$\text{UP } \tau_{tx} = \frac{1.2 \times 10^4}{50 \times 10^9} = 0.24\,\mu s$$

$$\text{UP } \tau_{\text{total}} = 0.48\,\mu s$$

Same plane delay analysis	
For line rate 10 Gbps	
R_{line}	10.1376 Gbps
UP L	12 kb
CP L	1.024 kb (128*8, for split 7)
UP C_{proc}	10.1376 Gbps
UP R_t	25 Gbps
CP C_{proc}	1 Gbps for high traffic
CP R_t	1.4 Gbps (for 64T64R, 100 MHz)
UP τ_{proc}	1.18 μs
UP τ_{tx}	0.48 μs
UP τ_{total}	1.66 μs
CP τ_{proc}	1.02 μs
CP τ_{tx}	0.73 μs
CP τ_{total}	1.76 μs
τ_{total}	3.42 μs
For line rate 12 Gbps	
R_{line}	12.1651 Gbps
UP C_{proc}	12.1651 Gbps
CP C_{proc}	1 Gbps
UP R_t	25 Gbps
UP τ_{proc}	0.99 μs
UP τ_{tx}	0.48 μs
UP τ_{total}	1.47 μs
CP τ_{proc}	1.02 μs
CP τ_{tx}	0.73 μs
CP τ_{total}	1.76 μs
τ_{total}	3.23 μs

Table 4.5: same Plane split delay analysis

For Line rate 24 Gbps	
R_{line}	24.3302 Gbps
UP C_{proc}	24.3302 Gbps
CP C_{proc}	1 Gbps (for heavy traffic)
UP R_t	25 Gbps
CP R_t	1.4 Gbps
UP τ_{proc}	$0.49\ \mu s$
UP τ_{tx}	$0.48\ \mu s$
UP τ_{total}	$0.97\ \mu s$
CP τ_{proc}	$1.02\ \mu s$
CP τ_{tx}	$0.73\ \mu s$
CP τ_{total}	$1.76\ \mu s$
τ_{total}	$2.73\ \mu s$
For Line rate 50 Gbps	
R_{line}	50 Gbps
UP L	12 kb
CP L	1.024 kb
UP C_{proc}	49 Gbps
CP C_{proc}	1 Gbps
CP R_t	1.4 Gbps
UP R_t	50 Gbps
UP τ_{proc}	$0.24\ \mu s$
UP τ_{tx}	$0.24\ \mu s$
UP τ_{total}	$0.48\ \mu s$
CP τ_{proc}	$1.02\ \mu s$
CP τ_{tx}	$0.73\ \mu s$
CP τ_{total}	$1.76\ \mu s$
τ_{total}	$2.24\ \mu s$

Table 4.6: same Plane split delay analysis

For separate plane delay analysis

$$\text{UP } \tau_{\text{proc}} = \frac{1.2 \times 10^4}{10.1376 \times 10^9} = 1.18\,\mu s$$

$$\text{UP } \tau_{\text{tx}} = \frac{1.2 \times 10^4}{25 \times 10^9} = 0.48\,\mu s$$

$$\text{UP } \tau_{\text{total}} = 1.66\,\mu s$$

$$\text{CP } \tau_{\text{proc}} = \frac{1.024 \times 10^3}{1 \times 10^9} = 1.02\,\mu s$$

$$\text{CP } \tau_{\text{tx}} = \frac{1.024 \times 10^4}{1.4 \times 10^9} = 0.73\,\mu s$$

$$\text{CP } \tau_{\text{tx}} = 1.76\,\mu s$$

$$\text{UP } \tau_{\text{tx}} = \frac{1.2 \times 10^4}{50 \times 10^9} = 0.24\,\mu s$$

$$\text{UP } \tau_{\text{proc}} = \frac{1.2 \times 10^4}{49 \times 10^9} = 0.24\,\mu s$$

$$\text{UP } \tau_{\text{total}} = 0.48\,\mu s$$

$$\text{CP } \tau_{\text{proc}} = \frac{1.024 \times 10^3}{1 \times 10^9} = 1.02\,\mu s$$

$$\text{CP } \tau_{\text{tx}} = \frac{1.024 \times 10^4}{1.4 \times 10^9} = 0.73\,\mu s$$

$$\text{CP } \tau_{\text{total}} = 1.76\,\mu s$$

Separate plane delay analysis	
For line rate 10 Gbps	
R_{line}	10.1376 Gbps
UP L	12 kb
CP L	1.024 kb (128*8, for split 7)
UP C_{proc}	10.1376 Gbps
UP R_t	25 Gbps
CP C_{proc}	1 Gbps for high traffic
CP R_t	1.4 Gbps (for 64T64R, 100 MHz)
UP τ_{proc}	$1.18\ \mu s$
UP τ_{tx}	$0.48\ \mu s$
UP τ_{total}	$1.66\ \mu$
CP τ_{proc}	$1.02\ \mu s$
CP τ_{tx}	$0.73\ \mu s$
CP τ_{total}	$1.76\ \mu$
For line rate 12 Gbps	
R_{line}	12.1651 Gbps
UP L	12 kb
CP L	1.024 kb
UP C_{proc}	12.1651 Gbps
CP C_{proc}	1 Gbps
UP R_t	25 Gbps
CP R_t	1.4 Gbps
UP τ_{proc}	$0.99\ \mu s$
UP τ_{tx}	$0.48\ \mu s$
UP τ_{total}	$1.47\ \mu$
CP τ_{proc}	$1.02\ \mu s$
CP τ_{tx}	$0.73\ \mu s$
CP τ_{total}	$1.76\ \mu$

Table 4.7: separate Plane split delay analysis

For Line rate 24 Gbps	
R_{line}	24.3302 Gbps
UP L	12 kb
CP L	1.024 kb
UP C_{proc}	24.3302 Gbps
CP C_{proc}	1 Gbps (for heavy traffic)
UP R_t	25 Gbps
CP R_t	1.4 Gbps
UP τ_{proc}	$0.49\ \mu s$
UP τ_{tx}	$0.48\ \mu s$
UP τ_{total}	$0.97\ \mu$
CP τ_{proc}	$1.02\ \mu s$
CP τ_{tx}	$0.73\ \mu s$
CP τ_{total}	$1.76\ \mu$
For Line rate 50 Gbps	
R_{line}	50 Gbps
UP L	12 kb
CP L	1.024 kb
UP C_{proc}	49 Gbps
CP C_{proc}	1 Gbps
CP R_t	1.4 Gbps
UP R_t	50 Gbps
UP τ_{proc}	$0.24\ \mu s$
UP τ_{tx}	$0.24\ \mu s$
UP τ_{total}	$0.48\ \mu s$
CP τ_{proc}	$1.02\ \mu s$
CP τ_{tx}	$0.73\ \mu s$
CP τ_{total}	$1.76\ \mu s$

Table 4.8: separate Plane split delay analysis’

4.4 Result Comparison

Comparing the analysis's findings reveals that the CPRI/eCPRI approach reduces delay as the data rate rises. The two approaches to CPRI/eCPRI differ slightly; in the first technique, certain parameters are introduced. Since CPRI is a defined data rate, it cannot go over its limit. 24.3302 is the maximum CPRI data rate. eCPRI is regarded as being over this data rate.

The outcomes of separate plane split and same plane split approaches are very different. As anticipated, there is less delay in the separate than in the same plane. This is because all of the parameters are evaluated on the same plane, and the total of the components is greater than the sum of the individual planes. While DU handles the controlling data, user data is evaluated at RU in a different plane. Thus, both DU and RU have explicit values. We have a UP total delay at RU and a CP total delay at DU.

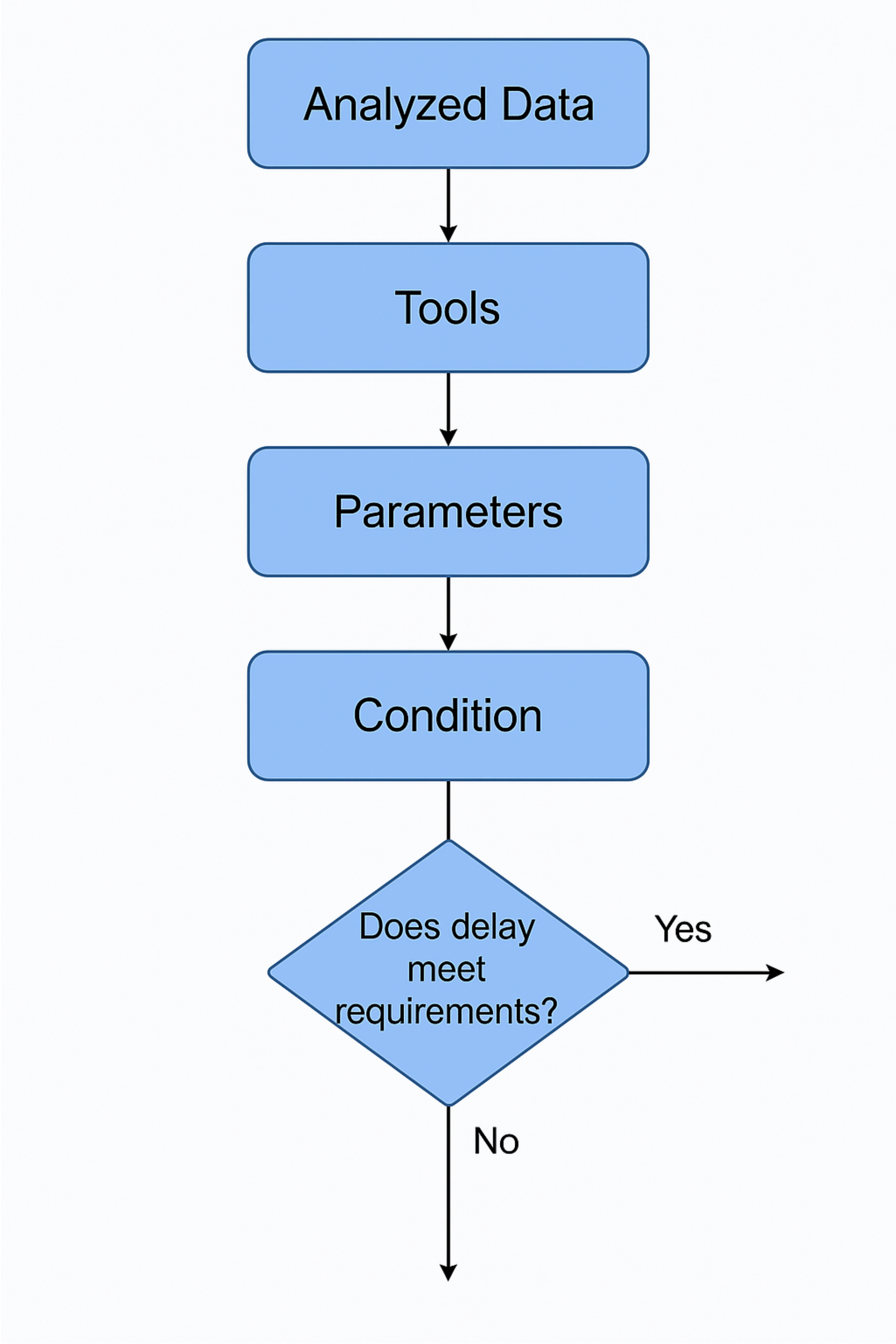


Figure 4.4: Methodology block diagram

Chapter 5

Result and Discussion

From the plane splitting approach with two scenarios significant output is obtained by varying the data rate and processing capacity of the user and control planes at the same plane and separate plane. The same plane means in this case that all data from either the CP or UP are transmitted or processed on the same logical or physical plane but for a separate plane, either logical or physical can be possible.

5.1 CPRI vs eCPRI Analysis

In percentage, the percentage change in data rate.

$$\text{CPRI } \tau\% = \frac{(\tau_{final} - \tau_{init})}{\tau_{final}} \times 100\% = \frac{(0.9860 - 1.184)}{0.9860} \times 100\% = -20\%$$

i.e., the delay decreases by 20% from the initial delay. i.e., achieved 20% of delay than previous.

$$\text{CPRI } R_{line}\% = \frac{(\tau_{final\ R_{line}} - \tau_{init\ R_{line}})}{\tau_{final\ R_{line}}} \times 100\% = \frac{(12.1651 - 10.1376)}{12.1651} \times 100\%. = 16.67\%$$

From this, the increasing data rate by 16.67, costs decreased due to the 20 fronthaul delay. Decreasing the delay means we have achieved the target by decreasing the percentage. Because our target is to lower the delay without disturbing the system's stability and other parameters.

$$\text{eCPRI } \tau\% = \frac{(0.24 - 0.493)}{0.24} \times 100\% = -105.4\%$$

i.e., the delay decreases by 105.4% from the initial delay.

$$\text{eCPRI } R_{line}\% = \frac{(50 - 24.3302)}{50} \times 100\% = 51.3396\%.$$

From this the data rate is 51.3396% than the initial data rate.

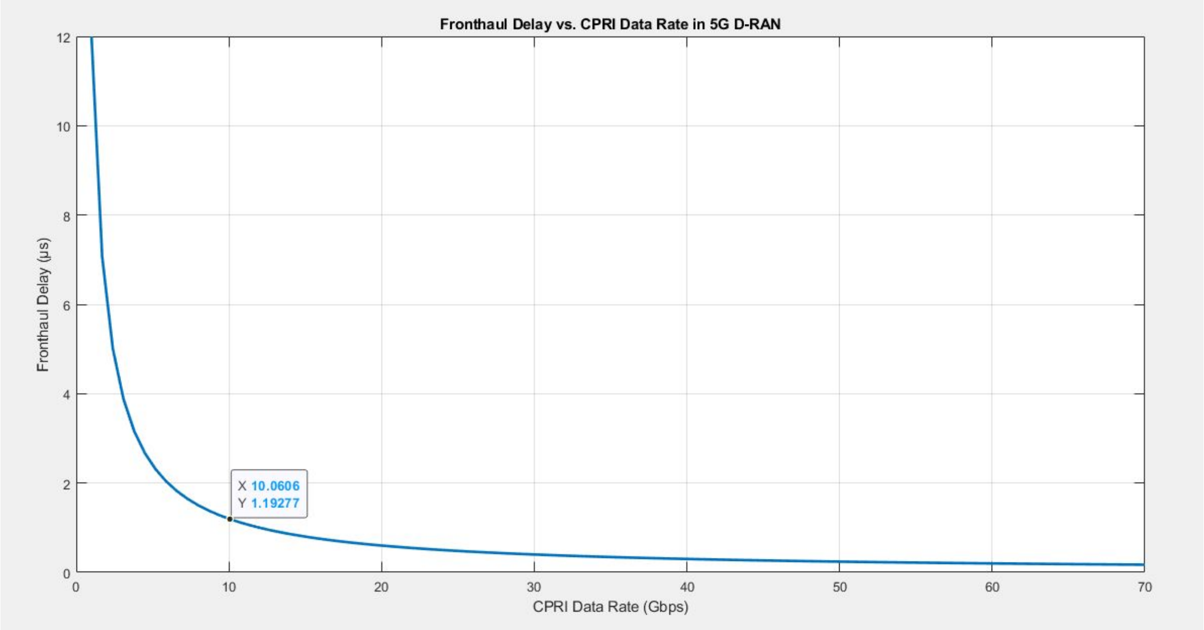


Figure 5.1: CPRI data rate vs fronthaul delay

From the graph as the data rate increases the fronthaul delay falls rapidly, due to varying line rates. CPRI/eCPRI analysis, we can conclude that doubling the data rate decreases the frontahaul delay by 100%. For the FH delay, we are using C-RAN with a splitting option. In D-RAN we do not have this option for current Ethio Telecom FH architecture.

Since the goal of this thesis is to maximize the available network and reduce the delay, eCPRI can handle up to 100 Gbps by dynamically altering the data rate. In reality, the maximum speed that Ethio Telecom uses is 25 Gbps because the data rate is not larger than the connection speed. But for the sake of a high data rate received by increasing link capacity equal to or greater than the data rate is taken for this thesis purpose.

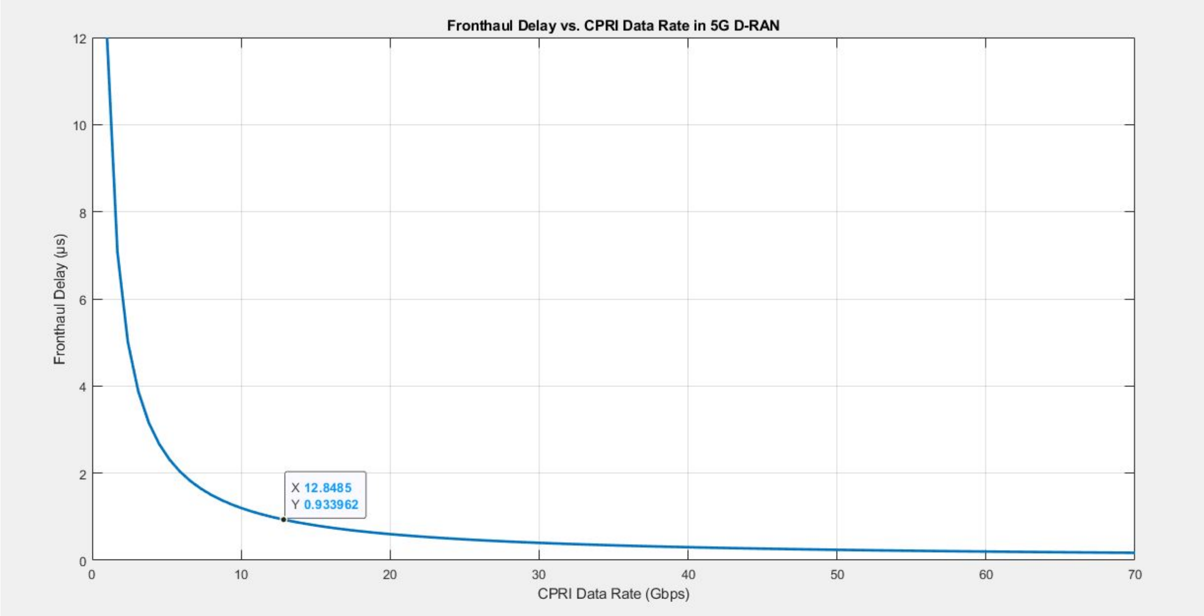


Figure 5.2: CPRI data rate vs fronthaul delay’

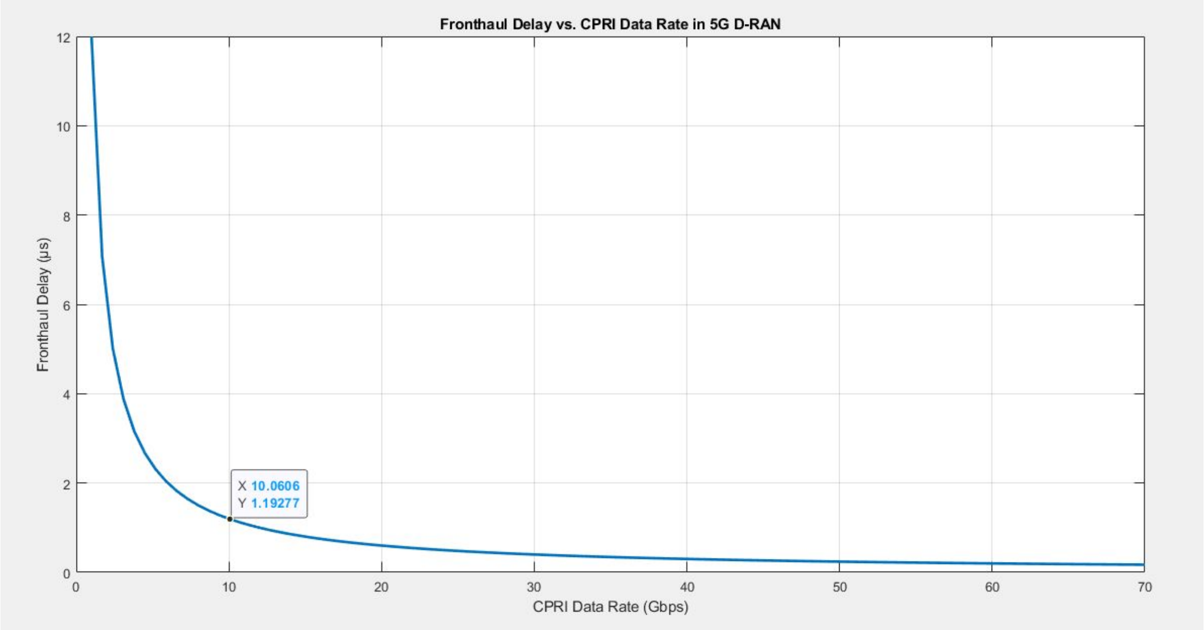


Figure 5.3: CPRI data rate vs fronthaul delay

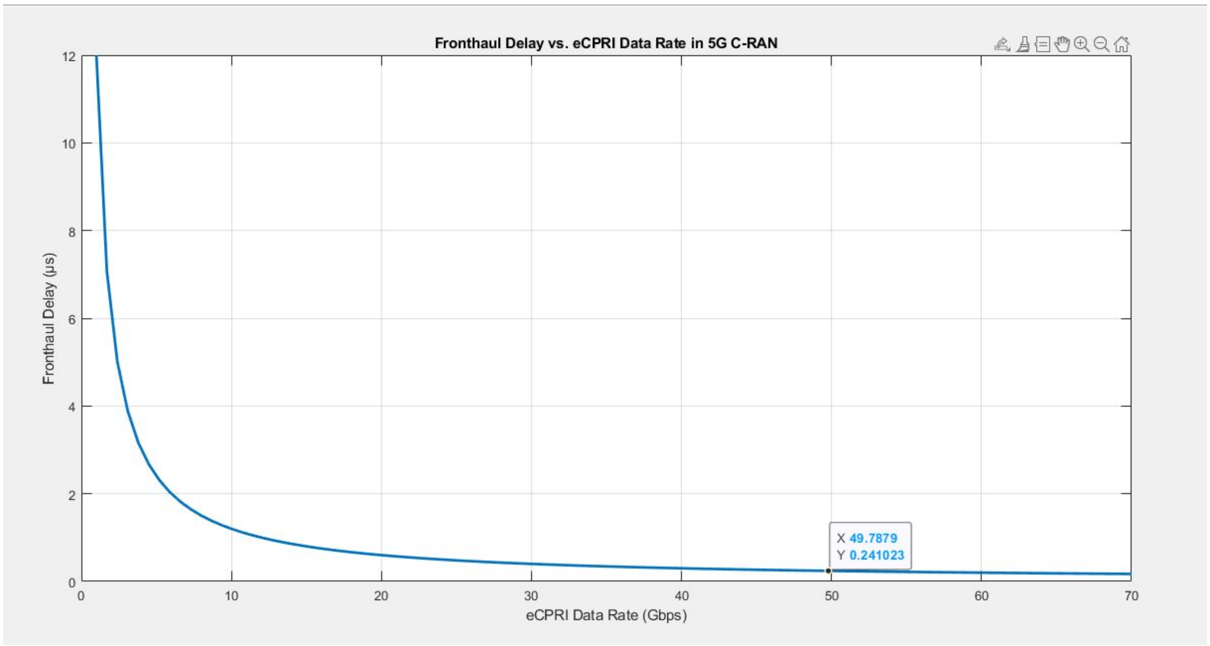


Figure 5.4: eCPRI data rate vs fronthaul delay’

5.2 Plane Split Analysis

For Same Plane: It is not necessary to examine the overall delay or variation in the control plane processing data rate in same plane analysis since the control plane delay remains constant throughout the table. Until the transmission rate is altered, the UP transmission remains constant as well.

$$\tau_{\%} = \frac{(\tau_{final} - \tau_{init})}{\tau_{final}} \times 100\% = \frac{(0.99 - 1.18)}{0.99} \times 100\% = -19.2\%$$

i.e., the delay decreases by 19.2% from the initial delay.

$$\text{R } \% = \frac{(R_{final} - R_{init})}{R_{final}} \times 100\% = \frac{(12.1651 - 10.1376)}{12.1651} \times 100\%. = 16.67\%$$

This indicates that we may reduce latency by 19.2% by decreasing data rate by 16.67%.

$$\tau\% = \frac{(0.24 - 0.49)}{0.24} \times 100\% = -104.2\%.$$

In other words, the delay is reduced by 104.2% compared to the initial delay.

$$\text{R}\% = \frac{(50 - 24.3302)}{50} \times 100\% = 51.3396\%.$$

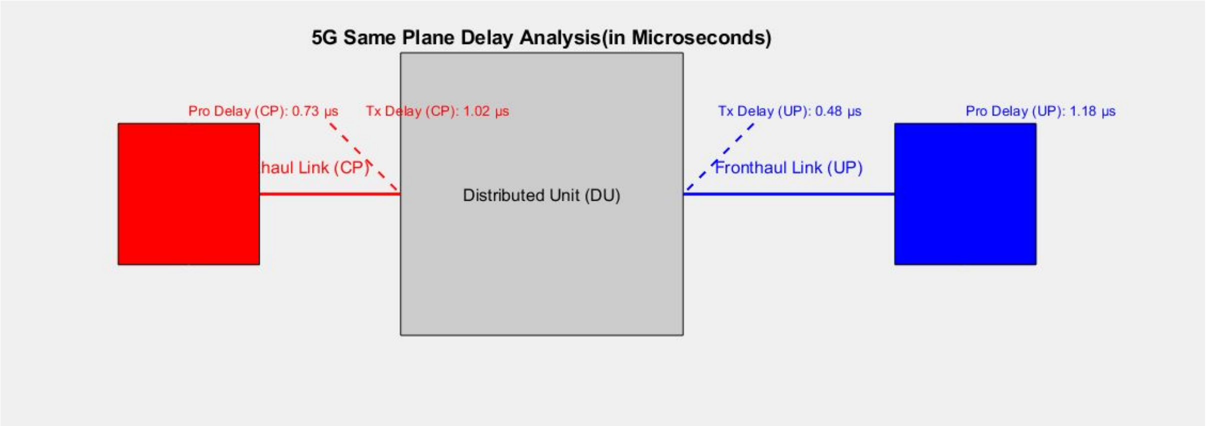


Figure 5.5: Same plane delay analysis

The fronthaul delay continues to increase by altering the processing capacity, even though the transmission delay did not increase, and the transmission rate and message size were unchanged. The transmission delay is cut in half when the transmission rate is doubled.

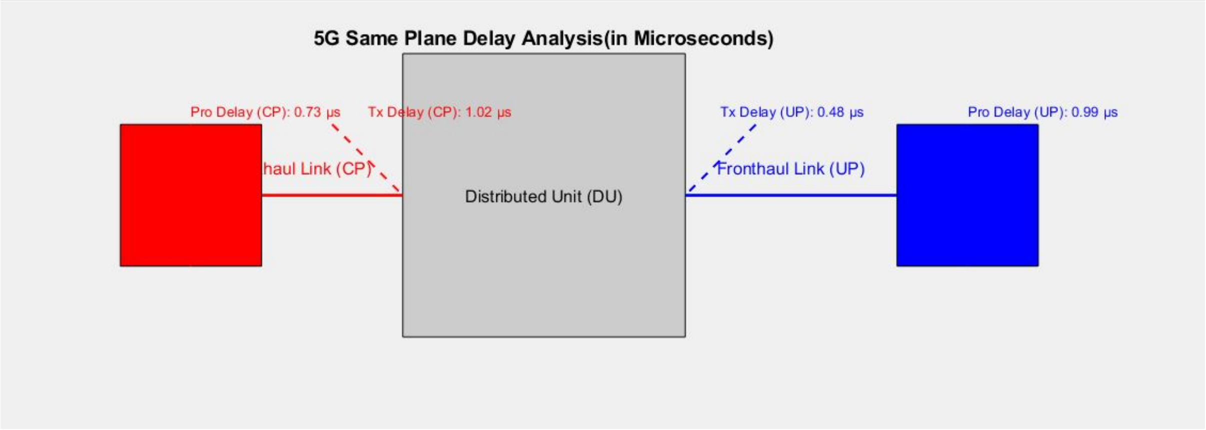


Figure 5.6: Same plane delay analysis’

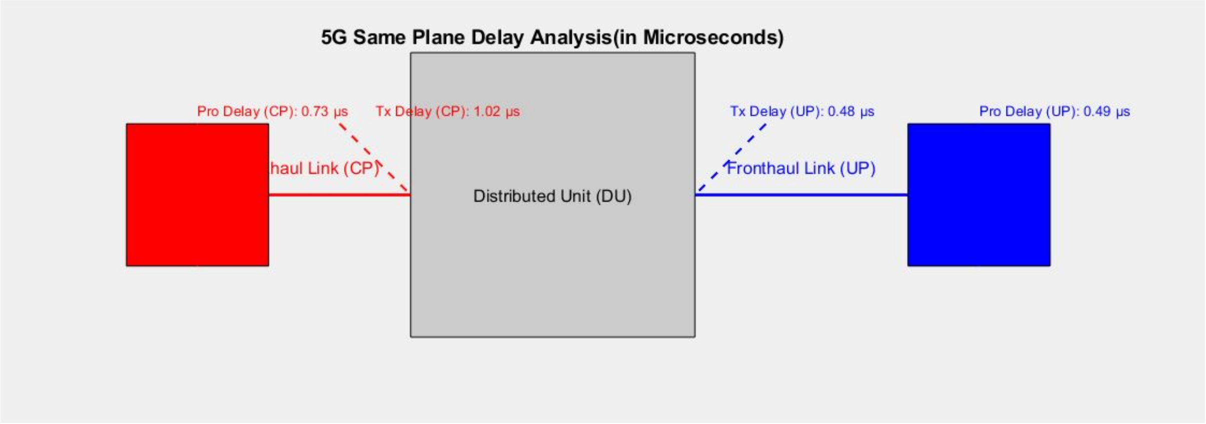


Figure 5.7: Same plane delay analysis 1

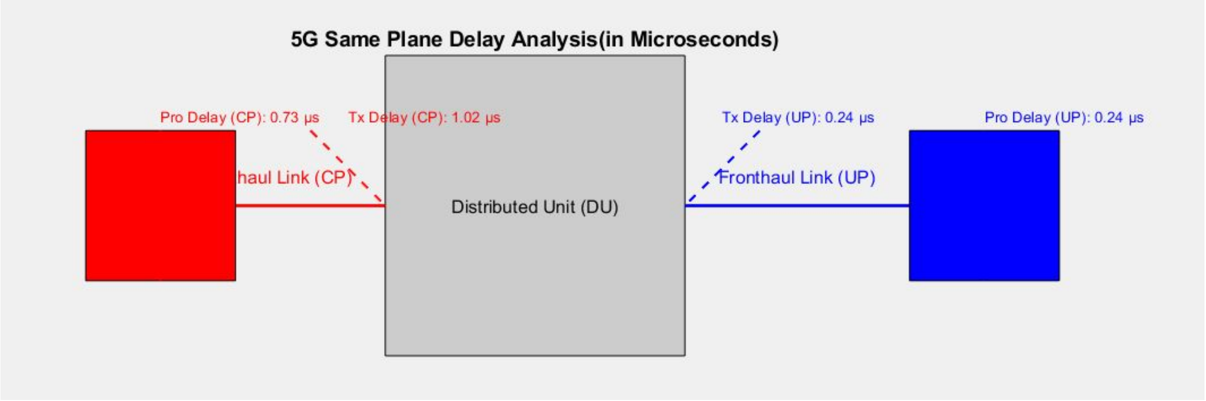


Figure 5.8: Same plane delay analysis 2

For Separate Plane: We have two components here that are examined independently in the case of separate plane analysis. In order to minimize user data delay, the RU analyzes the user plane data based on users' proximity. At the DU, the signaling or control plane is processed. As the result, our overall delay is the processing and transmission delay at the appropriate equipment rather than the combined delay of the CP and UP planes.

$$\text{UP } \tau\% = \frac{(\tau_{final} - \tau_{init})}{\tau_{final}} \times 100\% = \frac{(1.47 - 1.66)}{1.47} \times 100\% = -12.925\%$$

As a result, the delay is reduced by 12.925 percent.

$$\%\text{ UP } C_{\text{proc}} = \frac{(12.1651 - 10.1376)}{12.1651} \times 100\%. = 16.66\%.$$

$$\%\text{ UP } C_{\text{proc}} = \frac{(24.3302 - 12.1651)}{24.3302} \times 100\% = 50\%.$$

$$\text{UP } \tau\% = \frac{(0.97 - 1.47)}{0.97} \times 100\% = -51.55\%.$$

$$\text{UP } \tau\% = \frac{(\tau_{final} - \tau_{init})}{\tau_{final}} \times 100\% = \frac{(0.24 - 0.49)}{0.24} \times 100\% = -104.4\%$$

$$\%\text{ UP } C_{\text{proc}} = \frac{(49 - 24.3302)}{49} \times 100\%. = 50\%$$

We took into consideration many characteristics assessed separately in the separate plane analysis. The total delay is taken into account for simplicity's sake. There is no need for analysis because the control plane processing rate and transmission rate are the same at both locations.

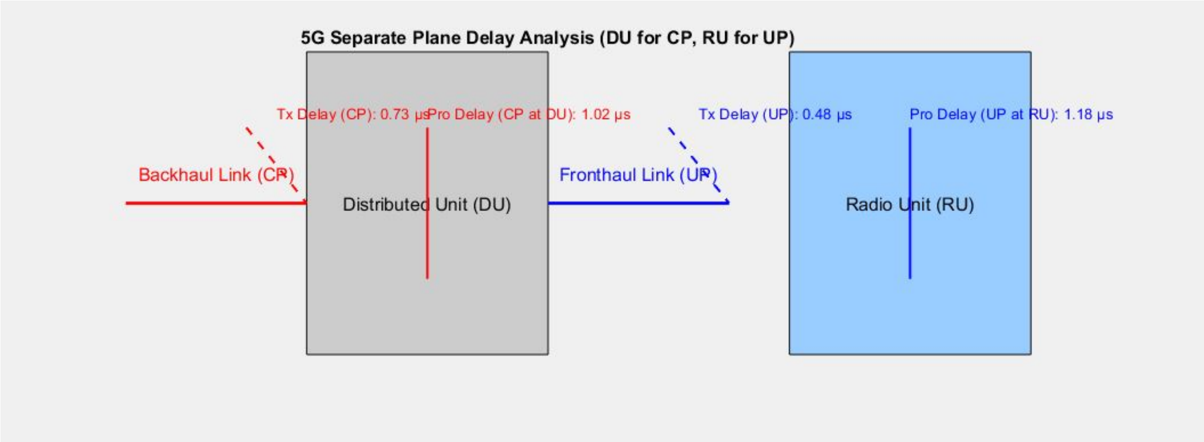


Figure 5.9: Separate plane delay analysis

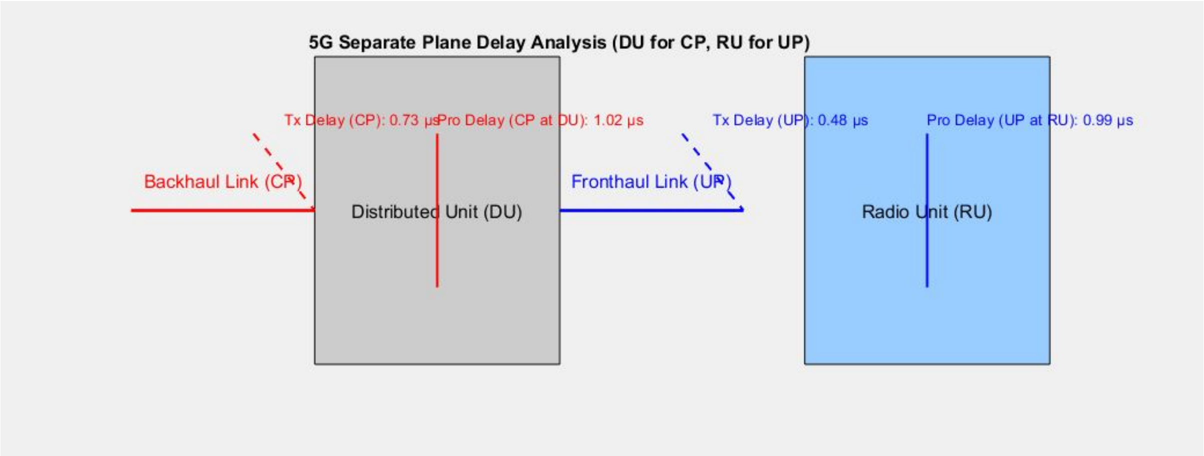


Figure 5.10: Separate plane delay analysis’

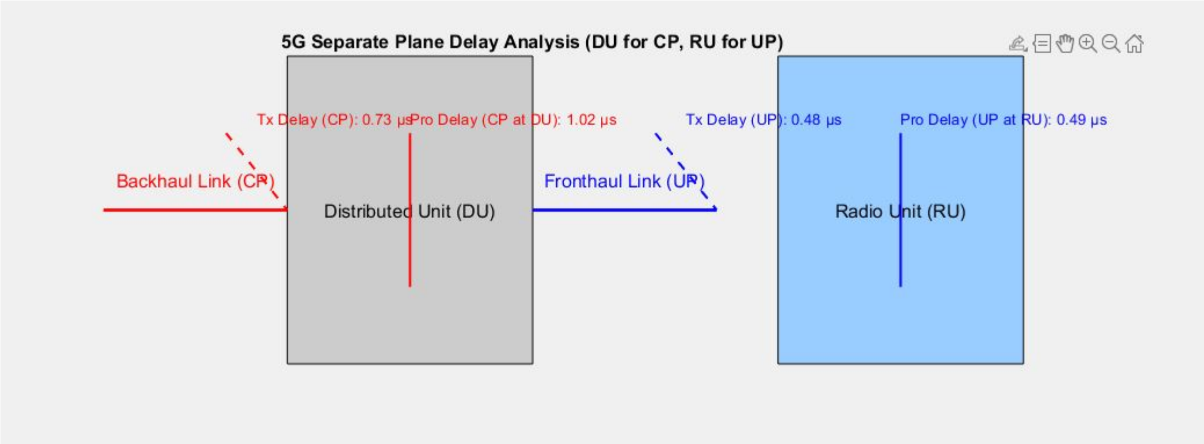


Figure 5.11: Separate plane delay analysis 1

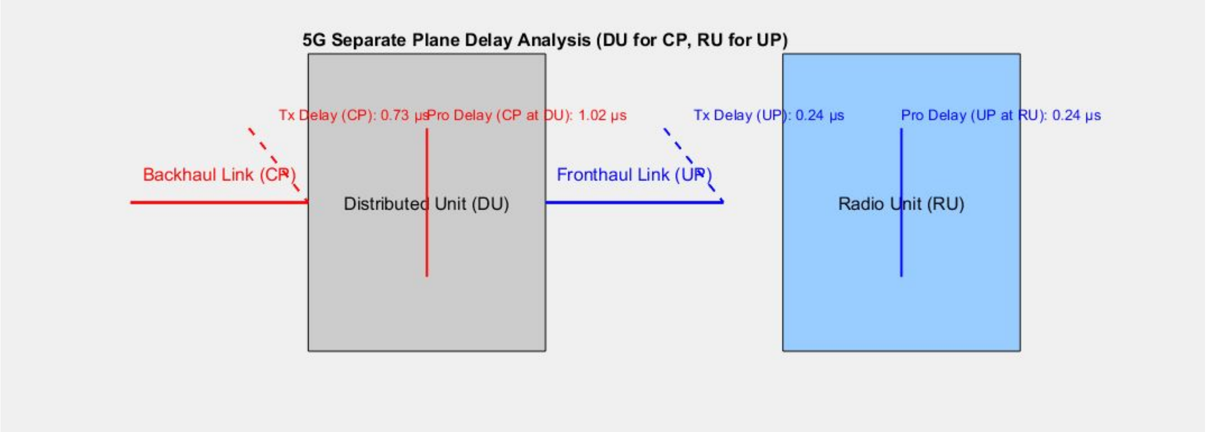


Figure 5.12: Separate plane delay analysis 2

Chapter 6

Conclusion And Future Work

6.1 Conclusion

The analysis result shows that the CPRI-based protocol is evaluated, a considerable output is seen in the protocol-based analysis, and the transmission delay decreases with increasing data rate. The delay of eCPRI is less than that of the CPRI protocol as eCPRI uses a higher data rate than CPRI. The minimum transmission delay achieved from the CPRI protocol was 0.493 μs whereas 0.24 μs was achieved from eCPRI at a 50 Gbps data rate. Less than 0.24 μs transmission delay can be achieved since the eCPRI data rate can be increased to 100 Gbps.

Reducing the processing delay of DU and RU through a logical or a physical division of the plane into user and control planes. Because C-RAN FH can scale to a larger data rate than D-RAN, C-RAN has fewer delays than D-RAN. We can create a total user plane processing delay of 0.48 μs by splitting the plane option.

This analysis and comparison do not include all the necessary parameters for a thorough study. Depending on how sophisticated or simple the architecture is, some of them are employed. The split option advantage in C-RAN and the network's inherent flexibility and scalability are examples of concepts. Split option 7 is among the best-split options available; it offers higher bandwidth efficiency, reduced delay, real-time performance and processing load, and edge computing than other options, but at the cost of more complicated fronthaul design and more complexity at RU. Option 7 is also chosen for the thesis analysis and comparison.

6.2 Future Work

There are several issues that can be addressed in future work related to this research area. This thesis touches on specific points on fronthaul and needs a detailed exploration of intrinsic delay effects like queuing delay and propagation delay if DU and CU are far apart.

The objective was to examine and contrast FH configurations based on delay measures, as these configurations have a direct impact on processing and transmission delays. However, queuing delays can be influenced by many variables outside of the FH setup such as core network load or user behavior, which were beyond the study's scope and future studies could extend this work by incorporating queuing delay into analysis.

Because the thesis focus is restricted to the Legehar area, propagation delay is also not included in this study. Because it measures how long it takes for the signal to reach its destination from its source over a medium or free space, the propagation delay is directly correlated with the distance. Thus, this kind of delay metric works better for a wide geographic area, and it can be incorporated into the future study. The logical and transport channel effect on fronthaul delay is another aspect of a new research area.

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