



Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Telecommunication Engineering Graduate Program

**ILP Based Optimal BBU Pool Planning for Cloud-RAN
Deployment: in the Context of Ethio telecom**

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DECLARATION

I, the undersigned, declare that this thesis is my original work, and has not been presented for a degree in this or in any other university. I have adequately cited and referenced the original sources. All sources of materials used for the thesis have been fully acknowledged as per the principles of Addis Ababa University. I declare that I have adhered to all principles of academic honesty and integrity, and have not misrepresented or fabricated or falsified any ideas/data/fact/source in my submission.

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ABSTRACT

Cloud radio access network (C-RAN) is a novel mobile network architecture that decouples the baseband units (BBUs) from their corresponding cell sites and takes the baseband processing unit to a virtualized and shared central location. This increases wireless networks' scalability, manageability, and significantly saves both the capital and operational costs of mobile network operators (MNOs). Although this BBU centralization enables power savings, it imposes much higher bandwidth on the fronthaul network.

Since with distributed radio access network (D-RAN) there is a higher building, maintenance and operational costs there should be a RAN architectural change, and in addition to previously done researches in this area this thesis comprise the impact of wireless interface delay on BBU centralization. We investigate the optimal planning of BBU pools for C-RAN deployment in the context of Ethio telecom and shows how to optimally determine the required number of BBU pools for different use cases using an integer linear programming (ILP) optimization problem and calculates the required budget to deploy a single BBU pool. We also figure out which functional split is cost-effective for fronthaul networks while providing the centralization benefits.

Simulation results show that the wireless interface delay has an impact on BBU centralization therefore it should be considered in the BBU pool planning process. On the other hand, the number of BBU pools required varies depending on the use cases considered, hence for the chosen area ultra-reliable and low latency communication (URLLC) services require 5 BBU pools, real-time functions such as voice over long-term evolution (VoLTE) require 3 BBU pools; in contrast latency-insensitive applications, such as email 2 BBU pools are sufficient to meet the required performance requirements. Furthermore, split option 7.2 was selected for the research as it was found to be the most cost-effective and performance-efficient option.

Key words: *BBU centralization, C-RAN, Fronthaul network, Functional split, ILP, Wireless interface delay.*

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LIST OF ACRONYMS

3GPP	3rd Generation Partnership Project
ACK	Acknowledgment
ARoF	Analogue Radio-over-Fiber
AWG	Arrayed Waveguide Gratings
BBM	Baseband Module License
BBSW	Baseband Software
BBU	Base Band Unit
BS	Base Station
CAP	Capacity Unit
CAPEX	Capital Expenditure
C-BBU	Centralized Base Band Unit
CBN	Cabinet Unit
CO	Central Office
COM	Common Plug-in Unit
COMP	Coordinated Multiple Point Transmission and Reception
COTS	Commercial Off-the-Shelf
CPRI	Common Public Radio Interface
C-RAN	Cloud Radio Access Network
CS	Cell Site
CU	Centralized Unit
DL	Down Link
D-RAN	Distributed Radio Access Network
D-RoF	Digital Radio over Fiber
DU	Distributed Unit
EE	Energy Efficiency

eICIC	Enhanced Inter-cell Interference Coordination
FEC	Forward Error correction
FFT	Fast Fourier Transform
FH	Fronthaul
F-RAN	Fog computing based radio access network
HARQ	Hybrid Automatic Repeat Request
H-CRAN	Heterogeneous Cloud Radio Access Network
ICT	Information and communication technology
ILP	Integer Linear Programming
IoT	Internet of Things
LC	Line Card
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MNOs	Mobile Network Operators
NACK	Negative Acknowledgment
NGMN	Next Generation Mobile Network
NGN	Next Generation Network
NRT	Non Real Time
OAM VM	Operations, Administration and Management Virtual Machine
OBSAI	Open Base Station Architecture Initiative
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPEX	Operational Expenditure
O-RAN	Open Radio Access Network
OTN	Optical Transport Network
PLS	Physical Layer Split

PON	Passive Optical Network
POP	Point of Presence
PtP	Point-to-Point
QOS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technologies
RF	Radio Frequency
RRH	Remote Radio Head
RTT	Round Trip Time
SCF	Small Cell Forum
SE	Spectral Efficiency
TCO	Total Cost of Ownership
TWDM-PONs	Time and wavelength division multiplexing passive optical networks
UL	Uplink
URLLC	ultra-reliable low-latency communication
VMs	Virtual machines
WDM	Wavelength-Division Multiplexing

CHAPTER ONE

1. INTRODUCTION AND BACKGROUND

1.1. INTRODUCTION

The fourth generation mobile network (4G) with a theoretical data rate of 300Mbps in the DL and 75Mbps in the UL has been developed by 3GPP in the late 2000s with the standards of LTE and WiMAX. Globally, the first 4G LTE was commercially released in 2009 in Sweden and it was introduced to the Ethiopian market in 2015. The fifth generation (5G) was globally released in the 2020s and began its pre-commercial services in Addis Ababa in six mobile stations on May 09, 2022. Its aim is to provide a significantly high data rate (theoretical 20Gbps), ultra-lower latency (<1ms), and better QOS compared to its predecessors. With the aforementioned capabilities, 5G will have the highest benefit in a variety of industries such as mission-critical services requiring real-time decisions, manufacturing plants, remote health care, precision agriculture, and real-time operations making them all a reality [1], [2], [3].

Moreover, the main concern of 5G is to handle the enormous amount of data traffic generated by small cells and to satisfy the rapidly increasing number of users and smart devices. It is also a good solution for the higher data rate requirements and to interconnect billions of smart devices to support both human and machine-centric traffic [4].

The major service categories of 5G such as enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra reliable and low latency communications (URLLC) have a wide range of performance requirements and traffic profiles. Operators require highly scalable and flexible networks to serve these new markets and significantly increase revenues. The ability to support these new use cases is related to cloud RAN development [5].

Among the key enabling technologies that help to meet these requirements, C-RAN is the one and it is a viable solution to meet the capacity requirements while at the same time addressing the scalability issues related to processing power [4].

Initially, C-RAN was proposed by IBM under the name wireless network cloud [6]. In C-RAN, all BBUs are separated from their corresponding RRHs and pooled into a centralized, shared, and virtualized BBU pool, hence the cell sites with the antenna and remote radio heads (RRHs)

are connected to their corresponding BBU pool through a high capacity fronthaul link. Every BBU pool can accommodate up to tens of RRHs, and is connected through a backhaul link with the core network [7]. Hence, the baseband resources in the BBU pool and the central processor will be shared with all connected RRHs and a significant reduction in the overall computational resources can be achieved due to multiplexing gain. Due to the centralized BBU various BBUs located in different geographical areas will form a cloud [8].

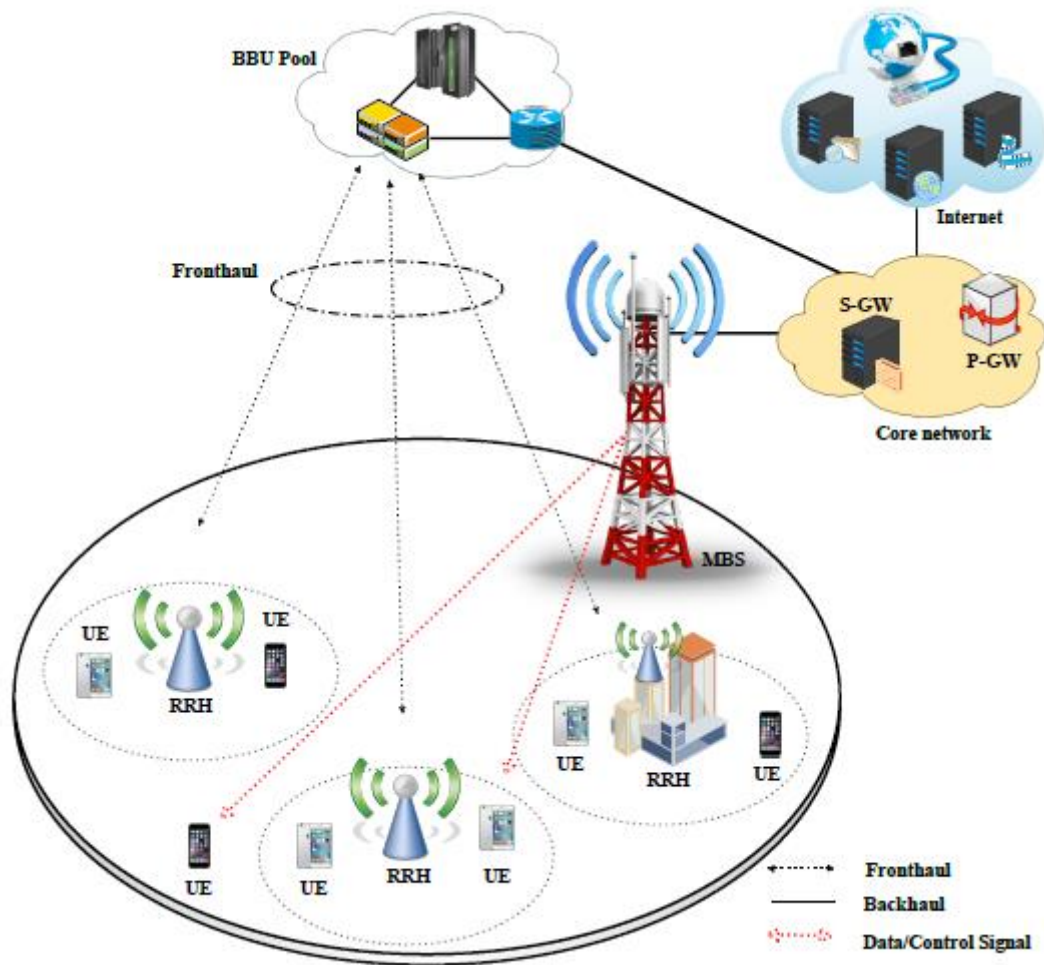


Figure 1. 1: C-RAN architecture [9]

As depicted in the above figure the main components of C-RAN are the BBU pool which is the main controlling and processing unit located at a central place, the RRH which is the radio unit located remotely 20-40km from the main BBU-Pool which is usually connected by optical cable based on the CPRI protocol, and the transportation link this is either a fronthaul or backhaul link. The new fronthaul traffic, i.e., the digitized baseband signals a.k.a. digital radio over fiber

(D-RoF) will be exchanged over each BBU/RRH pair, this can be transported over common public radio interface (CPRI) or Open Base Station Architecture Initiative (OBSAI) protocols [10]. Since facilities are shared in the central place lower lease and energy costs, lower management and maintenance expenses, and improved RAN performance i.e., enhanced network throughput due to advanced joint processing [8]. It also significantly reduces CAPEX and OPEX costs, and power consumption of operators and simplifies the network architecture allowing faster large-scale deployments. As centralized BBUs share resources dynamically among multiple RRUs and coordinate scheduling and processing, it improves spectral efficiency and reduces inter-channel interferences [10].

It is also recommended to deploy C-RAN in metropolitan areas to benefit from the statistical multiplexing gains as users move throughout the day while staying within the maximum distance of up to 40 km between RRH and BBU pool, and it is more promising for small scale deployments for urban areas with densely placed cells [5].

1.2. STATEMENT OF THE PROBLEM

The ICT sector is responsible for approximately 2-4% of global carbon dioxide emissions and consumes 4-6% of all electricity generated worldwide. About one-sixth of global electricity consumption is attributed to telecommunications networks, and the highest power consumer in wireless access networks is the base station (BS) [11], [12]. RAN technologies such as network densification and heterogeneous networks have been proposed to cope with the increasing demand for network capacity. However, these technologies have also resulted in a significant increase in energy consumption and carbon dioxide emissions. A study by China Mobile found that 72% of total power consumption in the company's network comes from cell sites [5], [13].

The main challenges with currently deployed D-RAN architectures include:- higher maintenance and operational costs, where with D-RAN building and maintaining a dense network infrastructure is very expensive [13]; on the other hand, BS resources can't be shared among other BSs located in other geographical areas, hence, BSs are dimensioned for the peak hour traffic that occurred within a busy hour period in the day implies the over-dimensioning of BSs (underutilization of BS resources) [12], [14]; another challenge with D-RAN is an inability to mitigate the interference between BSs, this is due to the existence of high latency between BSs and low bandwidth of the fronthaul links, hence, effective CoMP algorithms such as joint transmission, carrier aggregation, and eICIC can't be utilized effectively [9].

Furthermore, recent wireless technologies such as 4G and 5G require C-RAN architecture to obtain a higher computational power for baseband processing, more specifically 5G is expected to offer better QoS than 4G, which requires more processing power.

Although millimeter wave communication, massive MIMO, ultra network densification, network slicing, SDN, NFV, and C-RAN are some of the key enabling technologies for 5G, [2], [7], [15], [16] most of these technologies are not yet implemented in our network and realizing the true 5G capabilities without these enablers might be very difficult [17]. Therefore, ethiotelecom has to properly plan the deployment of the energy-efficient and cost-effective C-RAN architecture on its network to reduce its energy consumption, carbon dioxide emission, and the underutilization of BS resources, in addition, the company has to obtain a higher computational power from this architecture.

Moreover, Hybrid Automatic Repeat Request (HARQ) is a communication protocol that uses error detection and correction techniques to improve the reliability of data transmission between a UE and eNodeB. According to [18], [19], the HARQ is a key protocol for next generation mobile networks to be used in cloud based RAN. Further, the distance between BBU and RRH is restricted by HARQ in terms of transmission time interval (TTI) and processing times. The HARQ time or the radio interface delay between UE and its associated RRH depends on the size of the cell radius [20], hence in addition to other RAN delay components such as round trip time of RF, CPRI, BBU, and active equipment the HARQ delay should also be considered in the link delay budget during the planning phase of C-RAN design.

In addition, improper planning of BBU pools leads to an increase in network transport delay and total link costs, hence the selection of functional split options can also highly affect BBU centralization [21].

Below are some of the questions that will be addressed by this thesis:

- How much BBU pool is optimal for different use cases?
- Which of the 3GPP's RAN functional split is cost-effective for fronthaul networks while providing the centralization benefits?
- Does the wireless wave propagation delay i.e., between UE and its associated RRH, has an impact on the required number of BBU pools?

1.3. OBJECTIVE

1.3.1. General Objective

The main objective of this research is to find the optimal number of BBU pools for the selected area by using currently available BSs and study the wireless interface delay impact on BBU centralization. The BBU pool design is aimed to meet the latency, and bandwidth requirements of the fronthaul network while maximizing the centralization benefits and satisfying the network constraints.

1.3.2. Specific Objectives

- To propose a possible solution to reduce the network operating and energy costs,
- To describe the potential benefits and challenges of C-RAN architecture before deploying it,
- To figure out which functional split(s) fits a cost-effective fronthaul transport network while keeping the centralization benefits for a C-RAN deployment,
- To design an optimal BBU pool deployment that satisfies different QoS requirements,
- To determine the optimal number of BBU pools for different use cases and provide performance guaranteed service,
- To study the impact of wireless interface delay on BBU centralization.

1.4. SCOPE AND LIMITATION

The centralized BBU pool placement conducted in this research is for the selected area of the Addis Ababa network that is around Bole International Airport, and its main focus is on finding the optimal number of BBU pools and forming an RRH cluster useful for a C-RAN deployment in the future and it has only used ethiotelecom network.

Even though the ILP solver provides optimal results the complexity scales with the network size and it's difficult to obtain a good solution for larger networks in a reasonable time. Moreover, solving large ILP problems is computationally expensive because the complexity of the technique scales with the number of constraints and it becomes difficult to obtain a good solution for a large number of constraints. Therefore, due to the aforementioned ILP model limitations, it cannot be used for larger networks.

1.5. LITERATURE REVIEW

Chathurika Ranaweera et al. in [10], present a cost-optimal deployment of a 5G network with its optical transport and strongly believe that the evolution of RAN must be complemented by the evolution of transport networks, thus three optical fronthaul technologies and architectures, namely physical layer split (PLS), analogue radio-over-fiber (ARoF), and common public radio interface (CPRI) were evaluated by the deployment costs, and the ability to meet 5G latency and capacity requirements using Integer Linear Programming (ILP). Hence, CPRI-based C-RAN architecture limits the possible cost savings obtained from C-RAN because it requires a high-capacity fronthaul network. Moreover, the result showed that CPRI always requires more fronthaul bandwidth than PLS and the bandwidth of PLS grows with the number of users, whereas the bandwidth requirement of CPRI is constant for a given cell configuration and independent from the amount of real traffic associated with the cell. Furthermore, a comparison of the deployment costs for RRHs, BBU pools, and fronthaul showed that the highest cost contributor is the fronthaul network (due to fiber).

In [20], the authors allocated BBU pool positions for the C-RAN architecture using a real heterogeneous network, and the BBU pool placement is bounded only by the delay constraint. The research aimed to find the minimum number of BBU pools, and to determine the optimal central office position, considering the delay constraint including cell coverage radius. Two algorithms were adapted the Particle Swarm Optimization (PSO) algorithm which is used to cluster the RRHs, and the Quasi-Newton Method (QNM) algorithm to find the best location of the BBU pool for each cluster with respect to the latency constraint. Their model takes RRHs positions in the network as input and results in latency-optimal BBU pool positions. Results show that a minimum of five BBU pools cover the actual heterogeneous network of area 2,657 km² (56×47 km) considering the maximum fronthaul latency. Here the BBU pool allocation is computed based on the minimum Euclidean distances among all RRHs i.e., only from the latency point of view.

In [22], Mohamed et al had developed a centralized BBU pool placement problem for C-RAN deployment over an optical aggregation network and formalize it using ILP. The ILP model has three objectives with its optimization goals of minimizing the number of BBU pools, the number

of used wavelengths per fiber, and the computational resources. The research has compared the stated goals and demonstrate how latency and transport network capacity affect the best possible outcomes. The minimum number of pools at $W=6$ achieved is 4, but for $W=20$ the minimum number of BBU pools has been reduced to 2, but complete centralization is not possible due to the link capacity constraints. This shows link capacity is the main constraint for BBU consolidation at higher latency, and as the number of BBU pools decreases the number of required wavelengths will increase. Furthermore, they had observed minimizing the computational resources had resulted in a slight additional saving compared to minimizing the number of BBU pools.

Byomakesh Mahapatra et al. in [23] used a k-means clustering algorithm to find the number of centroids i.e. central-BBUs and then choose the centroid position in the cellular cluster for the optimal placement of the central-BBUs. RRHs are assigned to the C-BBUs based on the Euclidian distances, and form a cluster, the total transport delay and the link cost for each connection were also been determined by a link budget analysis. A Matlab and Tu-Vienna Matlab simulator was used by taking different sets of user equipment (UE) and results showed that the increase in the UE is directly proportional to the number of serving RRHs and also C-BBU. Moreover, as RRHs are assigned to the C-BBU based on the Euclidian distances, as the number of RRHs increases the cluster size will also increase and a new C-BBU is activated.

Henrik Holm et al. in [24] presented how to optimally assign cells to a BBU Pool, and minimize the CAPEX of operators using an ILP model for C-RAN deployment. While assigning cells to a BBU pool 20-30% from office cells, and 70-80% from residential cells were given to a single BBU pool to obtain the highest possible statistical multiplexing gain. The ILP model has minimized a CAPEX by either minimizing the required fiber in the fronthaul or the number of BBU pools and solving it using the GAMS modeling system. They define a cost factor and results with different cost factor values indicate that it is advantageous to use the proposed ILP model at a cost factor of 50 where 1 km of fiber equals the cost of 50 fully loaded BBUs, this is due to the BBU multiplexing gain in this case is more valuable than fiber when minimizing the CAPEX. The result also showed, how the new CAPEX is different from the case when only the cost of fiber is minimized, i.e. when all the RRHs are assigned to the nearest BBU Pool.

Francesco Musumeci et al. in [25], initially classified the WDM aggregation network into different architectures to place the BBU pool either in a first central office (CO) or at a higher-level CO and propose a BBU placement optimization problem using an ILP model. In addition to the BBU placement, the model also considered the electronic switches placement, and for the fronthaul link two transport networks, OTN and overlay were examined for their impact on the BBU centralization. Numerical results for the mobile traffic show that for the OTN fronthaul latency (FL) $> 70\mu\text{s}$ is required to allow BBU hoteling, whereas for overlay FL $> 35\mu\text{s}$ is sufficient. In the case of FMC traffic for higher values of FL $< 210\mu\text{s}$, the OTN enables higher consolidation compared to Overlay. This shows when higher traffic is transported on the network and if no stringent latency requirements are imposed, lack of capacity is the main constraint for BBU consolidation.

A. Marotta et al. in [26], had jointly optimized BBU placement with fronthaul deployment for C-RAN deployment in a brown-field scenario where traditional base stations are already deployed using an ILP model. The proposed optimization model aims to minimize the CAPEX and a Multi-commodity Flow approach is used to cluster the RRHs. Results show that the maximum allowable fronthaul delay has an inverse relation with CAPEX and the number of required BBU pools. This inverse relation between the delay budget and the number of required BBU pools has a significant impact on CAPEX. While considering higher latency values CAPEX has reduced significantly. Similarly, the OPEX result at higher delay values allows for cost savings of up to 72% in urban areas and 62% in rural areas this is due to the links' operating costs impact in the rural scenario being higher. Moreover, when capacity is not an issue such as in suburban cases, microwave links are a convenient choice for the operator which allows a reduction of CAPEX while requiring a 4% increase in investment.

M. Klinkowski in [27], had been analyzed two ILP models namely, ILP-basic and ILP with latency. Results show that the memory usage of the ILP model (the requirement for RAM) grows in proportion to network size, more specifically the ILP with latency model has a very high RAM requirement. The optimality gap also increased with network size and optimal solutions for both models were obtained only for a 5X5 network. Similarly, for the RRH coverage radius, which varies between 150 and 400 meters, the optimality gaps increase with the RRH coverage radius.

Finally, the installation of an optical fronthaul network is the most expensive which is about 60-70% of the total cost, while RRHs are the least expensive (about 3%).

To address the capacity and latency challenges of fronthaul traffic, authors in [28], seek to determine the ideal position for BBU pools in a WDM hierarchical network while taking heterogeneous split choices into account to reduce the number of BBU pools. They introduce the concept of a mixed functional split for the C-RAN deployment by dynamically allocating split options to each node based on their requirements and addressing the tradeoff between required bandwidth and improved function centralization. As lower split choices resulted in less centralization benefits and more complex CSs they explored split options 6, 7, and 8, and compared them with a fixed split. Their comparison result showed that the required capacity of requests in split 8 or fixed split is higher as compared to the mixed split thus higher number of BBU pools are needed for the fixed split, and BBU centralization is higher for the mixed split scheme. Moreover, an ILP and a heuristic algorithm were also compared, and higher centralization is achieved through the ILP, and for both schemes, ILP yields better results.

Ahmed M. Awad et al in [29], compute a BBU placement problem for Cloud-RAN deployment over 5G optical aggregation networks and formulate it using an ILP optimization problem. The multi-objective optimization problem minimizes the number of BBU pools, the number of wavelengths used per fiber, and the number of inter-CoMP users. Furthermore, the CoMP services were divided into two categories i.e. inter-BBU CoMP and intra-BBU CoMP where in the former case the cooperating RRHs are assigned to different BBU pools, hence they introduce overhead signaling over an X2 interface which imposes a large back-haul bandwidth requirement. Their findings show that up to 97% and 78% of inter-CoMP users can be switched to being intra-CoMP users at a low latency value of $50\mu\text{s}$ and higher latency of $80\mu\text{s}$, respectively. However, compared to the ILP output the optical link utilization can be increased up to 94%.

Tinini et al. [30] proposed a Cloud-Fog-RAN (CF-RAN) network architecture and extended the capabilities of C-RAN fronthaul by the dynamic activation of baseband processing functions in fog nodes closer to RRHs. During low load hours, more baseband processing is placed on the fog nodes instead of in the cloud node. To plan the activation of fog nodes and dimensioning of wavelengths on a TWDM-PON fronthaul network they propose an ILP formulation and a graph-

based heuristics algorithm that reduces the execution time of the ILP. Results show that compared to a traditional D-RAN architecture the CF-RAN shows a 96% reduction in energy consumption with providing a maximum transmission latency of about $20\mu\text{s}$ in the fronthaul. Moreover, there is a trade-off among propagation latency, power consumption, and blocking probability.

Carapellese et al. [31], studied the energy-efficient BBU placement optimization problem using ILP model whose objective was to minimize the aggregation infrastructure power, and the BBU hoteling technique was implemented over an FMC-WDM aggregation network. The evaluation for the energy savings of BBU hoteling shows that the proposed architectures enable savings up to about 60%–65% in dense-urban or urban and about 40% in rural geotype.

Al-obaidi et al. [32], investigated how to optimize the deployment of new C-RAN networks by minimizing the CAPEX using microwave links as fronthaul. They proposed two deployment options: partial microwave radio links in the fronthaul to reduce fiber in the C-RAN, and partial site replacement for cloud, where only some sites are connected to the BBU Pool and some work as standalone BSs connected via fiber fronthaul. The simulation results have shown that microwave fronthaul sites can only minimize CAPEX at population densities above $8000\text{users}/\text{km}^2$. In the second deployment approach, it will be less costly to deploy a majority of independent sites backhauled by microwave than fiber front hauled RRHs, especially for coverage areas over 20km^2 . This is because the cost of fiber deployment increases non-linearly with the coverage area, while the cost of microwave deployment remains relatively constant.

The main objectives set by the majority of works in the above articles were minimizing the number of BBU pools, minimizing the number of wavelengths used per fiber links, and minimizing the computational resources, and in all cases, a tradeoff had been shown between fiber cost due to its number of wavelengths and the number of required BBU pools. In addition, the majority of the authors use the ILP model to solve the optimization problem where different input parameters, such as latency, BBU's processing capacity, and link capacity were taken as input, and BSs located both at office and residential areas were taken as input which is useful to share a BBU resources in a particular time as loads in a particular time are different on this areas.

Generally, the number of available fibers per link, the number of wavelengths per fiber and their line-rate capacity, the set of traffic requests, the number of RRHs and the maximum allowed fronthaul latency are parameters used to determine the required number of BBU pools. In addition, results showed that at lower fronthaul latency the tight latency requirements do not allow BBU consolidation but as latency increases further BBUs can be consolidated to a central pool.

Based on the aforementioned works, we conduct optimal BBU pool planning using the ILP model in the context of ethiotelecom network where RRHs are located around Bole International Airport, and their peak traffic is taken as input. The latency constraints and a transmission delay of fiber i.e. $10\mu\text{s}$ per km, are taken to predefine the number of required BBU Pools [24], and the capacity of a fronthaul link is also considered.

While connecting the RRHs to their respective centralized BBU pool, the bandwidth requirement in the fronthaul depends on the interface in use and the functional split option chosen; the CPRI as a fronthaul interface has a higher deployment cost, and its bandwidth requirement is fixed for a given cell configuration and independent of the amount of real traffic associated with the cell, thus to deploy C-RAN in a cost-effective manner this research will use other functional split options other than the CPRI. Physical Layer Split (PLS) fronthaul architecture is the 3GPP option 7 (Intra PHY split) that requires a much lesser bandwidth compared to the CPRI [10].

To the best of the researcher's knowledge, optimal BBU pool planning for C-RAN deployment in the context of ethiotelecom network has not been explored yet.

1.6. METHODOLOGY

The major methodologies followed to achieve the stated objectives are:

- Literature review
- Primary data collection from ethiotelecom mainly from RAN planning and optimization division,
- Model the BBU pool design problem using ILP formulation,
- ILP simulation outputs are presented using MATLAB tool and analyzed.

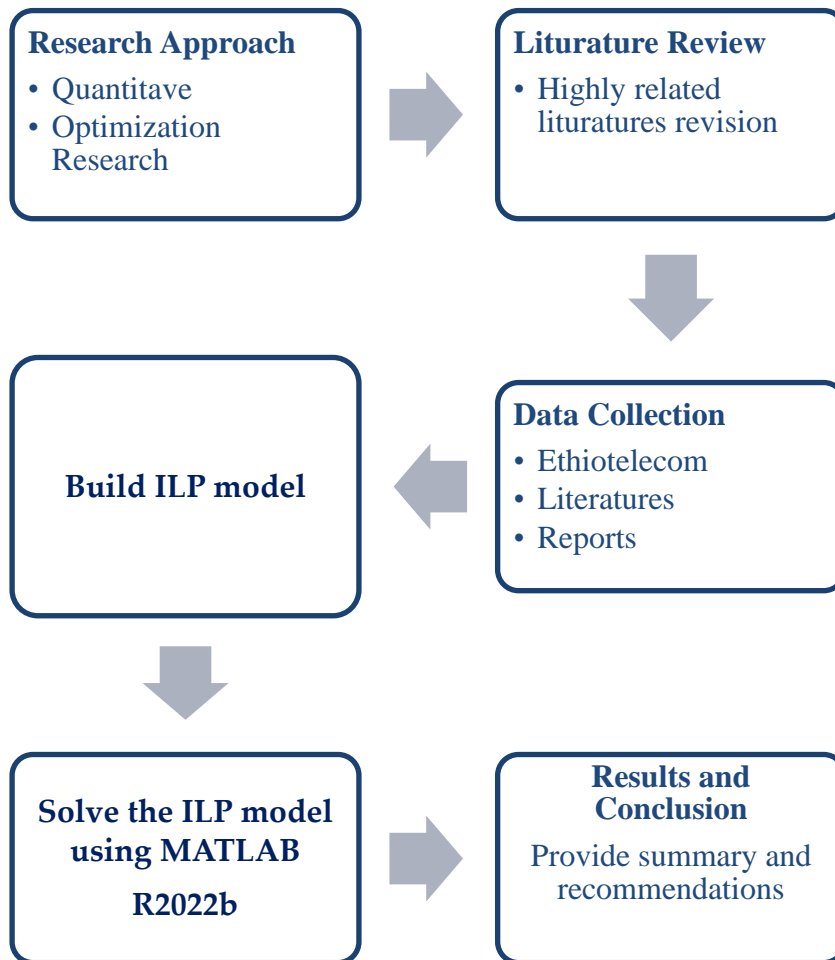


Figure 1. 2: Schematic diagram of methodology followed

1.7. THESIS CONTRIBUTION

By carefully considering the potential benefits and challenges of Cloud-RAN architecture, MNOs can make an informed decision about whether or not to deploy it. Hence, this thesis will help ethiotelecom to make informed decisions on C-RAN design, for the reason that the work will help to find the optimal number, and locations of centralized BBU pools using currently deployed base stations in the context of ethiotelecom network. It will also answer questions such as, which functional split is cost-effective at the same time meets the centralization benefits, and will the HARQ delay has an impact on BBU centralization. Therefore, the cell coverage range as part of the HARQ RTT dimension design is included.

1.8. THESIS LAYOUT

The rest of this paper is organized as follows: Chapter 2 will discuss the fundamentals and background of C-RAN architecture. Chapter 3 will present BBU pool planning for C-RAN deployment considering current and NGN. Chapter 4 will discuss the system model. Chapter 5 will discuss the numerical results and their analysis. Finally, Chapter 6 will conclude and provide future directions.

CHAPTER TWO

2. FUNDAMENTAL AND BACKGROUND OF C-RAN

The volume of mobile data transmission is steadily increasing with smart phones and tablet users. As a result, MNOs must increase network capacity by using different techniques such as by adding more cells, by implementing techniques such as massive MIMO, and using the raw and yet unused spectrum i.e., mmWave communication. The TCO (total cost of ownership), which includes CAPEX and OPEX, is derived from network construction, operation, and maintenance. While deploying more BSs, CAPEX and OPEX will rise significantly. The CAPEX rises because BSs are the most expensive components of a wireless network infrastructure, while the OPEX rises because cell sites require a significant amount of power to operate. But C-RAN is a novel mobile network architecture that has the potential to address the issues raised above [33].

2.1. BASE STATION ARCHITECTURE EVOLUTION

Traditionally, users in cellular networks communicate with a BS that serves the cell in which they are located. Base station's functionalities are divided into baseband processing and radio functionalities: the main role of baseband processing module includes coding, modulation, FFT, etc. and, the radio module is responsible for digital processing, frequency filtering and power amplification.

i. Traditional architecture

In this configuration, the radio and baseband processing functionalities are integrated inside a cabinet and placed on the ground at the base of the macro BSs mast. A heavy and large diameter coaxial feeder cables were used to connect the RRHs to the antenna located at the top of the cell site and this exhibit 3dB losses meaning that the antennas receive only half of the signal power transmitted by the BS chassis. It causes a large equipment footprint, high deployment costs, higher power consumption and underutilization of BS resources. X2 interface was used between BSs and S1 interface links a BS to the mobile core network. This architecture was widely used for the deployment of 1G and 2G mobile networks [34], [35], [36].

ii. Fiber-based Base station with RRH

In this architecture the BS is divided into two parts: a radio unit and a signal processing unit, where the radio unit or RRH is separated from the cabinet and located near the antenna at the top of the cell site, and is linked to the BBU with fiber based connection. The replacement of copper cabling by fiber provides significant benefits such as increased bandwidth, reduced noise, lower power requirements, and increased network coverage. Moreover, Fiber overcomes distance, weight and eliminate 3dB feeder loss existed in the traditional architecture. When compared to traditional base stations, the equipment power consumption and base station operation costs can be reduced partly. This architecture was introduced during the deployment of 3G networks, and it is still used by the majority of base stations today. Either optical fiber or microwave links can be used between them where BBU can be located within 20-40 km away from the RRH. RRHs can be installed on poles or rooftops, allowing for more efficient cooling and lower air conditioning costs in BBU housing [34], [35], [36].

iii. Centralized base station architecture

In a centralized RAN architecture, each BBU connects only one RRH via a dedicated fiber optic cable. This architecture eliminates the need for BBUs at each RRH, which can reduce costs and improve efficiency. It is a more complex architecture than the D- RAN architecture, but it can offer significant benefits in terms of cost savings, efficiency, and performance [25]. It is also more scalable than the D-RAN architecture, making it easier to add new RRHs and capacity as needed. However, the centralized RAN architecture is also more vulnerable to single points of failure. In addition, there is no or limited coordination between the BBUs, which can make it difficult to share resources between the BBUs, and can further reduce efficiency [12].

iv. Cloud-RAN

In C-RAN, BBUs from many cell sites are consolidated into a centralized location a.k.a. a BBU Pool/Hotel i.e., up to 40 km away from the RRHs, while the RF component is located near the antennas. This centralization of BBUs will enable network virtualization, where the BBU pools can be replaced by a server. A BBU pool is a virtualized cluster of general-purpose processors

used to perform baseband (PHY/MAC) processing. The X2 interface in a new form, known as X2+, organizes inter-cluster communication [36].

The BBU pool is also shared and virtualized among cell sites. The optical fronthaul network with high transmission capacity and low latency links a large number of RRHs to a pool of BBUs located in a central office (CO) and one BBU is used to run multiple towers [7], [12].

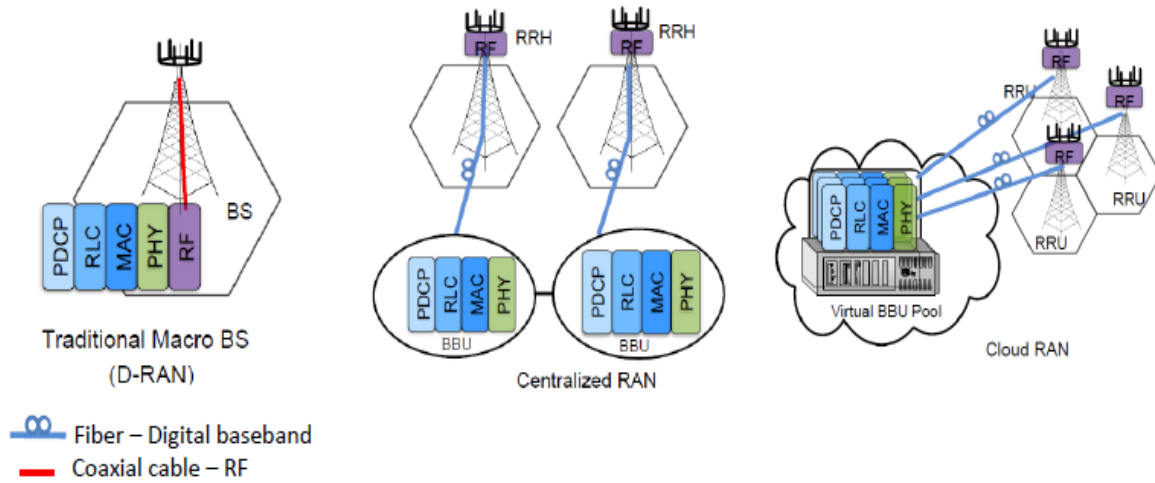


Figure 2. 1: RAN evolution from D-RAN to C-RAN [12]

v. Cloud Computing-based RAN (CC-RAN)

By incorporating cloud computing into the wireless communication system, the CC-RAN is able to provide high spectral efficiency (SE) and Energy Efficiency (EE) performance. Cloud-RAN, heterogeneous cloud radio access network (H-CRAN), and fog computing based radio access network (F-RAN) are the application models of CC-RANs [9].

2.2. C-RAN ARCHITECTURE

Since our focus is on cloud based RAN, in this subsection we will discuss in detail about this architecture.

i. Remote Radio Head (RRH)/ Remote Radio Units (RRUs)

RRUs are the RF processing units; and the wireless transceivers that are primarily consisted to antenna heads [37]. They perform all RF functionalities such as transmit and receive functions, filtering, and amplification of RF signals and connect mobile devices to the network. In the downlink, the RRH sends RF signals to UEs whereas in the uplink it sends baseband signals

from UEs to the BBU pool for further processing. Moreover, the RRHs perform up/down conversion, analog to digital or digital to analog conversion and interface adaptation [25], [38].

ii. BBU pool

The BBU pool is a centralized, shared, and virtualized site that contains numerous BBUs that have high computational and storage capabilities, which is interconnected via the X2 interface, and operates as virtual BSs to optimize the network resource allocation by processing baseband signals in the centralized place and dynamically allocate resources to RRUs based on the current network needs.

BBUs are composed of high-performance programmable processors and apply real-time virtualization technology. Here all the RRHs may be connected to a switch/central device which can flexibly schedule processing resources in the BBU pool for one RRH or a set of RRHs. It enables a flexible resource sharing and efficient energy efficiency by performing joint scheduling. Beside the implementation of efficient interference avoidance and cancellation techniques across multiple cells, it also provides a way to selectively turn RRHs on and off in accordance with traffic fluctuations in various scenarios.

BBUs are installed on VMs using a hypervisor over physical computing cores present in the cloud data center [39]. The centralized BBUs can enable software defined networking (SDN) and network function virtualization (NFV).

iii. Transportation links (Fronthaul/ Backhaul)

Fronthaul is the transmission link between the centralized BBU pool and multiple distributed RRHs/RRUs whereas the backhaul connects the BBU pool to the core. Basically there are two types of fronthaul: wireless and wired; the wired link uses optical fiber as a candidate to be used in the Next Generation Network (NGN). It is also capable of meeting the increasing demands for higher data rates. CPRI, OBSAI, and ORI are the radio interface protocols widely used in the fronthaul [34], [35]. The backhaul is the S1 interface that connects a BBU to the mobile core network [39]. Today, dark fiber is the primary fronthaul transport solution often based on a point-to-point connection between the antenna site and the Cloud-RAN hub site.

2.3. C-RAN SYSTEM STRUCTURE

Based on where functionalities are placed either on the BBU pool or resides in the DU, a C-RAN architecture can be classified into two categories, i.e, fully centralized and partially centralized.

- I. **Fully centralized:** All Layer 1 (Physical), Layer 2 (MAC) and Layer 3 (Network) functionalities are moved into the BBU Pool [37]. Therefore, the BBU pool handles all the functions of managing and processing resources. It is clear and simple but it generates high bandwidth IQ data transmission on the fronthaul [7], [13].
- II. **Partially centralized:** Layer 1 processing is co-located with the RRH, since Layer 1 takes major computation parts of RAN this reduces the burden in terms of bandwidth on the fronthaul links. However, Layer 2 and Layer 3 related functions are integrated in the BBU. Here, some advanced features such as CoMP and joint processing Distribute Antenna System, cannot be efficiently supported. The interaction between MAC and PHY could be complicated as well. It also makes the interconnection between Layer 1 and Layer 2 more difficult. Therefore, the tradeoff between the burden on fronthaul and the flexibility of resource schedule should be considered while planning the C-RAN deployment.

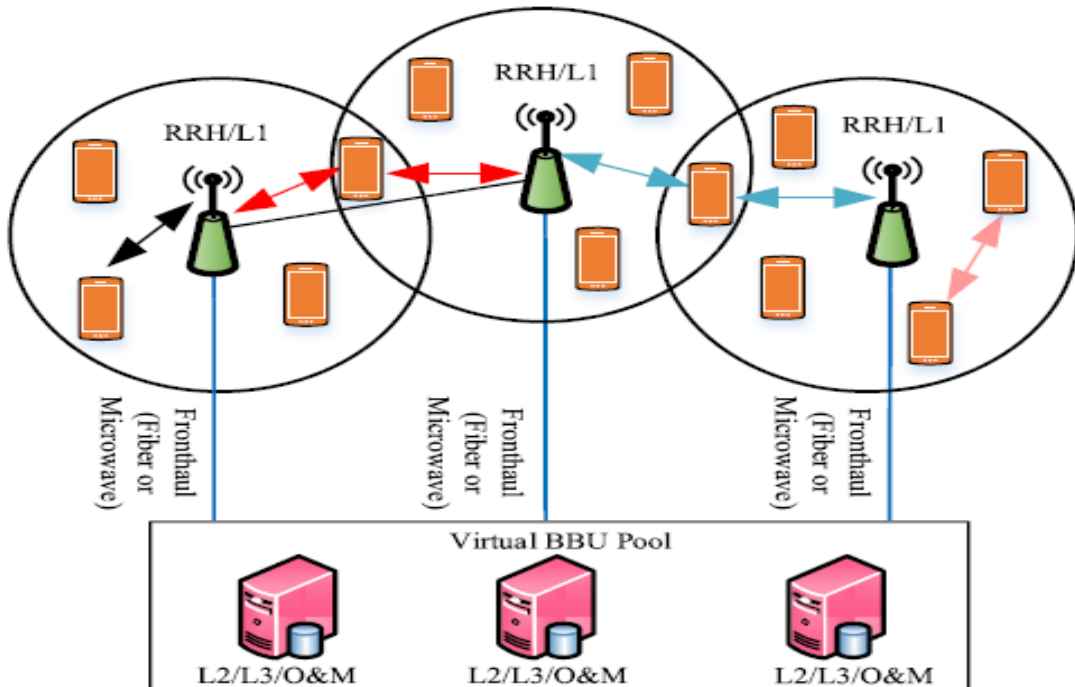


Figure 2. 2: Partially centralized RRH-BBU function split [7]

2.4. ADVANTAGES OF C-RAN ARCHITECTURE

Cloud based RAN has several advantages for mobile network operators, this includes reduced expenditure for cooling infrastructure at cell sites, reduced space requirement at cell sites, improved overall network performance, easier test access with faster deployments. Further, with C-RAN it is possible to implement network virtualization, dynamic resource allocation, and easier to implement advanced technologies in the BBU. Below we will see some of the benefits of C-RAN in detail;

i. Adaptability to non-uniform traffic and scalability

In C-RAN, one BBU can run multiple RRHs that have varying data traffic loads throughout the day, this is because cell sites are deployed both in residential and office areas where office area cells are highly loaded during working hours in the morning and afternoon while residential areas cells are lightly loaded, and vice versa. Consequently, it is possible to share the resources and processing between the BBUs to accommodate more loaded sites [20], [40].

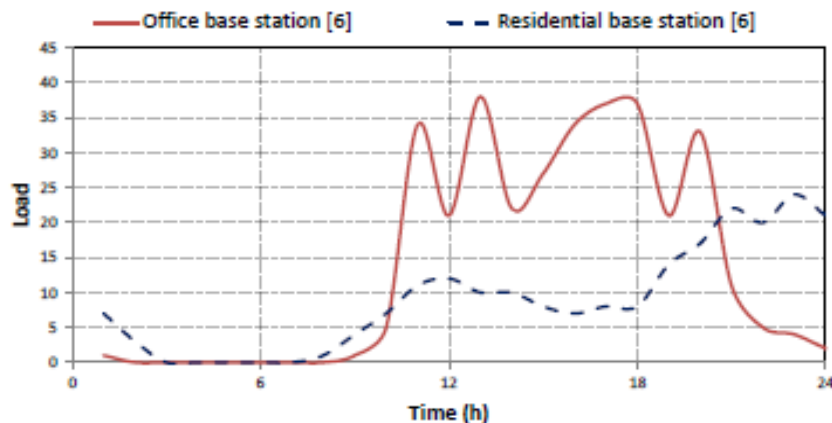


Figure 2. 3: Base station's daily load varies depending on their deployed location [24]

As the above figure shows network load varies throughout the day where peak traffic loads can be up to ten times higher than off-peak hours. Base stations are often designed for peak hours, when users move from office to residential areas, a tremendous amount of processing power is lost in the locations from which they have moved. C-RAN improves the overall utilization rate because baseband processing of multiple cells is performed in a centralized BBU pool.

Network coverage expansion, and network capacity enhancement or deployment of new cells in general can more easily be achieved by adding additional RRHs to the existing BBU Pools, which increases network flexibility. On the other hand, if the overall network capacity is needed to be increased, this can also be achieved by upgrading the BBU pool, either by adding more hardware(s) or replacing existing BBUs with more powerful ones [35].

ii. Energy and cost savings due to the statistical multiplexing gain in BBU Pool

Power amplifiers in wireless network consumes energy while supplying power and air conditioning to the RRHs and BBU. The reduction of required number of BBUs in C-RAN has resulted in lower electricity costs compared to the traditional RAN architecture, compared to D-RAN cloud based RAN reduce the TCO up to 68% [29] . It is also possible to switch off some BBUs in the pool during low traffic periods without affecting overall network coverage.

The centralization of site equipment has reduced the required civil work on remote sites, which contributes to additional OPEX savings. According to [13], cooling resources takes 46% of cell site power consumption, and 41% of OPEX on a cell site is spent on electricity. Compared to traditional RAN architecture, a total of 15% CAPEX and 50% OPEX savings are anticipated by C-RAN. It also saves up to 71% of power consumption compared to traditional RAN architecture.

Since baseband resources in the BBU pool are virtualized and shared by several BSs, a large reduction in the overall computational resources will be achieved due to multiplexing gain [7].

iii. Increase/improve network throughput,

Inter-cell interference mitigation techniques such as eICIC works to minimize inter cell interference, while CoMP utilizes interference paths constructively. In the simplest CoMP implementation i.e., Coordinated Scheduling (CS) and Coordinated Beamforming (CB), all cells in the CoMP set jointly decide on how to do scheduling and beamforming in order to minimize interference. This needs base station synchronization (0.05ppm frequency and $3\mu\text{s}$ timing accuracy), as only one base station is actively transmitting to one user at a time. Similarly, joint transmission i.e., the most advanced CoMP scenario requires a tight base station synchronization (0.02 ppm frequency and $0.5\mu\text{s}$ timing accuracy) and it is thus beneficial to use a centralized RAN architecture. These features are greatly facilitated by the pooling of BBU resources in a C-RAN,

as signal processing from many cells can be done over one BBU Pool, easing implementation and reducing processing and transmitting delays. When all cells in a CoMP set are served by a single BBU Pool, a single entity will handle signal processing which allows for tighter interaction between base stations. As a result, interference will be minimized, and throughput will be increased [40].

iv. Ease in network upgrades and maintenance

Since several BBUs are co-located in few centralized locations, whenever a hardware failure occurred or upgrades are required the servicing or human intervention is only required in a very few BBU pool locations, this highly eases network maintenance where servicing might be needed at all the cell sites for traditional RANs [37], [41], [18].

A well-known technology called Software Defined Radio (SDR) makes the implementation of radio functions such as modulation/demodulation, signal generation, coding, and link-layer protocols in software easier, and it also enables the C-RAN BBU Pool to support software-configured multi-standard multi-system radio communications that can be remotely programmable, upgradable and optimizable. Therefore, instead of replacing hardware components upgrades to new frequencies and standards can be made through software updates. Moreover, it is anticipated that the cost of network development and Operations, Administration and Maintenance will decrease with the use of multi-mode base stations [7].

2.5. CHALLENGES OF C-RAN ARCHITECTURE

Even though C-RAN architecture brings many benefits, in terms of cost reduction and RAN performance, it also brings some challenges:

i. Higher bandwidth, low latency, and low cost requirements in the fronthaul network [30]

The optical fiber link between the RRHs and BBU has to carry a large amount of baseband sampling data in real time. The wideband requirements in LTE and above technologies and MIMO technology, makes the capacity of optical transport link to transmit multiple RRHs baseband sampling data at multiple gigabit level [13].

Transporting fronthaul traffic across access networks is challenging for two reasons. i.e., very high bit-rate, in the order of tens of Gb/s for a CS, must be transported, so fronthaul requires much more capacity, and strict latency constraints must be met while transporting fronthaul [12].

In addition to the conventional backhaul traffic the new fronthaul traffic, i.e., the digitized baseband signals, a.k.a. Digital Radio-over-Fiber (D-RoF), exchanged by BBUs and RRHs, Thus, higher bandwidth independent from user traffic, high capacity and low latency is required in the fronthaul [25]. Since total bandwidth depends on number of sectors and MIMO configuration. The required fronthaul data rate largely depends on the employed functional split options.

Table 2. 1: Fronthaul bitrate for different split options [21], [28], [30], [35], [42],

Cell Configuration (LTE, LTE-A)	Fronthaul Bit rate
1×1 MIMO, 10 MHz bandwidth	614.4 Mbps
2×2 MIMO, 20 MHz bandwidth (baseline for op 8)	2.5Gbps
2×2 MIMO, 20 MHz bandwidth with 3 sectors (op 8)	7.5Gbps
4×2 MIMO, 20 MHz bandwidth with 3 sectors	16.6Gbps
32 antenna ports, 100 MHz bandwidth (OP 8)	157.3Gbps (UL, DL)
TD-LTE, 3 sectors	30Gbps
LTE, 20 MHz bandwidth, 2 × 2 MIMO with 3-sectors (OP 8)	6.29 Gbps
LTE-A, 2×2 MIMO, 5×20 MHz with 3 sectors	13.8Gbps

In addition to the high bandwidth and cost efficient requirements in the fronthaul, it also needs to support strict latency and jitter requirements. This is due to:

- Even though it is easier for CoMP/JT to cope with synchronization challenges in C-RAN compared to traditional RAN, it still requires 0.5 μ s timing accuracy for collaboration between base stations, which is the stringent constraint.
- To satisfy HARQ requirements, the sub-frame processing delay on a link between RRHs and BBU should be less than 1ms. Due to the delay requirements of HARQ, the maximum separation between RRH and BBU does not exceed 20-40km [6].

ii. Base station virtualization technique

Virtualization creates a logically, isolated networks over the physical networks which can be shared in a flexible and dynamic way. It has been used for data storage virtualization, desktop virtualization and network virtualization for many years. However, network virtualization is an important technique to realize C-RAN architecture. It is crucial to design virtualization

techniques to distribute or group the processing units into virtual base station entities once the BBUs have been pooled to the centralized pool. The main challenges of virtualization includes: implementing real-time processing algorithms, virtualizing the baseband processing pools, and dynamically allocating processing capacity to deal with the dynamic cell load in system [13].

iii. Typically dark fiber based (expensive)

Optical fiber is a feasible solution to transport fronthaul traffics because it can provide both the high capacity and low latency requirements, however it comes with the problem of very highest cost. Therefore, the trade-off between delay, bandwidth and cost needs to be considered before it come to reality. Below table compare and summarize the two RAN architectures.

Table 2.2: Comparison between distributed and cloud based RAN architectures [43], [44]

Comparison factor	D-RAN	Cloud-RAN
Small cell or RRH costs	High	Low
Small cell or RRH complexity	High	Low
Cost for planning, deployment, and maintenance of small cells or RRHs	High	Low
Energy efficiency of small cell or RRH	Low	High
Baseband unit cost	N/A	High
Planning, deployment, and maintenance of Baseband units	N/A	Low
Energy efficiency of Baseband units	Low	High
Ability of resource pooling	Restricted	High
Fronthaul latency requirements	Relaxed	Crucial
Cost of fronthaul and backhaul links	High	Higher
Inter cell site coordination	Restricted	Extremely high
Small cell or RRH complexity	High	Low

2.6. BBU POOL PLACEMENT OPTIONS

Given the physical separation between BBU and RRH, various placements across an aggregation network are possible.

i. At the CS Cabinet or distributed BS

It is the first step towards BBU-RRH segregation in which the cell sites (CSs) cabinet contains a BBU and an RRH. However, in this option the RRH is connected to the antenna and is linked to the BBU, which is located in the CS cabinet. A switch connects the BBUs to the backhaul network, and traffic is routed to the core central office (CO) through the backhaul links. Here backhaul traffics which are generated by each BBU is aggregated by a CS gateway (CSGW) and routed to the core via the remaining aggregation-network portion, which consists of several intermediate and one core CO [25].

ii. At the Access CO

This is the basic BBU centralization technique, in which BBUs from various CSs are located in their first or access COs, i.e., a BBU pools or data centers, where the CO is directly connected to the CSs and becomes a hotel site. RRHs, on the other hand, are remoted to the antennas on top of the tower. Here the fronthaul links the CS to the CO that houses the BBU pool, while the backhaul connects the BBU pool to the core CO. With this architecture, the CO can manage a large number of hotels more efficiently, resulting in a significant reduction of cost and energy savings [15]. BBU pools can be co-located with macro-cells which improves computational locality and shortens fiber links [33].

iii. At the Main or Core CO

This is another placement option where BBUs are placed at higher-level COs such as at the main and core COs, instead of at first COs. This architecture allows for greater BBU centralization in single hotels, resulting in greater reduction of the network costs due to its energy and cost savings. However, this architecture is constrained by the stringent fronthaul latency requirements due to its longer distances between CSs and the BBU pools [28].

CHAPTER THREE

3. BBU POOL PLANNING FOR C-RAN DEPLOYMENT

Optical fiber is a feasible solution in the fronthaul in terms of its capacity and latency, and it needs to be carefully designed because it has the significant role towards the capacity, end-to-end latency, network deployment and the cost of the C-RAN. The fronthaul delay highly determines the distance between the pool and RRH sites.

Table 3.1 lists the delay budget required in the fronthaul link and the round trip time delay (RTT) values of all components in the fronthaul, that is useful to evaluate the total delay established in the link between RRH and BBU as well as to calculate the maximum allowable optical fiber link distance, where the maximum fiber link length depends on the maximum tolerated delay in the fronthaul link, i.e. $250\mu\text{s}$ [30], [45] and fiber propagation delay is assumed to be $10\mu\text{s}/\text{Km}$ [46], [12], [42]. The RTT delay components are transmission delay, propagation delay, queuing delay, and processing delay.

Table 3. 1: RTT delay values of C-RAN [20], [30]

No.	Delay Components	Unit delay	Min	Max
1	RTT of RF processing	RRH (δ_R) UL/DL	$25\mu\text{s}$	$40\mu\text{s}$
2	RTT of CPRI processing	RRH, BBU ($\delta_{R,B}$)	$10\mu\text{s}$	$10\mu\text{s}$
3	RTT of BBU processing	BBU (δ_B)	2.7ms	2.7ms
4	RTT of Active equipment	Fronthaul equipment (δ_F)	$4\mu\text{s}$	$40\mu\text{s}$
5	Fronthaul delay	Propagation delay (δ_p)	0	$250\mu\text{s}$

As the below figure depicted the main latency contributors in the RAN are latency due to processing in the RRH and BBU, fiber propagation delay, and the electronic switch delay which is accountable for $20\mu\text{s}$ for each electronic switch [22].

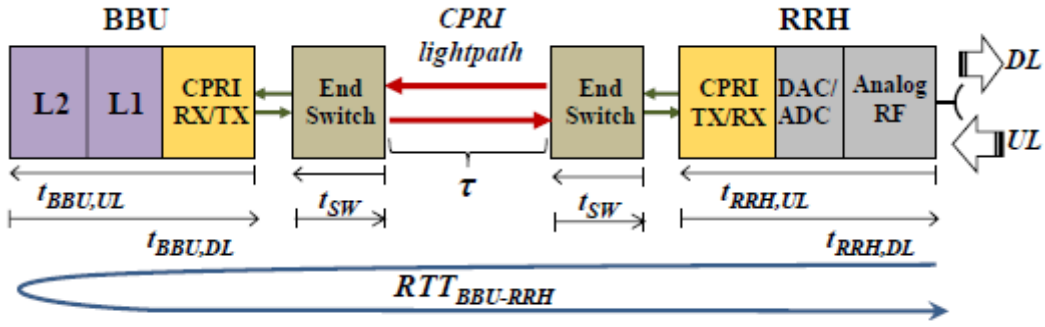


Figure 3. 1: Latency contributions on the fronthaul processing [31]

$$RTT_{BBU-RRH} = 2\tau + t_{RRH,UL} + t_{BBU,UL} + t_{BBU,DL} + t_{RRH,DL} + 4t_{SW} \leq 3ms \quad (3.1)$$

Where the first term in equation (3.1) depends on the distance between RRH sites and its serving BBU, while the last term is distance independent delay such as for queuing, switching, optical line termination, line card and processing [15]. Logically, operator's decision to select a lower delay budget implies greater costs due to the need for additional BBU pools, but it positions the deployment to be ready for future evolution of technology and network requirements.

Real-time functions such as voice over LTE, IoT, tactile applications, and other time-sensitive applications require a very low fronthaul delay [42]. To support this latency critical applications the fiber length in the fronthaul should not be longer than 15km in order to maintain one way latency under $75\mu s$ [47]. Moreover, use cases such as tactile internet, autonomous driving or augmented and/or virtual reality require a constrained latency in the fronthaul network, the analysis from the same work reveals that for URLLC applications the fronthaul latency is a critical performance metric [12], and according to [46], [48], the end to end delay of CPRI for high priority fronthaul transport should not exceed $100\mu s$.

The end-to-end latency for 5G networks varies depending on the type of application being used. For example, URLLC applications require an end-to-end latency of less than 0.5 milliseconds for both UL and DL. Tactile internet, industrial networking or smart cities, and factory automation applications require an end-to-end latency of less than 1 millisecond for both UL and DL, on the other hand, eMBB applications have a relaxed latency requirement of 4 milliseconds for both UL and DL [49].

3.1. WIRELESS DELAY BETWEEN UE AND RRH

The hybrid automatic repeat request (HARQ) is an error detection and correction technique between the UE and RRH that takes place in the MAC layer of the OSI model. It enforces UEs to receive ACK/NACK messages from the BBU pool in three sub frames after sending UL data to the RRH. However, if the ACK/NACK message is not received within these three sub frames, the UEs will retransmit the data again to the RRH [30]. The interaction of HARQ within C-RAN is displayed below in the figure.

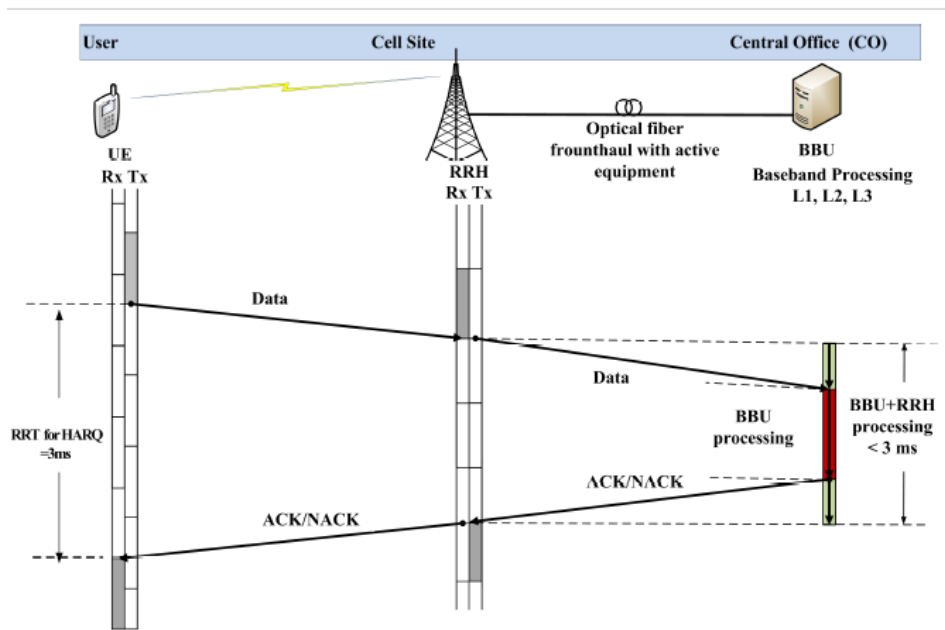


Figure 3. 2: Delay link budget of MAC-Layer RTT in C-RAN architecture [20]

The wireless interface delay can be determined using [20]:

$$\delta_{U,R} = 2 * \frac{r}{c} * 10^3 \mu s \quad (3.2)$$

Where, the 2 factor represents UL and DL RRT between the RRH and user, r is distance between the RRH and UE, and c is speed of light in vacuum. Shows the linear increment of 6.7 $\mu s/km$.

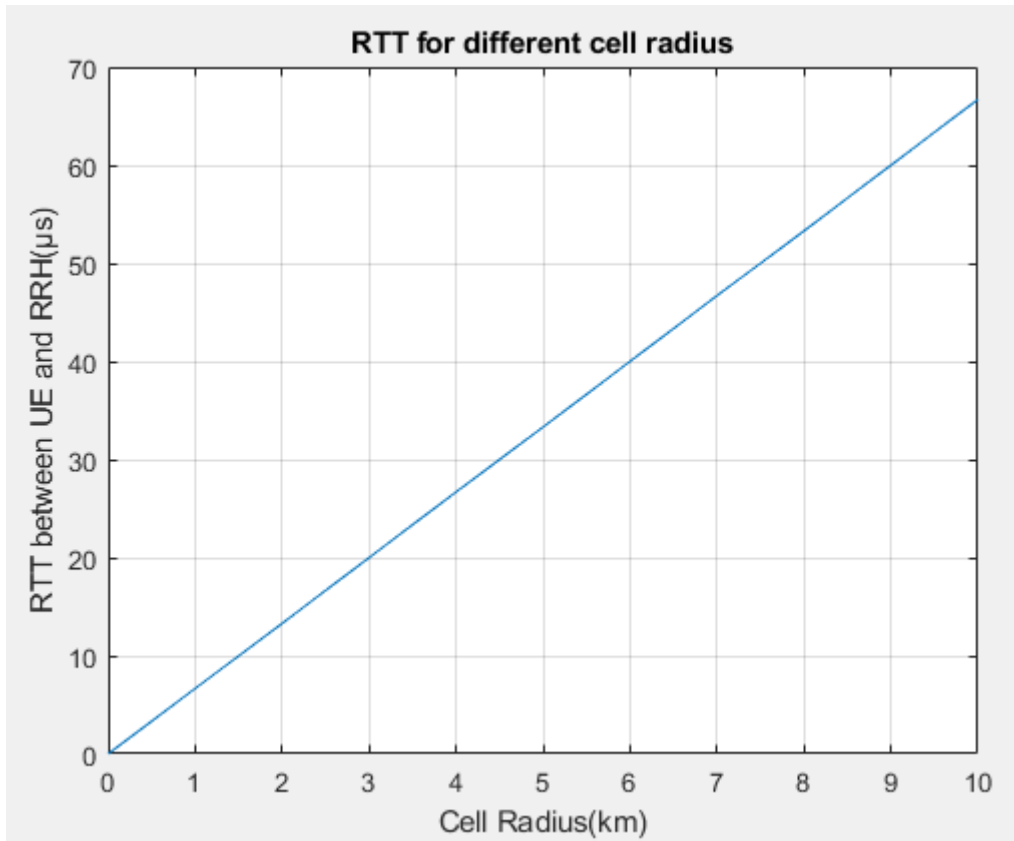


Figure 3. 3: RTT between UE and RRH for different cell radius [20]

3.2. FRONTHAUL TRANSPORT TECHNOLOGIES

The fronthaul is a key for flexible RAN deployment, where CPRI and OBSAI are the two transmission protocols for fronthaul transport, and CPRI is more widely adopted in the industry than OBSAI [12].

3.2.1. CPRI Transport

Common Public Radio Interface (CPRI) is a digital interface protocol for encapsulating radio samples between the RRH and the BBU. CPRI: high speed serial communication protocol transferring digitized radio data control info between BBU and RRH [50]. The interface burden is not packet-based; signals are multiplexed in a low-latency timeslot-like fashion. CPRI is based on carrying time domain baseband IQ samples between RRH and BBU. Thus, CPRI needs a high capacity fronthaul, low latency, low delay variation and fine synchronization [51].

3.2.2. enhanced CPRI (eCPRI)

eCPRI was introduced by the eCPRI forum to meet the 5G requirements, and it was defined for the original centralized RAN configuration. This protocol is flexible, scalable, and makes more

efficient use of bandwidth than its predecessor. It is a packet-based which brings enormous advantages to the fronthaul network such as, it enables PHY functional split and can now run over Ethernet and other transport technologies instead of relying on the availability of fiber. Further, the fact that the ability of eCPRI to run on Ethernet is a significant advantage for urban areas and indoor settings like factories and office buildings where 5G coverage will be necessary. It also enables use of sophisticated coordination algorithms to guarantee best possible radio performance [9]. Number of optical distribution technologies for eCPRI transport options are viable in the C-RAN architecture including dedicated fibers, passive WDM, active WDM, PON, OTN, and Ethernet fronthaul.

- I. **Dedicated fiber:** In cases where there is an already existing installed base of readily available fiber this is a desirable choice, even when fiber is present it must be used wisely because installing new fiber is expensive, which restricts the applicability of this alternative [9], [40].
- II. **Passive Optical Network (PON):** is a potentially alluring choice for CPRI transport in densely populated locations where small-cell deployment is most likely to take place. These are often large stadiums, busy shopping malls, metropolitan areas, and college campuses. PON is prone to additional latency and power loss because optical splitters are required to divide and collect optical signals, which further reduces the cell radius and makes fault isolation challenging [40], e.g. PON induce a significant power loss (5, 10 dB) but have low latency [52].
- III. **Optical Transport Network (OTN):** A well known FEC techniques which can expand the coverage of metro optical networks were introduced by OTN. Further, it enables traffic grooming for fronthaul similar to the backhaul. At intermediate nodes, the light paths from various RUs can be combined into shared light paths before traveling to the BBU pool. It is important to think carefully before using OTN for CPRI transport because some of its highly beneficial features add latency [25].
- IV. **CPRI over Ethernet (CoE):** Using existing Ethernet cable infrastructure to encapsulate and transport CPRI from a centralized BBU pool to the RRH cuts cost significantly. CPRI data on the link is not sent continuously, but as discrete Ethernet 802.3 frames. To meet latency and jitter requirements, CoE sometimes demands dedicated Ethernet links between endpoints.

The CoE cabling low propagation delays and high data throughput, while being an economical choice, both in equipment costs and in its use of fiber resources [9], [46].

- V. **Wavelength-based systems:** WDM offers a good combination of characteristics for CPRI transport. In particular, active WDM networks regenerate the signal at each hop, which eliminates the power loss issue but adds latency [52]. WDM-based optical aggregation networks are suitable candidate solution for meeting the requirements of the fronthaul [40], [53].
- VI. **TWDM-PON:** In time and wavelength division multiplexing passive optical networks (TWDM-PONs) both time and wavelength division multiplexing are performed at different network layers to gain the bandwidth efficiency of WDM and the cost efficiency of TDM. In this architecture, the optical network units (ONUs) are located at the cell site to tune RRHs to a wavelength and connected to the optical line terminal (OLT) at the BBU pool that demultiplex several wavelengths transmitted on a single fiber carrying the data from multiple RRHs/cell sites through optical fiber link. These two components are responsible for electrical to optical signal conversion or vice versa. The OLT is composed of a wavelength division multiplexer, and a line card (LC) for each digital units. The ONUs share the same number of wavelengths as the OLT, for which every wavelength is served by a LC or optical transceiver. Consequently, one LC can serve multiple ONUs at various sites, resulting in energy savings. It is a promising architecture to support the low-latency and high-capacity requirement of fronthaul transport network in C-RAN [7], [30], [54], [55], [56]. Here the fronthaul transport network is assumed to be a TWDM-PON where a fiber with a maximum line rate of 200Gbps, i.e., a maximum of 20 wavelengths per fiber each having 10Gbps capacity.

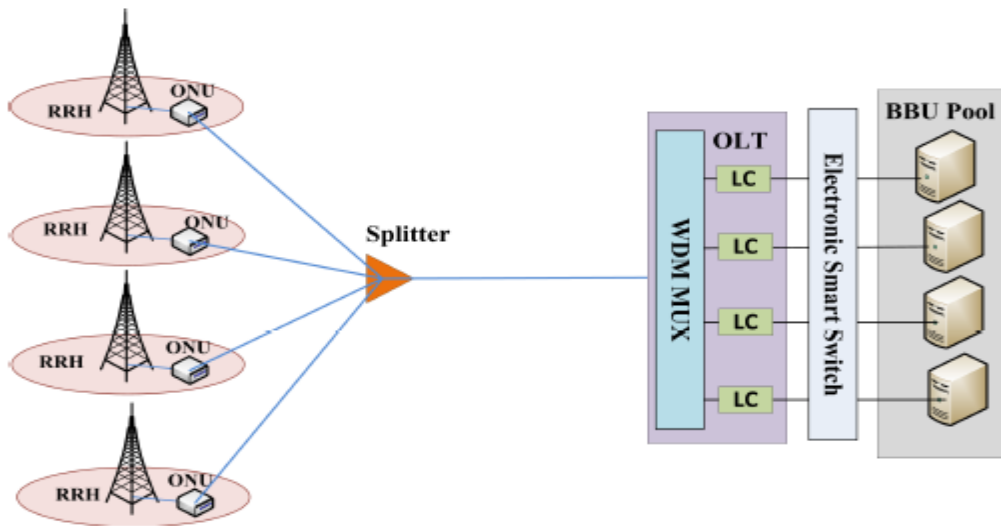


Figure 3. 4: TWDM PON fronthaul architecture [20]

3.2.3. Microwave

For short distances (1 km or less), microwave transport is another potential option. High capacity microwave links can be used in the fronthaul [32].

3.3. TYPES OF C-RAN DEPLOYMENT

Based on the type of RRHs or number of radio access nodes served by a single BBU pool C-RAN deployment scenarios can be classified in to two categories: homogenous and heterogeneous C-RAN deployments [20].

Homogeneous C-RAN Deployment

In the homogeneous C-RAN deployment only macro or micro cells having the same type of RRHs is clustered to the BBU pool, and the transmitted power of the RRHs has a same output level, identical antenna patterns, receiver noise floors and a similar fronthaul connectivity to the corresponding BBUs [20].

Heterogeneous C-RAN Deployment

In heterogeneous C-RAN deployment number of high power consuming macro cells, and low power consuming micro cells or small calls will be pooled to the central processing location [20] where, the small cells increase system capacity while macro cells manage mobility, control the network, and enhance performance [7]. By providing a high power nodes than RRUs, which is in charge of controlling signaling in a geographic area heterogeneous C-RAN attempted to address the latency problem [33].

3.4. USE CASES FOR C-RAN DEPLOYMENT

The following are the most important use cases for C-RAN deployment [5], [57]:

- Large public venues such as stadiums, malls, amusement parks etc. are critical places,
- Targeted outdoor urban areas such as public squares, shopping streets, etc.
- High-density urban areas,
- Large urban areas.

3.5. OVERVIEW OF RAN FUNCTIONAL SPLIT

The BBU functionality in a RAN architecture is divided into two functional units: that is a distributed unit (DU) that is accountable for the real-time L1 and L2 scheduling, and a centralized unit (CU), which is in charge of non-real-time, higher L2 and L3 scheduling or CU hosts the network layer functionality (RRC) and the PDCP functionality from the Data Link Layer. As per the 3GPP technical specifications, there are eight functional split options [45], where each option has different number of functions being centralized and it also require different bit-rate and delay requirements. In general, as more functions are situated in the DU, more processing will be done before the data goes to the fronthaul network, therefore the required bitrate on the fronthaul will be lower. The transport network for NR traffic which is the crosshaul or xhaul network is formed by the backhaul and fronthaul networks together [58].

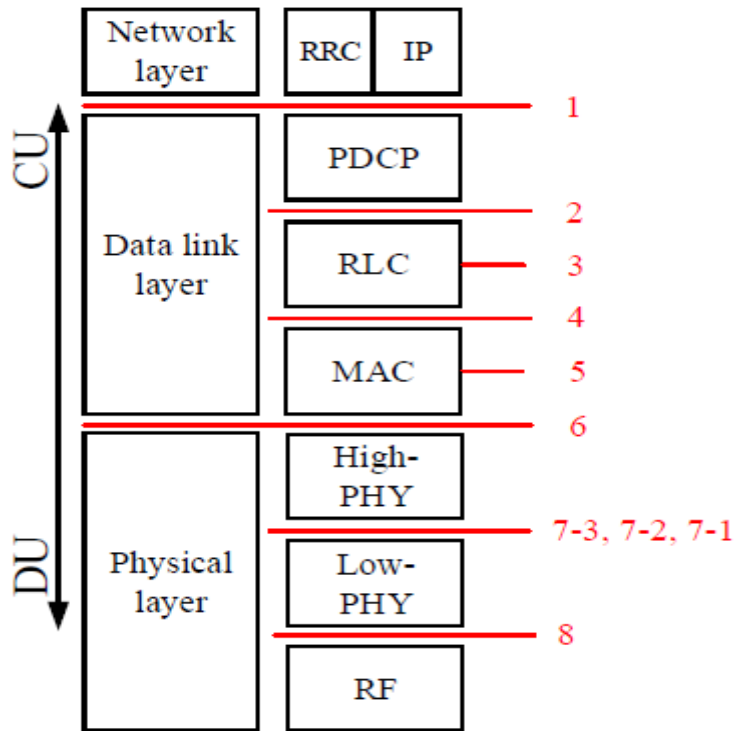


Figure 3. 5: LTE protocol stack and layers with 3GPP's functional split options [42], [45].

It is known that no single functional split suits for all scenarios and choosing the best option isn't always straightforward, therefore MNOs are responsible to choose the best split option for their network depending on the services they offer and the economics of the available transport networks. Furthermore, telecom equipment manufacturers should also decide which functional split is best for the markets they target. Say for instance, option 2 has been suggested by 3GPP for applications such as fixed wireless access, where there is no requirement for cell-site coordination and relatively relaxed latency and bandwidth requirements on the transport network, option 6 is being proposed by the Small Cell Forum (SCF), as it's the best split for low-cost, and low-capacity deployments. On the other hand, the O-RAN Alliance advocates option 7.2 for networks with high-capacity and high-reliability requirements. This split option also enables a relatively simple RU whose power consumption and size supports network densification and allows sharing by multiple operators.

In general, as more functions are placed in the DU lower bitrate is required on the fronthaul, this is due to the fact that more processing has already been done before data is transmitted on the fronthaul network. Moreover, split options 1 up to 5 have relaxed fronthaul latency requirements

since the HARQ and other time-sensitive functions reside in the lower MAC sub-layer, whereas split options 6 to 8 have very strict latency requirements in the fronthaul [12], [42].

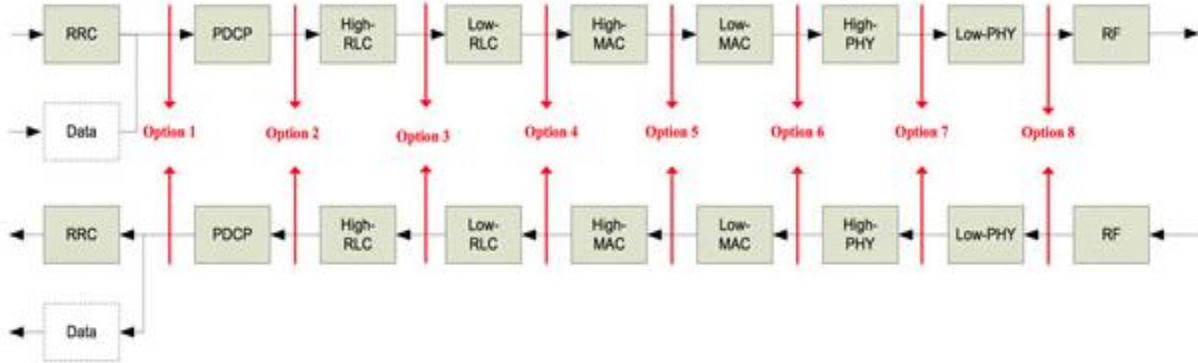


Figure 3. 6: 3GPP functional split options [45]

3.5.1. Fronthaul Bandwidth Dimensioning

In this sub-section, we will discuss the 3GPP's functional split options in detail and cover their respective benefits and downsides. Split 1 to 5 have relaxed latency and bandwidth requirements on the fronthaul, but they are less interesting because they do not exploit the centralization benefits and have complex RUs [28]. However, split 6 to 8 have very strict fronthaul latency requirements; plus the HARQ process and other time critical functions are located in the lower MAC, hence they are feasible for 5G. On the other hand, the intra-PHY functional splits provide the centralization benefits, and have received particular attraction within the industry, hence, we more thoroughly analyze the lower level splits (option 7.x) family.

I. Option 6: MAC-PHY Split

All physical layer functionalities and RF are in the distributed unit, while upper layers are in the central unit. As more functionalities are placed in the DU, more processing has already been done before data is transported on the fronthaul network, hence the less bandwidth is needed on the fronthaul network. Here, there is no possible energy savings for the physical layer [42], [45]. The required fronthaul bitrate for split option 6 in the DL can be calculated by [42]:

$$DL\ FH\ bitrate = (PR + CR) * (BW/CBW) * (LA/CLA) * (8/6) \quad (3.3)$$

The required fronthaul bitrate for split option 6 in UL

$$UL\ FH\ bitrate = (PR + CR) * (BW/CBW) * (LA/CLA) * (6/4)$$

(3.4)

Where PR is Peak rate measured in Mbps, CR is the schedule/control signaling rate measured in Mbps, BW is bandwidth, CBW is the control signals bandwidth, LA is number of layers, CLA is the number of layers for control signaling.

II. Option 7 (intra-PHY functional splits)

In this split some portion of physical layer functionalities and RF are in the DU, whereas upper layers are in the CU. Higher splits are less attractive compared to the lower ones because they involve a complex RUs and do not achieve the centralization advantages. Therefore, particular attention has been paid to the intra-PHY functional splits due to their ability to exploit the centralization benefits, and most research efforts have been turned to compression techniques to reduce the required bitrate in the fronthaul network.

On the other hand, splits 7.x family provides the best balance between inter-cell site cooperation, fronthaul bandwidth and RU complexity, plus they support the key centralization benefits, such as carrier aggregation, MIMO and CoMP, their main difference being the data-rate requirement on the fronthaul network where splits 7.1 and 7.2 might be bandwidth-greedy. The figure below illustrates why there is so much industry interest on the intra PHY functional splits.

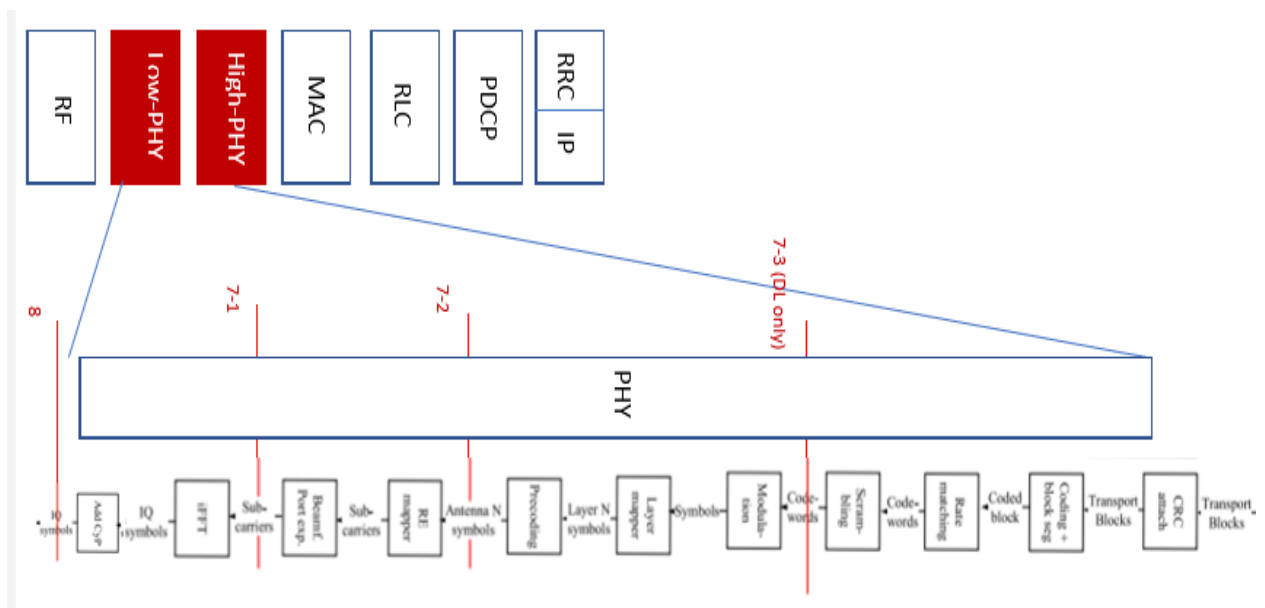


Figure 3. 7: PHY layer functional splitting shows where functions are located [42]

i. **Option 7-1: Low PHY**

This split support CoMP without any performance degradation, i.e., JT in UL and JR in DL and there is huge difference between UL and DL bandwidths. The required fronthaul bitrate for split option 7-1 that is used for both DL/UL [42]:

$$FH \text{ bitrate (7.1)} = SC * SY * AP * BTW * 2 * 1000 + MAC \text{ info} \quad (3.5)$$

Where SC is the number of subcarriers, SY is the number of symbols, AP is the number of antenna ports (how many antennas are present in the DU), BTW is bitwidth (the number of I and Q bits),

Alternatively the fronthaul bandwidth can be calculated as [59],

$$FH \text{ bitrate (7.1)} = \frac{2 * IQ_{bw} * N_{sc} * N_{ant} * N_{layers}}{T_s} (bps) \quad (3.6)$$

For split option 7.x the required bandwidth in the fronthaul is mainly determined by physical features such as: number of subcarriers N_{sc} (e.g., 1200 sub-carriers for a cell of 20 MHz), O_m i.e., modulation order O_m , N_{layers} represent the number of MIMO used, N_{ant} is the number of antenna ports used in the RU, the IQ_{bw} which represents the I/Q size or the required number of bits to code a constellation point (e.g., 32 bits for both in-phase and in-quadrature data) and, T_s is the symbol period given by the number of symbols carried in a time slot. For instance, when using normal cyclic prefix, LTE transmits 7 symbols per slot of 0.5 milliseconds ($T_s = 0.5/7 = 0.07ms$).

ii. **Option 7-2x: Low PHY/High PHY split**

This split reduces the traffic in the fronthaul and it offers the best balance between bringing the O-RAN technology to market quickly and its deployment cost [21]. Hence, the best option to be adopted in the context of ethiotelecom network is option 7.2. It is a low-level split for URLLC and near-edge deployment. It support variable bitrate in the fronthaul and support CoMP without any performance degradation,

The required fronthaul bitrate for split option 7-2 used for both DL/UL [42]:

$$DL \text{ or } UL \text{ FH bitrate} = SC * SY * LA * BTW * 2 * 1000 + MAC \text{ info} \quad (3.7)$$

Where SC is the number of subcarriers, SY is the number of symbols (SY), LA is the number of layers, BTW is bitwidth (the number of I and Q bits/IQ size). Alternatively,

$$FH \text{ bitrate (7.2)} = \frac{2 * IQ_{bw} * N_{sc} * N_{layers}}{T_s} (bps) \quad (3.8)$$

iii. Option 7-3: High PHY

Here the Modulation /demodulation functions are in the DU, thus the fronthaul carries bits instead of I/Q symbols. Therefore, in the downlink the required bitrate in the fronthaul will be divided by $2 * IQ_{bw}$, and will be given as

$$FH \text{ bitrate (7.3)} = \frac{N_{sc} * N_{layers} * O_m}{T_s} (bit/sec) \quad (3.9)$$

For a cell with bandwidths of 10 MHz, and 20 MHz, 2x2 MIMO ($N_{layers} = 2$), four antenna ports ($N_{ant} = 4$), and 16 QAM modulation ($O_m = 4$), the required fronthaul capacity in the DL is shown in the table below. In addition, the peak data rate capacity of a cell using 100 MHz, 8 MIMO layers, I/Q size of 2x16 bits, 32 antenna ports, and soft bit size of 5 bits the required fronthaul bandwidth at a modulation of 256 QAM is also presented.

Table 3. 2: Maximum required fronthaul bitrate for different functional split options

Split option	Required Capacity for 10 MHz (Mbps)	Required Capacity for 20 MHz (Mbps)	100 MHz bandwidth & 32 antenna ports
6	1700	4133	5.6Gbps (DL), 7.1Gbps (UL)
7.1	2150.4	4300.8	9.2 Gbps DL, 60.4 Gbps UL.
7.2	537.6	1075.2	9.8Gbps (DL), 15.2Gbps (UL)
8	3677.2	7357.4	157.3 Gbps (UL, DL)

III. Option 8: PHY-RF Split

In option 8 functional split only the radio frequency functions are performed at the radio unit (DU) while the remaining upper layer stack functionality is centralized, and leaving a very simple RU and it corresponds to the original C-RAN configuration. This split option provides the highest degree of function centralization enabling load-balancing and sharing of the processing capability across the RUs. It also that support different RATs (e.g. GSM, 3G, LTE) [42], [45]. Full centralization of network functions reduces both CAPEX and OPEX, efficiently support CoMP, MIMO, load balancing, and mobility with efficient resource management. However, the cost of the fronthaul network is a challenge for MNOs because fronthaul bitrate is constant, very high and scales with the number of antennas, and fixed CU/DU mapping, i.e, not very scalable for massive MIMO scenarios. The equation given below helps to determine the required fronthaul bitrate for split option 8 for both DL and UL [21], [60].

$$FH \text{ bitrate} = SR * BTW * AP * 5$$

(3.10)

Where SR is sample rate (number of samples per second), BTW is bitwidth (the number of I and Q bits), AP is the number of antenna ports (how many antennas are present in the DU).

In general the required fronthaul bitrates operating at 20 MHz, LTE carrier using 2 DL antennas and 64 QAM is given below as an example, where a large gap is shown between fronthaul bitrates for the different functional split options, and the figure also clearly shows why there is so much industry interest in the Option 7, or PHY-level functional splits. It also offers a good balance between RU complexity, fronthaul bandwidth, and inter-cell cooperation.

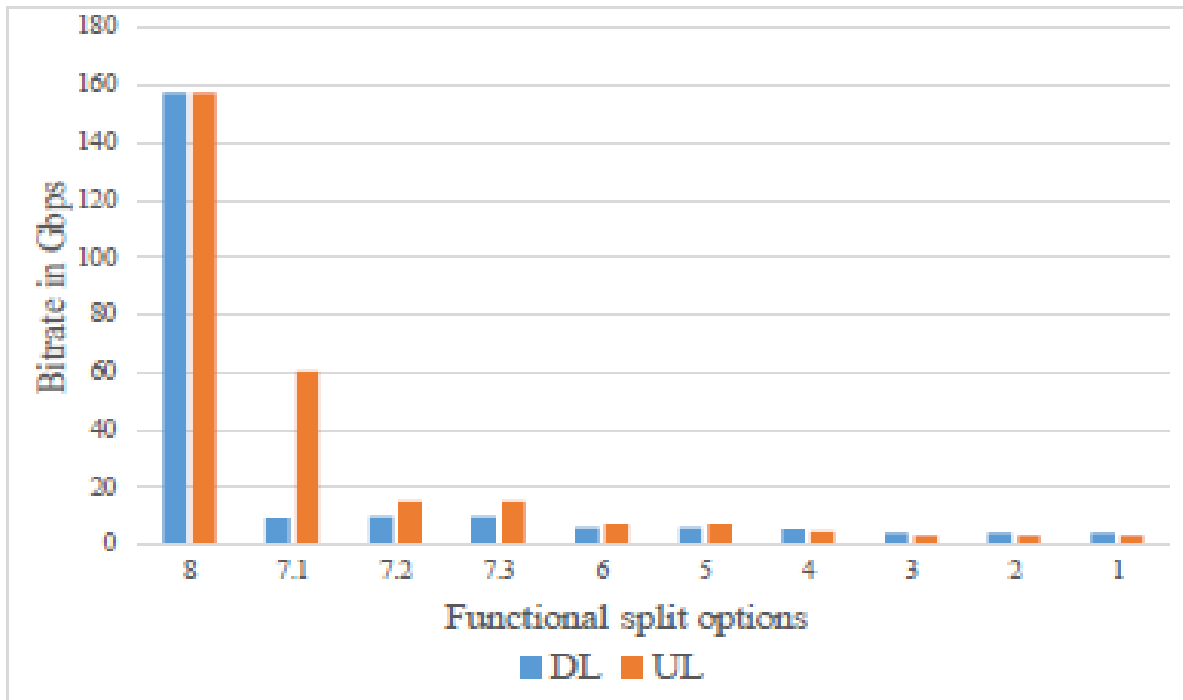


Figure 3. 8: UL and DL fronthaul bandwidth for each split [42].

In general, split option 6 need to carry at least 0.17 Gbps bitrate in the fronthaul, split option 7-2 needs at least 0.3 Gbps, split option 7-1 need at least 138 Gbps, and split option 8 need to carry at least 2360 Gbps in the fronthaul.

Table 3. 3: Proposed split options for C-RAN assessment [42], [45], [61]

Split options	Functions in DU	Functions in CU
6	All physical processing, i.e., full stack of the PHY layer and the RF functions are executed at the RU.	- MAC, RLC and upper layers -HARQ, MAC scheduler, and other time critical Procedures -20% of the overall baseband processing
7-1	UL: FFT, CP removal and possibly PRACH filtering functions, DL: iFFT and CP addition functions	-ARQ - the rest of PHY functions

Split options	Functions in DU	Functions in CU
7-2	<p>UL: FFT, CP removal, resource de-mapping and possibly pre-filtering functions</p> <p>DL: iFFT, CP addition, resource mapping and precoding functions</p>	<p>-ARQ</p> <p>- the rest of PHY functions</p>
7-3	The scrambling, modulation and layer mapper of the PHY functions exist in the DU	<p>-FEC in the CU-pool useful for the close cooperation between the FEC and the MAC.</p> <p>- Only the encoder exist in the CU</p>
8	RF sampler and the up converter	-Processes of all the protocol stacks are centralized, therefore, a very tight coordinated RAN exists

Table 3. 4: Pros and Cons summary for the eight split options [42]

Split option	Pros	Cons
1	Separation of the user plane	Complexity of RUs
2	Support mobility coordination	Lost the COMP capability and Low centralization
3	Support reliability	In some scenarios its latency sensitive
4	Low data rate requirement in the FH	The close relationship between the MAC and RLC layers disappeared
5	The DU holds real time functions	Complex interface
6	Centralized scheduling and it consume less optical bandwidth compared to split options 7 and 8	limited centralization of functions and cannot use joint decoding

Split option	Pros	Cons
		lower performance in terms of cell-edge user throughput and average cell throughput The close relationship between MAC and FEC disappeared
7.1	Less RU complexity	FH bandwidth scales with the antennas used
7.2	Provides a good balance between FH bandwidth, RU complexity, and inter-cell cooperation. The bitrate in the FH scales with the spectrum used instead of the antennas used	High and constant bit rate required in the FH network
8	The most energy efficient split option due to highest functions centralization, simple RUs	Highest and constant bandwidth is required in the FH which scales with the number of antennas used

Simulations to compare split 8, 7-3 and 6 were conducted on [42], and split 6 shows lower performance in terms of average cell throughput and cell-edge user throughput. However, it shows the lowest average optical bandwidth. A trade-off has been shown between RU complexity and required fronthaul bandwidth.

3.6. NETWORK DIMENSIONING

Network dimensioning of a C-RAN architecture requires BBM dimensioning as well as cloud server dimensioning. Here network configuration data and subscriber traffic are used to determine the required RF, baseband, and cloud software licenses. Hence, the output of the network dimensioning process is bill of material consisting of all the baseband processing hardware and software licenses for the C-RAN deployment.

3.6.1. Baseband module Dimensioning

One of the hardware component required in the Cloud-RAN is the baseband module. It has three components named as Capacity plug-in unit (CAP), Common plug-in unit (COM) i.e., the main processing unit, and cabinet unit (CBN). A detailed description of the BBM unit functions, cell connectivity, and C-plane traffic requirements is given below in the table.

Table 3. 5: Baseband module unit functions, and Cell connectivity requirements [14]

BBM units	Functions	Cell connectivity requirement
CAP	-Provide the baseband processing, where the number of cells supported by a single CAP unit is determined by the cell's bandwidth and MIMO configuration: -primarily responsible for cell connectivity.	Higher bandwidth and MIMO configurations need more resources from the CAP unit, therefore enough amount of CAP units per site must be available to satisfy the total processing capacity requirements by the cells
COM/ Main Processing Unit	-Used for processing control plane traffic and connects multiple BBMs: -It provides transport and centralized control functions for the RAT and antenna data routing.	-A minimum of one COM unit is required per cabinet
CBN	-It hosts the CAP and COM units and links them. It also provides a backplane for internal communication and air conditioning for the underlying units.	The number of required CBN units is determined by the maximum capacity for hosting the CAP and COM units, i.e, how many cells one CAP can support and how many COM units are required to handle the C-plane traffic demand.

3.6.2. Cloud Server Dimensioning

In C-RAN part of the baseband processing is computed on top of commercial off-the-shelf (COTS) cloud servers which is virtualized to the BBU pools. In the virtualized BBU pool there are different virtual machines which handle non-real time baseband processing, this include user VM, cell VM, central eNB VM, and OAM VM. VNF requires at least one of this VMs to be operational, and redundant cell VMs and OAM VMs might be deployed as backup to guarantee higher availability. On the other hand, VMs also require a cloud server's processor cores as resources for their processes. The number of cloud servers required per VNF (S_{VNF}) can be calculated as:

$$S_{VNF} = \frac{VNF_{cellVM} * C_{cellVM} + VNF_{UEVM} * C_{UEVM} + C_{CVM} + C_{OAMVM}}{C_{server}} \quad (3.11)$$

VNF_{cellVM} and VNF_{UEVM} represents the total number of required virtual machines per VNF, C_{cellVM} , C_{UEVM} , C_{CVM} , and C_{OAMVM} represents the number of CPUs required in the virtual machines and C_{server} represents the number of CPUs per server. The required number of cloud servers in the network can then be calculated as:

$$N_{cloud\ servers} = S_{VNF} * VNF_{total} \quad (3.12)$$

Where S_{VNF} represents the cloud servers required per VNF and VNF_{total} represents total VNFs available in the network. Finally, other required hardware equipment such as switches, controllers and server racks can also be calculated in the bill of material.

CHAPTER FOUR

4. SYSTEM MODEL

The problem addressed by this work is the optimal deployment of BBU pools and its corresponding fronthaul network in urban scenario with already existing BSs and backhaul infrastructures; it also considers the minimum deployment cost and respecting different constraint. Signal propagation delays in the fronthaul and the existence of the processing delays in the BBU, makes the maximum separation between the RRH and BBU up to 40 km which is a barrier for C-RAN deployment.

Based on the network architecture, the split option chosen, the maximum number of fibers per link, the total number of wavelengths per fiber, maximum wavelength capacity, and maximum allowable fronthaul latency we will determine the number of required BBU pools while satisfying the network constraints.

4.1. MODEL IMPLEMENTATION

In this section, a high level view of the planned model is presented in the flow chart below which addresses BBU pools and fronthaul link dimensioning. Basically the model can be divided into four steps, a graphical overview being given in Figure 4.1, where ILP model formulation, simulation, BBU pool dimensioning, and positioning are the major tasks conducted in this work.

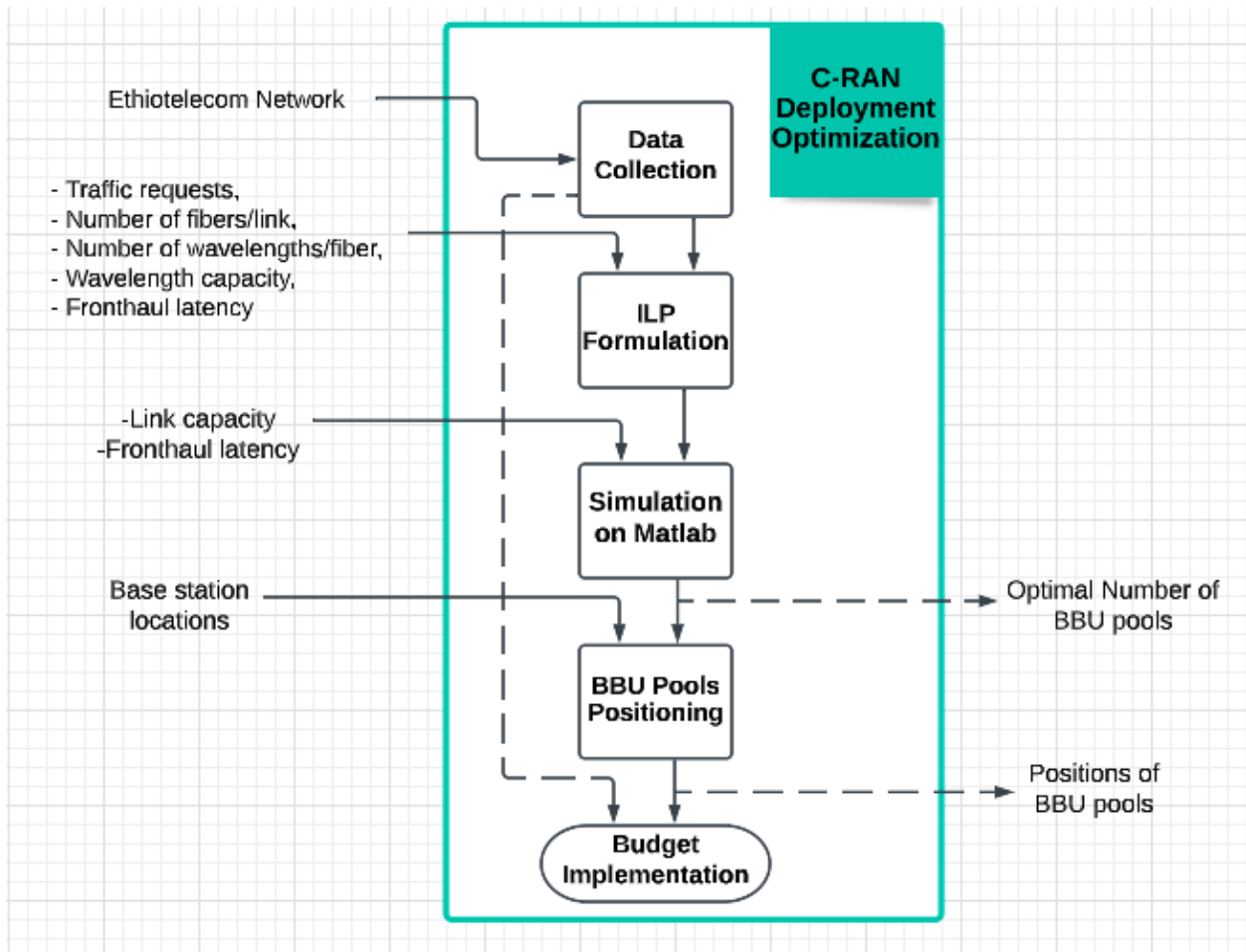


Figure 4. 1: System Model overview

Data Collection

Relevant data for the work will be collected both from primary and secondary sources, where the primary data is gathered from Ethiotelcom live network that includes cell site data, network configuration data, financial data, hardware and software data, while the secondary data is from different standards, publications, renowned company reports, and related works i.e., 3GPP, NGMN, IEEE articles and journals, ITU publications, and C-RAN deployment related dissertations and books.

ILP Model Formulation

To determine the optimal number of required BBU pools the research implements ILP model, which consisting of a network with 53 CSs and a single core CO. Further, only mobile and fronthaul traffic are carried through the network and latency dimensioning, BBU pool dimensioning, available link capacity, and the associated costs are also considered.

Simulation on MATLAB

After developing the ILP model the simulation were run on MATLAB, using intlinprog and results are expressed in terms of the number of BBU pools. The ILP model obtains optimal results, but its complexity scales with the network size and it will become more difficult to obtain a good result for larger networks in a reasonable time.

BBU Pool Positioning

After finding the optimal number of BBU pools for the chosen area appropriate locations should be determined to place the pool because not all the locations could be considered as best for the BBU pools placement. Therefore, the chosen place is expected to be able to host infrastructures required for a BBU pool.

Budget Calculation

Finally, after the BBU pools positioning step every cell site in the scenario is assumed to be associated with a BBU pool, and all BBU pools are positioned. Based on the required equipment, link and software licenses different costs such as hardware and software required at the BBU pool sites has been identified and calculated to estimate the required budget for the chosen site.

4.2. DEPLOYMENT COST REDUCTION TECHNIQUES

The deployment of the fronthaul links considers the links capacity and delay constraints which affects the link length. Substantial savings can be obtained by reusing the existing infrastructures and cascading links among RRHs for the connection to the serving BBU, and it is possible to minimize the total network cost in terms of fiber length per kilometers to be deployed since fiber rental or purchase represents a significant share of networking costs.

Moreover, available links between two sites can also be shared for connecting more than one RRHs to the same serving BBU, this allows for more effective use of the link capacity and reduce deployment costs, assuming each link serves only one BBU cluster at most [26].

Since CAPEX is the primary factor influencing the C-RAN design utilizing an existing fiber link instead of deploying a brand-new one will result in a significantly higher cost reduction. Two scenarios for fiber deployment were considered that is existing CSs having microwave backhaul link is assumed as a greenfield deployment scenario, and the optical infrastructure must be deployed through digging and roll-out operations, the second scenario is existing CSs having

fiber backhaul link is assumed as a brownfield deployment where the optical infrastructure is already partially deployed, hence it reduces the costs of fiber digging and roll-out.

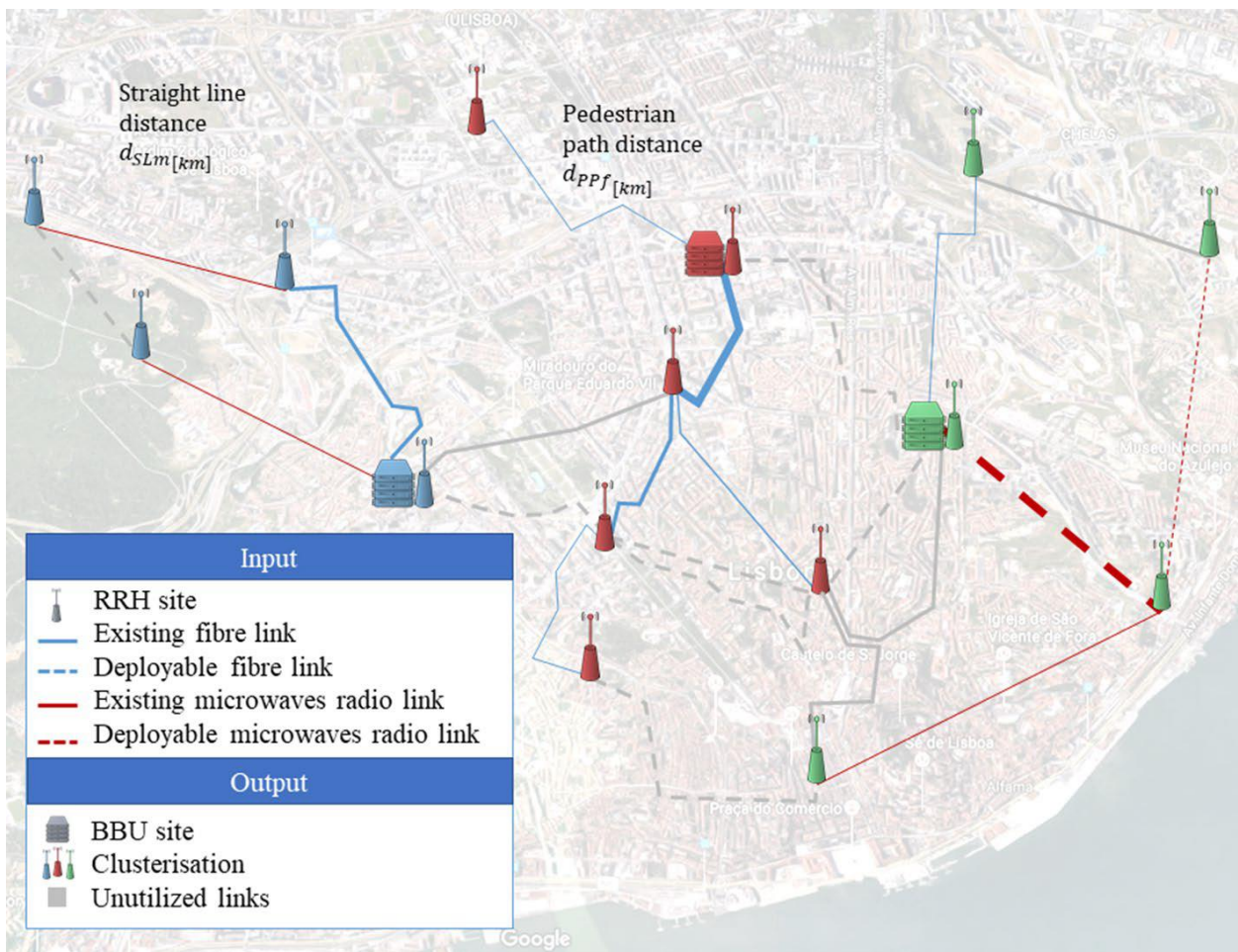


Figure 4. 2: Deployment scenario with microwave and fiber links [26]

4.3. BBU POOL DIMENSIONING

Here, an ILP optimization framework is established to plan a cost-optimal C-RAN deployment while satisfying network constraints. From a high-level perspective, the input parameters can be divided into three categories: Physical, related to the infrastructural deployment and to the physical constraints, Network, related to network planning, such as fronthaul delay, link capacity and BBU-RRHs connections, BBU pool processing capacity and economic: these inputs are related to deployment costs.

I. Input Parameters

The inputs given for the mathematical framework are: network topology, split option, traffic requests, maximum number of fibers per link, total number of wavelengths per fiber, maximum wavelength capacity (10 Gbps), maximum allowable fronthaul latency and positions of BSs in

ethiotelecom network are inputs used for the proposed mathematical model. For LTE network ethiotelecom is currently using a 2x2 MIMO, 10MHz bandwidth with 64-QAM, and a 4x4 MIMO, 20MHz and 64-QAM configuration [62]. The notations in the table are the input variables of the proposed optimization problem.

Table 4. 1: ILP input variables

Notations	Description
N	Set of nodes in the physical network
l_p	Fiber propagation delay
l_{EL}	Electronic switch delay
D	Maximum allowable fronthaul delay
W	Number of wavelengths per each physical link
C_r	Required capacity of a mobile request
w_i	Number of BBU pools
f_e	Number of fibers
K	Maximum number of link used
$C_{BBUpool}$	Processing capacity of the BBU pool
$C_{RRH,i}$	Processing capacity of RRH i

II. Expected Outputs

Optimal number of BBU pools for the selected area, possible BBU pool sites that satisfy the resource constraints. Moreover, placement of BBU pools so that each RRH is connected to two BBU pool one as the primary or working and the other is used as a backup.

III. Set of constraints [20], [22], [25], [28], [63]

- i. **Maximum allowable fronthaul delay:** As per 3GPP, SCF, and NGMN presented the maximum allowable optical fiber link distance between the RRH and its corresponding BBU depends on the maximum allowable one-way latency in the fronthaul, i.e., 250 μ s [42], [64]. This is affected by the RTT values of all components of the link in the fronthaul, the fiber propagation delay l_p and delay due to electronic switches l_{EL} should be less than or equal to the total allowable fronthaul latency. Each

RRH should be connected to a BBU with a series of physical links that introduce a delay lower than the maximum allowable one [28].

$$\sum_{p \in P} (l_p + l_{EL}) y_p^{-r} + l_{EL} \leq D, \forall_n \in N_M, r \in R_C^n$$

(4.1)

ii. **Wireless interface delay** [20];

$$\delta_{U,R} = 2 * \frac{r}{c} * 10^3 \mu s$$

(4.2)

Where, the 2 factor represents UL and DL RRT between the RRH and user, r is distance between the RRH and UE, and c is speed of light in vacuum. Shows the linear increment of 6.7 $\mu s/km$.

iii. **Links capacity**: The sum capacity of all requests that are routed through a particular virtual link is less than the capacity of that virtual link. It ensures that the sum of virtual link's capacity should not exceed the total capacity of the requests routed through it [25].

$$\sum_{r \in R_M} C_r y_v^r + \sum_{r \in R_C} \sum_{p \in P_v} C_r y_p^r \leq \sum_{p \in P_v} \sum_{\lambda \in A} C_{U_{p\lambda}}, \forall_v \in V.$$

(4.3)

C_r represents mobile requests capacity, and the first term of the left-hand side represents the sum of mobile requests capacity that are routed through virtual link v, the second terms represents request capacity, and the right hand side is the maximum capacities of the virtual link v, for all available wavelengths.

iv. **Fibers deployment and upper bound (Fiber availability constraint)**

Since the transmitting medium used to connect BBUs with RRHs is fiber, this constraint first establishes light paths or the number of fibers used in each link, i.e., $f_e = \max_{\lambda} \sum_p U_{p\lambda}$, then limits this number to the upper bound K. The output is the set of connections between RRH sites and BBU pools [28].

$$\sum_{p \in P^e} U_{p\lambda} \leq f_e \leq K, \forall e \in E, \lambda \in \Lambda$$

(4.4)

v. BBU limit [25]:

Each node must be associated with exactly one BBU,

$$\sum_{i \in N} x_i^n = 1, \forall n \in N_M.$$

(4.5)

vi. BBU association [28]:

Identify hotels as nodes which host at least one BBU, only a deployed BBU pool at i^{th} node can host a BBU for n ,

$$w_i \geq x_i^n, \forall n \in N_M, i \in N$$

(4.6)

vii. BBU processing capacity constraint [65]:

The capacity supported by a BBU pool depends on the number and capacity of links connected to the site. Each RRH has a traffic processing demand, and each BBU pool is equipped with a certain capacity to serve all the traffics comes from the RRHs, hence the sum of processing capacities of RRHs connected to the BBU pool should not exceed the processing capacity of the pool.

$$\sum_{i=1}^{N_{CRRH}} C_{RRH,i} \leq C_{BBU\text{pool}}$$

(4.7)

Where: N_{CRRH} represents the number of RRHs that is connected to the BBU pool, $C_{RRH,i}$: capacity of the i^{th} RRH expressed in terms of link capacity or processing power. According to [66], the maximum processing capacity of a BBU pool can be 2Tbps to 5Tbps.

viii. Protection for BBU pool failures [22]:

A C-RAN should be designed with a protection, as a BBU pool failure can cause service outage for a large serving area with a significant number of users, hence increasing reliability is typically

accomplished through redundancy, we propose a resilient C-RAN where each RRH is connected to two BBU pools, i.e., one served as a working (primary) pool and the second one used as a backup (secondary) pool. Moreover, mobile network operators have to choose BBU equipment from several cloud providers with less failure probability.

$$\sum_i X_{i,m} = 1, \quad \forall_m$$

(4.8)

$$\sum_j Z_{j,m} = 1, \quad \forall_m$$

(4.9)

$$X_{i,m} + Z_{i,m} \leq 1, \quad \forall_i, \forall_m$$

(4.10)

IV. Optimization Problem (Multi objective cost function)

Since the main objective of the proposed model is to minimize the total deployment cost of the C-RAN, where the cost of the network is highly dependent on the total number of BBU pools and the total number of fibers, the multi objective optimization function is given in (eq. 4.11), where the first term is to minimize total number of BBU pools whereas the second term is to minimize total number of optical fibers and α, β are weights of each objective which are tunable to select the primary objective of the optimization such that $\alpha, \beta \in [0, 1]$.

$$F = \alpha \sum_{i \in N} w_i + \beta \sum_{e \in E} fe$$

(4.11)

$$LPP : \min F \quad s.t. \text{ Constraints (4.1) – (4.10)},$$

Below there are additional explanations of our approach to the problem:

- We assumed that the maximum link capacity available for this work is 0.2 Tbps, which corresponds to 20 channels each at 10 Gbps in optical TWDM PON networks.
- As a performance metrics, the research has considered number of BBU pools, which quantifies the degree of BBU consolidation, and latency, link capacity and economical cost.

- We also consider the costs associated with deploying BBU pools, such as the cost of hardware, software, and links.
- To reduce the total C-RAN deployment costs, either the total number of BBU pools or fibers deployed in the network should be minimized, but higher weight is given for minimizing number of BBU pools.
- Moreover, the maximum processing capacity of the cloud is 80 RRHs and up to 20 wave lengths each with 10 Gbps capacity [30].

The locations of the RRHs/CSs can be taken as input for BBU pool hosting to compute the optimal positions and required number of BBU pools is the output by considering the fronthaul delay constraint including HARQ time and deployment costs into account. Since, all the positions cannot be considered as optimal places to host BBU pool, the position should be able to meet delay constraints and infrastructures required to host BBU pool [20].

4.4. BUDGET CALCULATIONS

In this subsection we will see the business aspect of a C-RAN architecture. CAPEX refers to the costs of setting up a network for the infrastructure and equipment (installation and purchase) expenses, including investments for BBM hardware, cloud server hardware and software licenses, while OPEX refers to cost of running the network. The CAPEX is based on the bill of materials, and financial data [14]. It is assumed that the costs are a constant costs that needs to be paid when deploying the BBU pools and the required links. Below there are different assumptions taken for the BBU pool planning process;

- The price of baseband software is assumed to be the same, or more in Cloud RAN due to lower number of baseband hardware is required for cloud based RAN.
- It is assumed that the RF hardware cost is the same for both the D-RAN and Cloud-RAN.
- Since ethiotelecom has its own data centers there is no cost for the rent of point of presence floor space and data center cabinet rental fees.
- Since a functional split is considered in the work, the fronthaul cost in the Cloud-RAN is assumed to be the same as the backhaul cost in the distributed RAN.
- The fiber used is unidirectional, where 1 core for Tx and the other for Rx.

- Existing BSs with microwave backhaul is assumed in the green field deployment of fiber; hence, digging and roll-out activities are required to install the optical infrastructure. However, in the brownfield case existing BSs with fiber backhaul is assumed; hence, the optical infrastructure is already partially deployed, and it reduces the costs of fiber digging and roll-out.

4.4.1. Power Consumption Model for C-RAN architecture

The power consumption of a C-RAN architecture is determined by three components, namely the power consumption of the base station, ONU, and DU pool. In C-RAN the OLT modules in the CO are shared among several RUs.

$$P_{CRAN} = N_{BS}(P_{BS} + P_{ONU}) + N_{pool}P_{pool} \quad (4.12)$$

Where N_{BS} , and N_{pool} is the number of BSs and number of BBU pool respectively, P_{BS} is power consumption of BS.

$$P_{pool} = N_{DU}(P_{proc} + P_{OLT}) + P_{cool} \quad (4.13)$$

Table 4. 2: Power consumption parameters [30], [67]

Parameter	Cost [Watt]
P_{proc}	100
P_{cool}	500
P_{ONU}	3.4
P_{OLT}	100
P_{LC}	5
vBBU	20
Total	728.4

In section 3.6, we identified the components required to implement the C-RAN architecture. Table 4.3 summarizes the different cost components used in this architecture.

Table 4. 3: Assumed Cost Values [10], [68], [69]

No.	Components	Cost [K\$]
1	Capacity unit (CAP)	50
2	Common plug-in unit (COM)	20
3	Cabinet unit (CBN)	5
4	Baseband software (BBSW)	10
5	Baseband module license (BBM)	8
6	Cloud Hardware	200
7	Cloud Software	55
8	Cost of trenching per km	0.856
9	Fiber rollout per km	4.18
10	Fiber cost per km for a pair of fiber (12 Core)	0.493
11	Fiber cost per km (G652, 24 core)	0.62
12	Fiber cost per km for a pair of fiber (48 Core)	1.037
13	Optical Network Unit (ONU)	0.275
14	Passive Splitter	0.11
15	Arrayed Waveguide Gratings (AWG) filters	0.275
16	Optical Line Terminal (OLT) access module	7.15
17	OLT shelf	38.5
18	Annual OAM	10% of equipment

Note: Fiber trenching, and rollout costs are not considered for brownfield scenario.

4.4.2. CAPEX Calculation

The initial investment costs for the MNOs such as BBU pool build-out, different equipment costs are considered in the CAPEX.

$$\begin{aligned}
 CAPEX = N_P \sum (C_{BBM} + C_{BBSW} + C_{BBLC} + C_{CHW} + C_{CSW} + C_{ONU}) + L_f C_f + N_f C_f + N_{oltm} C_{oltm} \\
 + N_{olt} C_{olt} + N_{awg} C_{awg}
 \end{aligned}$$

(4.14)

Where N_p is the number of pools is C_{BBM} represents the cost for BBM hardware, C_{BBSW} is baseband software cost, C_{BBLC} is baseband license cost, C_{CHW} represents cloud hardware cost, and C_{CSW} is the cost for cloud software [14]. L_f is the total fiber length, C_f is cost for fiber per km, N_f is the number of fiber, C_{otlm} , C_{olt} , C_{awg} are the costs for OLT module, shelf, and AWG, N_{otlm} , N_{olt} , N_{awg} are the number of Optical Line Terminal (OLT) module, shelf, and Arrayed Waveguide Gratings filters. CAPEX is mainly influenced by the number of require BBU pools [26]. For the link deployment it is assumed to use the existing infrastructure hence no digging and rollout costs assumed.

4.4.3. OPEX Calculation

The OPEX considered in this work are operation and maintenance (OAM) costs, and electric bills, where the annual electric bills are derived from the power model by assuming electric price 0.022 \$/kWh.

$$OPEX = N_p (C_{EL} P_{pool}) + N_{CS} (C_{EL} P_{ONU}) + C_{OAM} \quad (4.15)$$

Where N_p and N_{CS} are the number of BBU pools and cell sites respectively, C_{EL} is the electricity cost, P_{pool} and P_{ONU} are the power consumption of the BBU pool and ONU, and C_{OAM} is the cost of operation and maintenance. The power consumption of the pool can be defined as [67]:

$$P_{pool} = N_{pool} (P_{proc} + P_{OLT}) + P_{Cool} \quad (4.16)$$

Where P_{proc} denotes the processing power consumption of each digital unit, P_{OLT} represents the power consumption of OLT module, and P_{Cool} denotes the power consumption of the air cooling unit.

To estimate the annual power consumption costs (P_T) for the baseband processing hardware we use eq. (4.17) [14]:

$$P_T = \sum_i (P_i * n_i) \quad (4.17)$$

Where $i \in$ power consuming network elements, such as CAP, COM, CAB etc., n_i is the number of power-consuming network element i , P_i is the power consumption of i .

Therefore, the annual energy consumption in kWh can be computed as:

$$E_T = \frac{P_T}{1000} * \frac{\text{Hrs}}{\text{Day}} * \frac{\text{Days}}{\text{Year}}$$

(4.18)

Where P_T is annual power-consumption by the network elements in watt. The annual energy cost C_E can be computed as shown in Eq. (4.18):

$$C_E = E_T * C_{kWh}$$

(4.19)

Where E_T is the annual total energy consumption in kWh, C_{kWh} is the cost of energy per kWh.

4.4.4. TCO

Total cost of ownership (TCO), is the sum of all the costs associated with owning and operating an asset.

$$TCO = CAPEX + OPEX$$

(4.20)

CHAPTER FIVE

5. NUMERICAL RESULTS AND DISCUSSIONS

5.1. SIMULATION SETTING

We consider an optical transport network having 53 cell sites distributed over a dense urban region of 10km² around bole international airport as shown in figure 5.1. The core site is the primary choice for placing the BBU pools, and in our scenario it's located at site ID: 111136.



Figure 5. 1: Network topology consisting macro cells

Further, we will compare and discuss different numerical results that are computed with and without considering cell radius effect. To benefit from the cost reduction in the fronthaul link, and keep the centralization benefits the research assumed functional split 7.2, which require 9.8 Gbps fronthaul bitrate in the DL and 15.2Gbps in the UL. The ILP simulation were run on MATLAB optimization toolbox 2022b version on Core i7 Intel Processor, 8GB RAM on Windows 10 operating system and 64-bit Laptop.

The objective of the optimization problem is to reduce the overall cost of deployment while also satisfying necessary QoS and keep network constraints: this is done primarily by minimizing the number of BBU pools, and minimizing the number of wavelengths per fiber link, where we take alpha to be 0.9. Moreover, each cell site has 1 BBU, hence the maximum number of required BBU pools can be 53, while the minimum value is 2 corresponding to 1 BBU pool serving as a primary site, and the second as a backup. It's assumed that fiber propagation delay per km is $10\mu\text{s}$, and each electronic switch has a delay of $20\mu\text{s}$.

Both mobile and fronthaul traffics are carried through the network, and all the ILP outputs are obtained in terms of the number of BBU pools which is also taken as a performance metric. Furthermore, we evaluate the impact of wireless interface delay or cell radius on BBU centralization. All RRHs are connected to the BBU pool via optical fiber links with a maximum of two fibers per link, and a maximum of 20 wavelengths per fiber is available at 10 Gbps each. It's also assumed that four RRHs are connected to a multi-port ONU.

5.1.1. General Deployment Consideration

Fiber links are installed into cable ducts that are constructed in a way to be easily accessible for maintenance such as along streets. On the other hand, for the greenfield deployment scenario the new connection between BBU pools and it's corresponding RRHs, shortest path distance along a pedestrian path is preferable instead of straight line distance, this is because fiber digging is a very difficult, time taking, and costly task for MNOs, thus reusing the already existing access infrastructures will highly reduce the required cost for connecting links, and helps to achieve a cost-optimal BBU pool deployment. To evaluate the proposed optimization model we consider three scenarios i.e., very low, low, and high fronthaul latencies.

5.2. RESULTS FOR VERY LOW FRONTHAUL LATENCY VALUES

In this subsection, we evaluate the proposed optimization model by considering very low latency values with in the ranges $[3\mu\text{s}, 20\mu\text{s}]$, where the optimization goal is minimizing the number of BBU pools by relaxing the number of wavelengths (W) used per fiber, and r represents cell radius.

Table 5. 1: Required number of BBU pools for $r = 6\text{km}$, and very low latency values

Latency (μs)	Number of BBU pools, $W=36$		Number of BBU pools, $W=10$		Remark
	Without cell radius effect	With cell radius effect	Without cell radius effect	With cell radius effect	
3	47	47	47	47	Same
4	35	36	35	36	1
5	28	29	28	29	1
6	24	24	24	24	Same
7	20	21	20	21	1
8	18	18	18	18	Same
9	16	16	16	16	Same
10	14	15	14	15	1
11	13	13	13	13	Same
12	12	12	12	12	Same
13	11	11	11	11	Same
14	10	11	10	11	1
15	10	10	10	10	Same
20	7	8	7	8	1

The above table shows the impact of wireless interface delay on the required number of BBU pools at cell radius $r = 6\text{km}$, and very low latency values. Results show that for the same fronthaul latency values, one additional BBU pool is required when the wireless interface delay is considered in the planning process. On the other hand, at very low fronthaul latency values decreasing or relaxing the number of wavelengths used per fiber has no impact on the required number of BBU pools, however, a small variation in the fronthaul latency values can lead to a different maximum number of BBU pools. Therefore, for very small fronthaul delay values, it is recommended to use fewer wavelengths per fiber. Figure 5.2 summarizes the required number of BBU pools and the impact of cell radius on BBU centralization at very low latency values, where the maximum BBU centralization achieved in this case is 8 occurred at $L=20\mu\text{s}$.

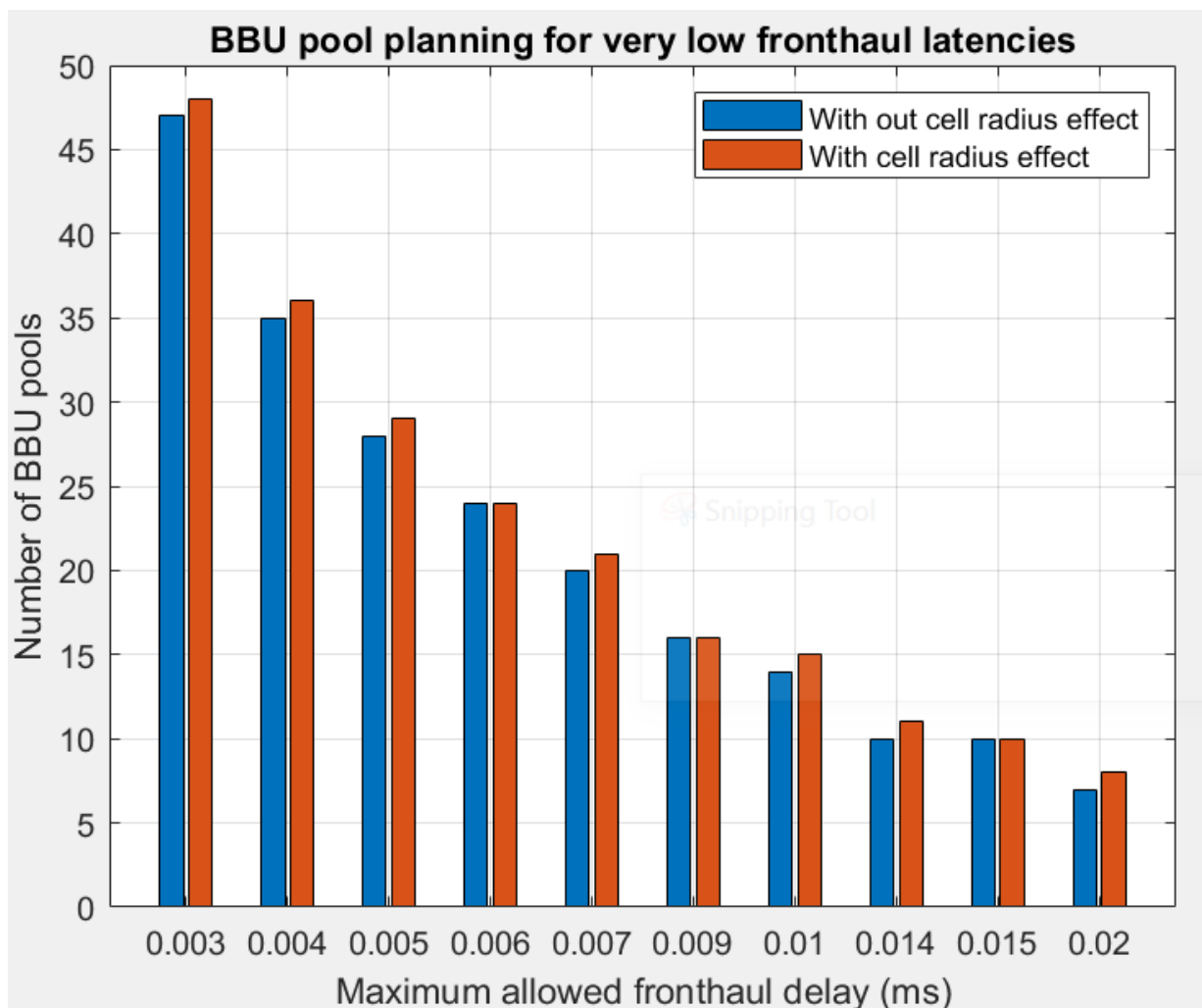


Figure 5. 2: Impact of wireless interface delay on BBU centralization for very low latency values

For minimum delay values, most of the BBUs are located closer to the RRHs, hence, less BBU centralization is takes place. Furthermore, the existence of low latency values in the fronthaul network is another cost for MNOs because it requires extra costs in terms of additional BBU pools. However, it's useful for future 5G deployments.

5.3. RESULTS FOR LOW LATENCY VALUES

In the second scenario, let's evaluate how the proposed optimization model performs when considering low latency values and varying them in different ranges, i.e., [25 μ s, 100 μ s].

Table 5. 2: Required number of BBU pools for low latency values

Latency (μ s)	Number of BBU pools, W=36		Number of BBU pools, W=10		Remarks
	Without cell radius effect	With cell radius effect	Without cell radius effect	With cell radius effect	
25	6	6	6	6	Same
30	5	5	5	5	Same
35	4	5	4	5	1
40	4	4	4	4	Same
45	4	4	4	4	Same
50	3	3	4	4	Same
60	3	3	4	4	Same
70	2	3	4	4	1
80	2	2	4	4	Same
90	2	2	4	4	Same
100	2	2	4	4	Same

For low fronthaul latency values [25 μ s to 100 μ s], a slight impact of wireless interface delay on BBU centralization is shown at 35 μ s and 70 μ s latency values, and when relaxing the number of wavelengths more BBUs can be centralized both in the case of considering and neglecting the cell radius impact. The higher BBU consolidation achieved in this scenario is 2 occurred at W=36 and fronthaul latency values above 80 μ s. However, for W=10 the maximum BBU centralization achieved is 4, this is due the fact that minimizing the number of wavelengths per fiber will lead to a decrease in the overall capacity of the optical network that couldn't handle the mobile and fronthaul traffics passing through the link. Therefore, as the allowable fronthaul delay increased minimizing the number of wavelengths per link has negative impact on BBU centralization.

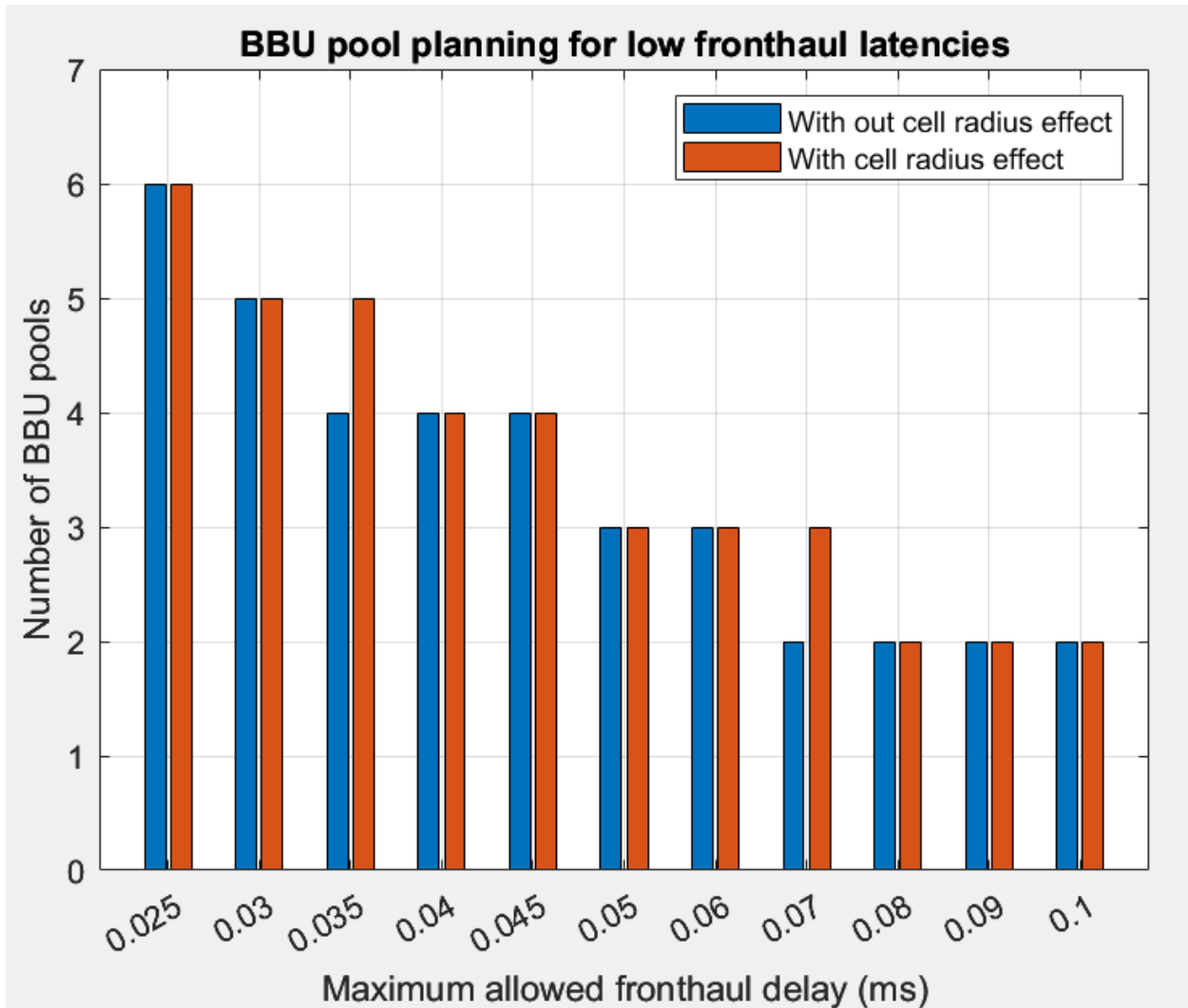


Figure 5. 3: Impact of wireless interface delay on BBU centralization for low latencies

In general, as the allowable fronthaul latency is relaxed further, more BBUs can be consolidated into BBU pools, for example, when the fronthaul latency is relaxed from 25 μ s to 100 μ s the required number of BBU pools decreases from 8 to 2. This is because the relaxed fronthaul latency allows for more BBUs to be shared between RRHs, which reduces the overall cost of the network.

5.4. RESULTS FOR HIGH LATENCY VALUES

In the third scenario, we evaluate the proposed optimization model for higher latency values, i.e., [110 μ s, 200 μ s].

Table 5. 3: Required number of BBU pools for high latency values

Latency (μ s)	Number of BBU pools, W=36		Number of BBU pools, W=10		Remarks
	Without cell radius effect	With cell radius effect	Without cell radius effect	With cell radius effect	
110	2	2	4	4	Same
120	2	2	4	4	Same
130	2	2	4	4	Same
140	1	2	4	4	1
150	1	1	4	4	Same
200	1	1	4	4	Same

For high fronthaul latency values a slight impact of the wireless interface delay on BBU centralization is shown at L=140 μ s. Moreover, considering higher delay values will also reduce the required deployment CAPEX. For higher values of W, where there is no capacity constraint in the link, and relaxed FH latencies the BBU pools can be placed at longer distances from their respective cell sites, therefore, a significantly higher BBU centralization is achieved for W=36 and with a latency above 150 μ s. on the other hand, minimizing the number of wavelengths used per fiber will lead to an increase in the BBU pool requirement.

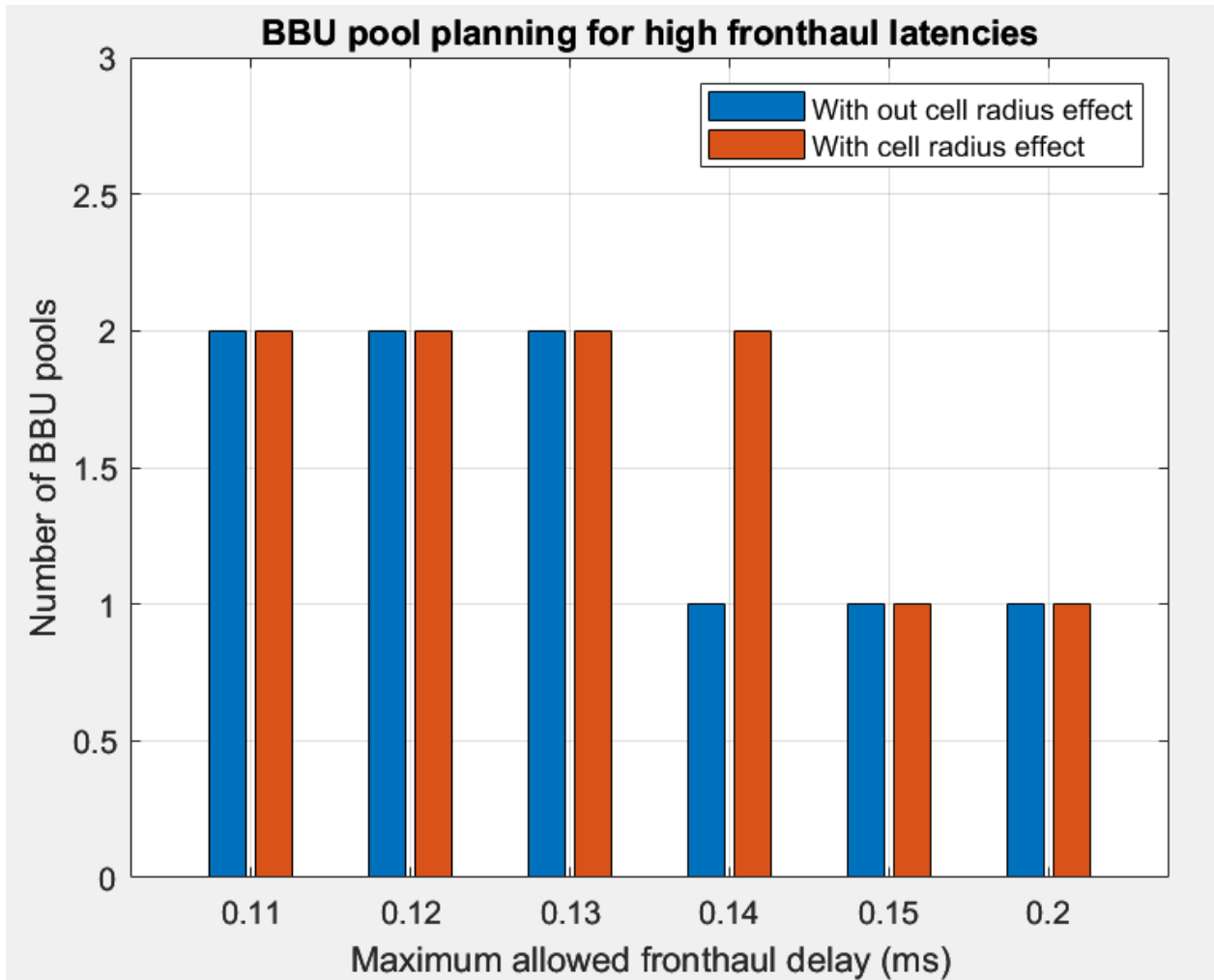


Figure 5. 4: Impact of wireless interface delay on BBU centralization for higher latencies

Generally, the simulation result for the third scenario show that by relaxing the FH latency and number of wavelengths used per fiber it is possible to achieve complete BBU centralization so that all of RRHs in the cluster can be served by a single BBU pool. However, deploying a single BBU pool for the entire area may create a single point of failure that could cause outages for a large number of users, hence, a better approach is to use a minimum of two BBU pools, this is because each RRH in the cluster will be connected to two BBU pools, where one BBU pool serving as a working pool and the other pool serving as a backup. This configuration provides redundancy and improves the overall system reliability. In the following we limit the maximum number of wavelengths used per fiber up to $W=20$.

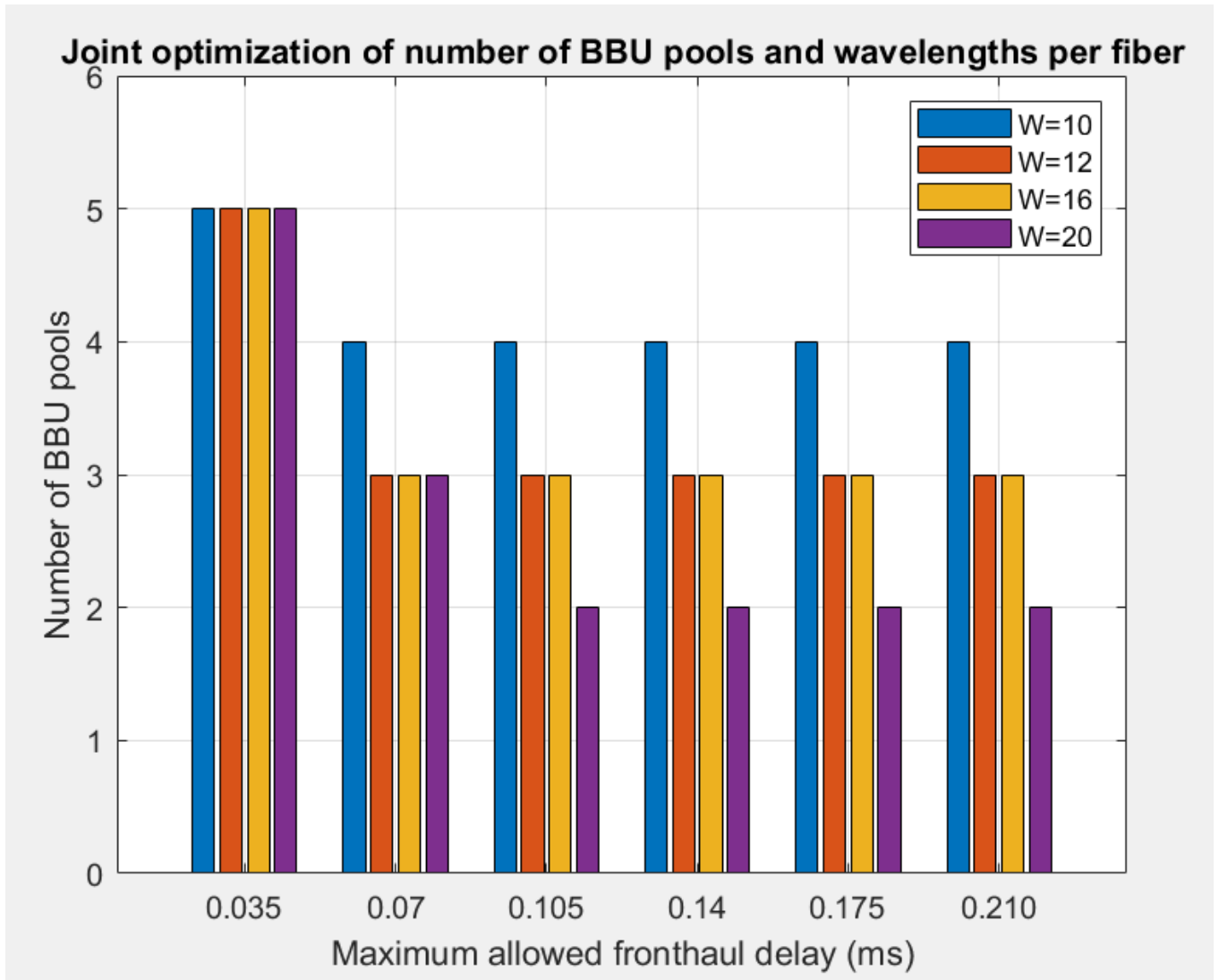


Figure 5. 5: Joint optimization of BBU pools and wavelengths per fiber

The above figure shows an inverse relationship between the maximum allowable fronthaul delay and the required number of BBU pools. The figure also shows an inverse proportional relationship between the available wavelengths per link and the number of BBU pools. This is because a smaller number of available wavelengths per link means that each BBU pool can support fewer RRHs, which requires more BBU pools to accommodate all of the RRHs. This is important to consider when designing a fronthaul network. On the other hand, a minimum of $W=10$ is required to start BBU centralization because the available capacity in the links is not enough to support the fronthaul traffic and the traffic generated by each RU.

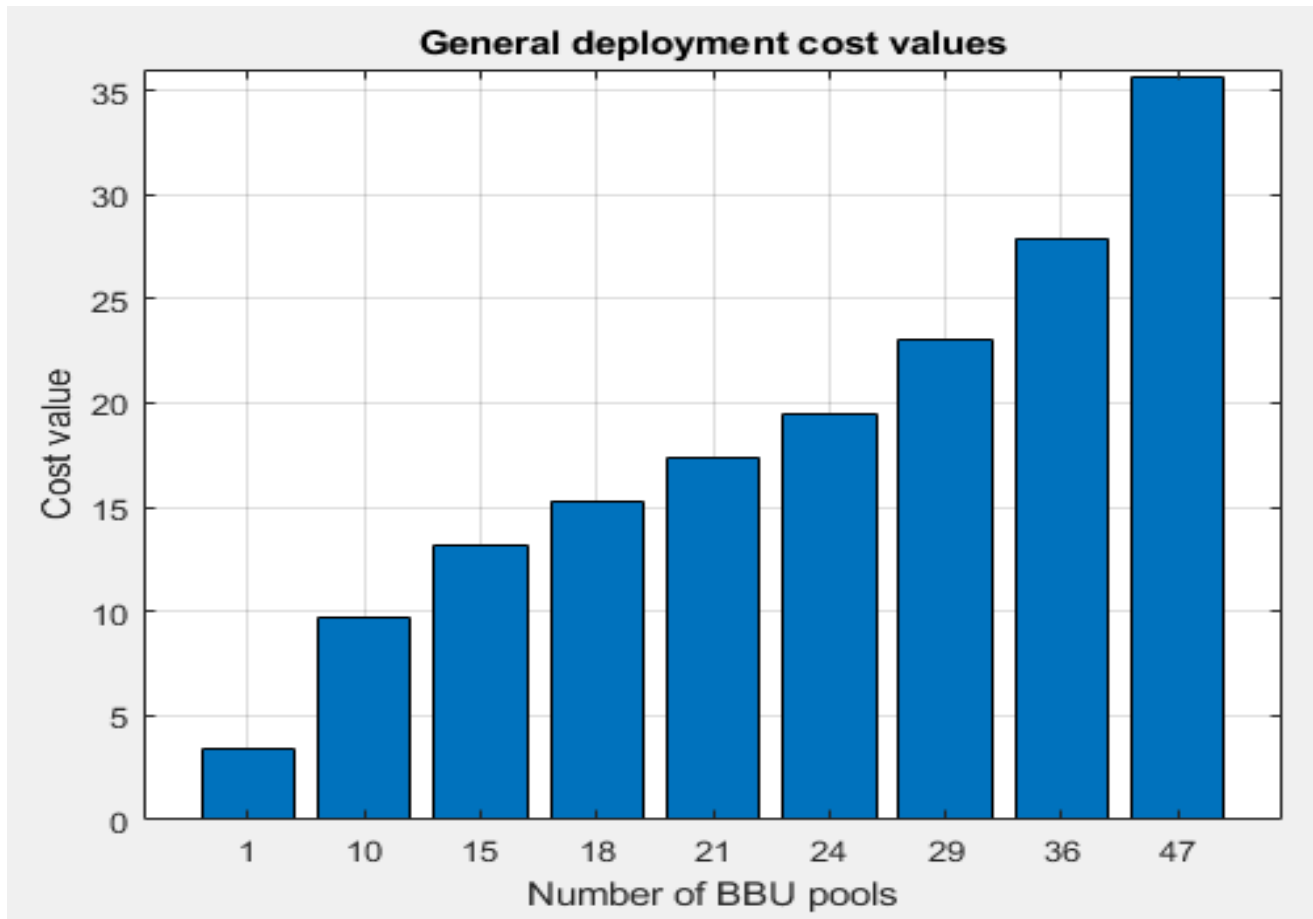


Figure 5. 6: General overview for the cost values

Moreover, in the case of joint minimization of the BBU pool and fiber case, the performance has been deteriorated for the same latency values. This is because additional BBU pools are required while minimizing the link capacity. The reason for this is that when the link capacity is minimized, the available bandwidth in the fronthaul is also minimized, hence, more BBU pools are required to support the same amount of traffic. Achieving a higher BBU centralization ultimately means highly minimizing the required network cost. This is because the CAPEX is highly influenced by the number of BBU pools, where a lower number of BBU pools means a lower CAPEX.

Figure 5.6 shows the general deployment cost, where the cost of a BBU pool is a more significant factor in the overall cost of the network than the cost of fiber links, because the cost of a BBU pool is much greater than the cost of fiber links, so the objective of minimizing the number of BBU pools is given a higher weight than the objective of minimizing the number of fiber links.

5.5. RESULT AND ANALYSIS FOR DIFFERENT USE CASES

As discussed in chapter 3, the end-to-end latency for 5G networks varies depending on the type of application being used. For example, URLLC applications require an end-to-end latency of less than 0.5 milliseconds for both UL and DL. Tactile internet, industrial networking or smart cities, and factory automation applications require an end-to-end latency of less than 1 millisecond for both UL and DL, on the other hand, eMBB applications have a relaxed latency requirement of 4 milliseconds for both UL and DL. The 5G URLLC requirements place a high emphasis on latency, making it even more important to minimize the fronthaul latency. Moreover, the fronthaul latency is a critical performance metric for URLLC and critical machine type communication services, because it can directly impact the end-to-end latency of these applications, hence, latency-sensitive applications require fronthaul latency below 75 microseconds. In order to support this latency critical applications and to maintain the latency requirement under 75 μ s, the fiber length in the fronthaul should not be longer than 15 kilometers. This is because the latency of the fronthaul link is proportional to the length of the fiber. Table 5.4 summarizes the required number of BBU pools for different service categories.

Table 5. 4: Required number of BBU pools for different use cases

Use cases	FH latency (μ s)	No. of BBU pools
Ultra low latency performance	25	6
URLLC	35	5
Real-time functions:- voice over LTE, IoT, tactile applications	50-70	3
For full E-UTRA or NR performance	100	2
-For installations where the lengths of fiber links are in the 40 km range -Non real time functions: web browsing and email.	200	2

CHAPTER SIX

6. CONCLUSION AND FUTURE WORK

6.1. CONCLUSION

C-RAN splits the traditional base stations into two physical entities, i.e., the radio unit and central unit, following this separation a new interface called fronthaul is introduced. As the centralization of functions varies, split option 7.2 is selected for the research as it offers the best trade-off between key centralization benefits, required fronthaul bandwidth, RU complexity, and inter-cell cooperation. An ILP optimization model was used to design a C-RAN deployment in a brownfield scenario where the model take into account the wireless interface delay when determining the delay budget. The model is evaluated in three different scenarios: very low, low, and high fronthaul latency values. Simulation results reveal that for very low fronthaul latency values the wireless interface delay has a higher impact on BBU centralization because for the same fronthaul latency values, one additional BBU pool is required when wireless interface delay is considered in the planning process. On the other hand, it has a slight impact on low and high fronthaul delay values, therefore wireless interface delay must be considered when planning for BBU pools, especially for very low latency values. This is because one additional BBU pool is required when the wireless interface delay is considered in the planning process. For very low fronthaul latency values, the number of wavelengths used per fiber has no impact on the required number of BBU pools, however for low and high latency values minimizing the number of wavelengths per link has a negative impact on BBU centralization. Therefore, for very small fronthaul delay values, it is recommended to use fewer wavelengths per fiber.

Another important consideration when designing a fronthaul network is the trade-off between the degree of centralization, the tight latency requirement (L), and available link capacity (W), because at a higher latency with no wavelength constraints higher degree of BBU centralization or even complete centralization can be achieved for $W = 36$ and $L > 150\mu s$. However, deploying a single BBU pool for the entire area may create a single point of failure which can cause service outages for a large serving area with a significant number of users, hence, we assume that each RRH in the cluster is connected to two BBU pools, where one BBU pool served as a primary

baseband processing unit, while the other will be used as a backup. This configuration provides redundancy and improves the overall system reliability.

On the other hand, cost is related to latency variation, and fronthaul bandwidth, where the lowest fronthaul latencies require additional CAPEX given the higher number of required BBU pools, and a small variation is related to the different maximum number of BBU pools. Furthermore, considering higher delay values until the processing capacity limitation of the BBU pool will reduce the required deployment CAPEX, given fewer BBU pools are required to serve all the RRHs. Therefore, choosing lower delay values in the fronthaul requires a higher cost for MNOs, however, it makes the deployment ready for the future evolution of technologies. Since CAPEX variation is mainly influenced by the number of BBU pools more weight has been given for minimizing the number of BBU pools instead of minimizing the number of wavelengths per fiber. It is also assumed that existing fiber infrastructure is reused and, the minimum cost for a single BBU pool deployment is estimated to be 447.55K\$.

Since, the end-to-end latency for 5G networks depends on the type of application being used, and the latency in the fronthaul can directly impact the end-to-end latency, use cases such as URLLC services require 5 BBU pools, real-time functions such as voice over LTE, tactile applications require 3 BBU pools while for latency insensitive applications 2 BBU pools are required for the chosen area to meet the required performance requirements.

6.2. FUTURE WORK

- Joint planning of an optimal C-RAN deployment and 5G network.
- Optimal BBU pool planning over converged high capacity wireless, and optical fiber link as a fronthaul (suburban and rural).
- BBU pool planning using fixed-mobile convergence (FMC) traffic, in the context of ethiotelecom network, i.e., the concept of designing and optimizing networks as a whole, using shared infrastructure and equipment between fixed and mobile networks.

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APPENDICES

Table 1: RAN functional split requirements

Split option	Required bandwidth in the Fronthaul	Max. allowed one way latency
1	4Gb/s (DL) 3Gb/s (UL)	10ms
2	4016Mb/s (DL) 3024 Mb/s (UL)	1.5-10ms
3	< option 2 for UL/DL	1.5-10ms
4	4000Mb/s (DL) 3000Mb/s (UL)	approximate 100 μ s
5	4000Mb/s (DL) 3000 Mb/s (UL)	hundreds of μ s
6	4133Mb/s (DL) 5640 Mb/s (UL)	250 μ s
7a	10.1~22.2Gb/s (DL) 16.6~21.6Gb/s (UL)	250 μ s
7b	37.8~86.1Gb/s (DL) 53.8~86.1Gb/s (UL)	250 μ s
7c	10.1~22.2Gb/s (DL) 53.8~86.1Gb/s (UL)	250 μ s
8	157.3Gb/s (DL/ UL)	250 μ s

ILP Based Optimal BBU Pool Planning for Cloud-RAN Deployment: in the Context of Ethio telecom

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Abstract—Cloud radio access network (C-RAN) is a novel mobile network architecture that decouples the baseband units (BBUs) from their corresponding cell sites and takes the baseband processing unit to a virtualized and shared central location. This increases wireless networks' scalability, manageability, and significantly saves both the capital and operational costs of mobile network operators (MNOs). Although this BBU centralization enables power savings, it imposes much higher bandwidth on the fronthaul network. Since with distributed radio access network (D-RAN) there is a higher building, maintenance and operational costs there should be a RAN architectural change, and in addition to previously done researches in this area this thesis comprise the impact of wireless interface delay on BBU centralization. We investigate the optimal planning of BBU pools for C-RAN deployment in the context of Ethio telecom and shows how to optimally determine the required number of BBU pools for different use cases using an integer linear programming (ILP) optimization problem and calculates the required budget to deploy a single BBU pool. We also figure out which functional split is cost-effective for fronthaul networks while providing the centralization benefits. Simulation results show that the wireless interface delay has an impact on BBU centralization therefore it should be considered in the BBU pool planning process. On the other hand, the number of BBU pools required varies depending on the use cases considered, hence for the chosen area ultra-reliable and low latency communication (URLLC) services require 5 BBU pools, real-time functions such as voice over long-term evolution (VoLTE) require 3 BBU pools; in contrast latency-insensitive applications, such as email 2 BBU pools are sufficient to meet the required performance requirements. Furthermore, split option 7.2 was selected for the research as it was found to be the most cost-effective and performance-efficient option.

Keywords— BBU Centralization, C-RAN, Fronthaul network, Functional split, ILP, Wireless interface delay.

I. INTRODUCTION

A. MOTIVATIONS

Major service categories of 5G such as eMBB, mMTC, and URLLC have a wide range of performance requirements and traffic profiles. Operators require highly scalable and flexible networks to serve these new markets and significantly increase revenues. The ability to support these new use cases is related to cloud RAN development [1]. Among the key enabling technologies that help to meet these requirements C-RAN is the one and it is a viable solution to meet the capacity requirements while at the same time addressing the scalability issues related to processing power [2]. In C-RAN, all BBUs are separated from their corresponding RRHs and pooled to a centralized, shared, and virtualized BBU pool, hence the cell sites with the antenna and remote radio heads (RRHs) are connected to its

corresponding BBU pool through a high capacity fronthaul link [3]. Hence, the baseband resources in the BBU pool and the central processor will be shared with all connected RRHs and a significant reduction in the overall computational resources can be achieved due to multiplexing gain. Since facilities are shared in the central place lower lease and energy costs, lower management and maintenance expenses, and improved RAN performance i.e., enhanced network throughput due to advanced joint processing [4]. It also significantly reduces CAPEX and OPEX costs, and power consumption of operators and simplifies the network architecture allowing faster large-scale deployments. It is also recommended to deploy C-RAN in metropolitan areas to benefit from the statistical multiplexing gains as users move throughout the day while staying within the maximum distance up to 40 km between RRH and BBU pool, and it is more promising for small scale deployments for urban areas with densely placed cells [5].

Base stations are the highest power consumer in wireless access networks, and with D-RAN there is a higher building, maintenance and operational costs, again BS resources can't be shared among other BSs located in other geographical areas due to that there exists over-dimensioning of base stations. The HARQ is an error detection and correction techniques that improve the reliability of data transmission between a UE and eNodeB and it is a candidate protocol for NGN to be used in C-RAN. The HARQ time (wireless interface delay) is determined by the cell radius [7], hence, in addition to other RAN delay components, it should be considered in the link delay budget during the planning phase of a C-RAN design. The rest of this paper is organized as follows: In Section II we present the fundamental and background of C-RAN architecture, in section III the system model that we approach the problem is discussed, in section IV numerical results of the proposed model is presented, finally in section V conclusion and recommendations are provided.

B. RELATED WORKS

In [6], the authors propose a cost-optimal deployment of a 5G network with its optical transport, where three optical fronthaul technologies and architectures, namely physical layer split (PLS), analogue radio-over-fiber (A-RoF), and common public radio interface (CPRI) were evaluated by the deployment costs, the ability to meet 5G latency, and capacity requirements using ILP. Results show that CPRI always requires more fronthaul bandwidth than PLS and the bandwidth of PLS grows with the number of users, whereas the bandwidth requirement of CPRI is constant for a given cell configuration and independent from the amount of real traffic associated with the cell.

The authors in [7], had allocated BBU pool positions for the C-RAN architecture using a real heterogeneous network and the BBU pools placement is bounded only by the delay constraint. The aim of the research was to find the minimum number of BBU pools, and determine the optimal central office position, considering the delay constraint including cell coverage radius. Results shown that a minimum of five BBU pools to cover the actual heterogeneous network of area 2,657 km² considering the maximum fronthaul latency.

In [8], Mohamed et al, had developed a centralized BBU pool placement problem for C-RAN deployment over an optical aggregation network and formalize it using ILP. Results shows link capacity is the main constraint for BBU consolidation at higher latency, and they had observed minimizing the computational resources had been resulted in a slight additional saving compared to minimizing the number of BBU pools.

Byomakesh Mahapatra et al. in [9], had used a k-means clustering algorithm to find the number of centroids i.e. central-BBUs and then choose the centroid position in the cellular cluster for the optimal placement of the central-BBUs, RRHs are then assigned to the C-BBUs. Different sets of UEs were taken and results show that the increased in the UE is directly proportional to the number of serving RRHs and also C-BBU.

Henrik Holm et al. in [10], had presented how optimally assign cells to a BBU Pool, and minimize the CAPEX of operators using an ILP model for C-RAN deployment. To obtain the highest possible statistical multiplexing gain a single BBU pool takes 20-30% cells from office areas, and 70-80% cells from residential areas.

Francesco Musumeci et al. in [11], propose a BBU placement optimization problem over WDM aggregation networks using an ILP model, the model also considered the electronic switches placement, and for the fronthaul link two transport networks OTN and overlay was examined their impact on the BBU centralization using mobile and FMC traffics. Simulation results show that when higher traffic is transported on the network and if no stringent latency requirements are imposed, lack of capacity is the main constraint for BBU consolidation.

A.Marotta et.al in [12], had jointly optimized BBU placement with fronthaul deployment for C-RAN deployment in a brown-field scenario where traditional base stations are already deployed using an ILP model. Results show that the maximum allowable fronthaul delay has an inverse relation with CAPEX and the number of required BBU pools. Similarly, the OPEX result at higher delay values

allows for cost savings of up to 72% in urban and 62% in rural areas. Moreover, when capacity is not an issue such as in suburban case, microwave links are a convenient choice for the operator which allows a reduction of CAPEX.

Authors in [13], introduce the concept of a mixed functional split for the C-RAN deployment by dynamically allocating split options to each node based on their requirements and address the tradeoff between required bandwidth and improved function centralization. They explore split options 6, 7 and 8, and compared it with fixed split. Results show that the required capacity of requests in split 8 is higher compared to the mixed split thus higher number of BBU pools are needed for split 8, and BBU centralization is higher for the mixed split scheme.

Ahmed M. Awad et.al in [14], compute a BBU placement problem for Cloud-RAN deployment over 5G optical aggregation networks, and formulate it using an ILP optimization problem. Their findings show that up to 97% and 78% of inter-CoMP users can be switched to being intra-CoMP users at low latency value of 50 μ s and higher latency of 80 μ s, respectively.

Tinini et al. in [15], proposed a Cloud-Fog-RAN (CF-RAN) network architecture and extend the capabilities of C-RAN fronthaul by the dynamic activation of baseband processing functions in fog nodes closer to RRHs. Results show that compared to a traditional D-RAN architecture the CF-RAN shows a 96% reduction in energy consumption with providing a maximum transmission latency of about 20 μ s in the fronthaul.

Carapellese et al. in [16], studied the energy efficient BBU placement optimization problem using ILP model whose objective is minimizing the aggregation infrastructure power. The evaluation for the energy savings of BBU hoteling show that the proposed architectures enable savings up to about 60%–65% in dense-urban or urban and about 40% in rural geotype.

Al-obaidi et al. in [17], investigated how to optimize the deployment of new C-RAN networks by minimizing the CAPEX using microwave links as fronthaul. The simulation results, have shown that microwave fronthaul sites can only minimize CAPEX at population densities above 8000users/km². Moreover, the cost of fiber deployment increases non-linearly with the coverage area, while the cost of microwave deployment remains relatively constant.

II. FUNDAMENTAL AND BACKGROUND OF C-RAN

A. C-RAN SYSTEM STRUCTURE

Based on where functionalities are placed either on the BBU pool or resides in the DU, a C-RAN architecture can be classified into two categories, i.e, fully centralized and partially centralized.

Fully centralized: All Layer 1 (Physical), Layer 2 (MAC) and Layer 3 (Network) functionalities are moved into the BBU Pool [18]. Therefore, the BBU pool handles all the functions of managing and processing resources. It is clear and simple but it generates high bandwidth IQ data transmission on the fronthaul [19].

Partially centralized: Layer 1 processing is co-located with the RRH, since Layer 1 takes major computation parts of

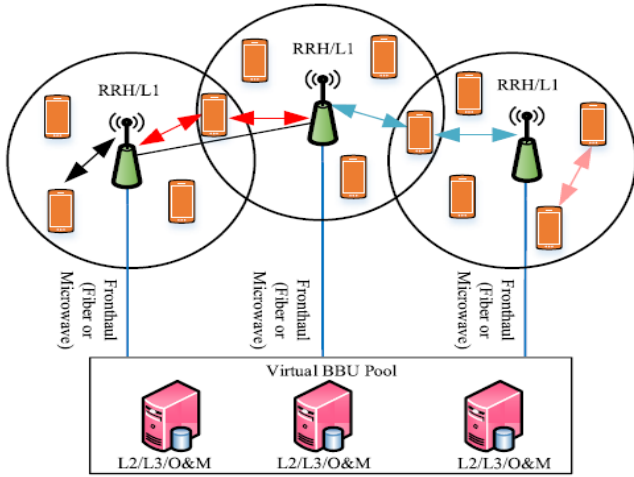


Fig 1. Partially centralized RRH-BBU function split [19]

RAN this reduces the burden in terms of bandwidth on the fronthaul links. However, Layer 2 and Layer 3 related functions are integrated in the BBU. Here, some advanced features such as CoMP and joint processing Distribute Antenna System, cannot be efficiently supported. The interaction between MAC and PHY could be complicated as well. It also makes the interconnection between Layer 1 and Layer 2 more difficult. Therefore, the tradeoff between the burden on fronthaul and the flexibility of resource schedule should be considered while planning the C-RAN deployment.

B. RAN FUNCTIONAL SPLIT

The BBU functionality in a RAN architecture is divided into two functional units: that is a distributed unit (DU) that is accountable for the real-time L1 and L2 scheduling, and a centralized unit (CU), which is in charge of non-real-time, higher L2 and L3 scheduling or CU hosts the network layer functionality (RRC) and the PDCP functionality from the Data Link Layer. As per the 3GPP technical specifications, there are eight functional split options [20], where each option has different number of functions being centralized and it also require different bit-rate and delay requirements. In general, as more functions are situated in the DU, more processing will be done before the data goes to the fronthaul network, therefore the required bitrate on the fronthaul will be lower. The transport network for NR traffic which is the cross-haul or x-haul network is formed by the backhaul and fronthaul networks together [21].

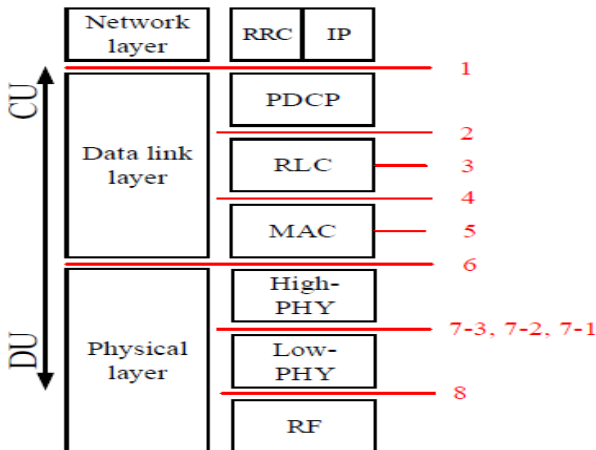


Fig 2. LTE protocol stack and layers with 3GPP's functional split options [22].

III. SYSTEM MODEL

A high level view of the planned model is presented below in the flow chart which addresses BBU pool and fronthaul link dimensioning. Basically the model can be divided into four steps, a graphical overview being given in Fig 3.

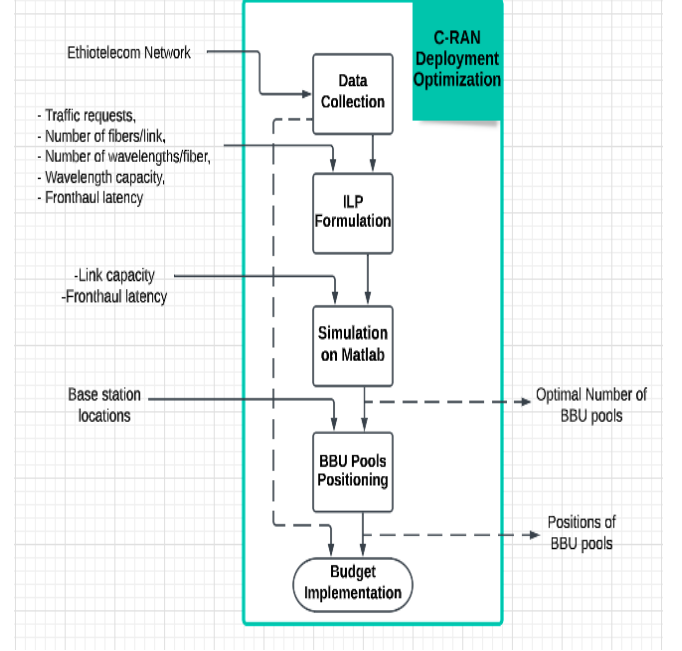


Fig 3. System Model Overview

A. Input Parameters

For LTE network ethiotelcom is currently using a 2x2 MIMO, 10MHz bandwidth with 64-QAM, and a 4x4 MIMO, 20MHz and 64-QAM configuration [23]. The notations in table I are the input variables of the proposed optimization problem.

Table I. ILP INPUT VARIABLES

Notations	Description
N	Set of nodes in the physical network
l_p	Fiber propagation delay
l_{EL}	Electronic switch delay
D	Maximum allowable fronthaul delay
W	Number of wavelengths per each physical link
C_r	Required capacity of a mobile request
w_i	Number of BBU pools
f_e	Number of fibers
K	Maximum number of link used
$C_{BBU pool}$	Processing capacity of the BBU pool
$C_{RRH,i}$	Processing capacity of RRH i

B. Set of Constraints

- i. **Maximum allowable fronthaul delay:** the round trip time of all components of the link in the fronthaul, the fiber propagation delay l_p and delay due to electronic switches l_{EL} should be less than or equal to the total allowable fronthaul latency, i.e., 250 μs [24].

$$\sum_{p \in P} (l_p + l_{EL}) y_p^{-r} + l_{EL} \leq D, \forall n \in N_M, r \in R_C^n \quad (1)$$

ii. **Wireless interface delay:** the HARQ time is determined by cell radius (r) and speed of light in vacuum (c).

$$\delta_{U,R} = 2 * \frac{r}{c} * 10^3 \mu s \quad (2)$$

iii. **Links capacity:** the sum of virtual link's capacity should not exceed the total capacity of the requests routed through it

$$\begin{aligned} \sum_{r \in R_M} C_r y_v^r + \sum_{r \in R_C} \sum_{p \in P_v} C_r y_p^r \\ \leq \sum_{p \in P_v} \sum_{\lambda \in A} C_{u_{p\lambda}}, \forall v \in V. \end{aligned} \quad (3)$$

iv. **Fibers deployment and upper bound:** Fiber availability constraint, this constraint first establishes light paths or the number of fibers used in each link and limits this number to the upper bound K .

$$\sum_{p \in P^e} U_{p\lambda} \leq f_e \leq K, \forall e \in E, \lambda \in \Lambda \quad (4)$$

v. **BBU limit:** Each node must be associated with exactly one BBU,

$$\sum_{i \in N} x_i^n = 1, \forall n \in N_M. \quad (5)$$

vi. **BBU association:** Identify hotels as nodes which host at least one BBU, only a deployed BBU pool at i^{th} node can host a BBU for n ,

$$w_i \geq x_i^n, \forall n \in N_M, i \in N \quad (6)$$

vii. **BBU pool processing capacity:** the sum of processing capacities of RRHs connected to the BBU pool should not exceed the processing capacity of the pool.

$$\sum_{i=1}^{N_{cRRH}} C_{RRH,i} \leq C_{BBU_{pool}} \quad (7)$$

viii. **Protection for BBU pool failures:** each RRH is connected to two BBU pools, where one served as a working pool and the second one is used as a backup.

$$\sum_i X_{i,m} = 1 \quad \forall m \quad (8)$$

$$\sum_j Z_{j,m} = 1 \quad \forall m \quad (9)$$

$$X_{i,m} + Z_{i,m} \leq 1 \quad \forall i, \forall m \quad (10)$$

C. OPTIMIZATION PROBLEM

The main objective of the proposed model is to minimize the total deployment cost of the C-RAN, which is highly dependent on the total number of BBU pools and the total number of fibers, hence, in the multi objective optimization function given in eq. 11, the first term is to minimize total number of BBU pools whereas the second term is to minimize total number of optical fibers and α, β are weights of each objective which are tunable to select the primary objective of the optimization such that $\alpha, \beta \in [0, 1]$.

$$F = \alpha \sum_{i \in N} w_i + \beta \sum_{e \in E} f_e \quad (11)$$

LPP: min F
s.t. Constraints 1 - 10

IV. NUMERICAL RESULTS

We consider an optical transport network having 53 cell sites distributed over a dense urban region of 10km² around Bole International Airport as shown in fig 4. The core site is the primary choice for placing the BBU pools, and in our scenario it's located at site ID: 111136.



Fig 4: Network topology consisting macro cells

Both mobile and fronthaul traffics are carried through the network, and all the ILP outputs are obtained in terms of the number of BBU pools which is also taken as a performance metric. Furthermore, we evaluate the impact of wireless interface delay on BBU centralization. All RRHs are connected to the BBU pool via optical fiber links with a maximum of two fibers per link, and a maximum of 20 wavelengths per fiber is available at 10 Gbps each. It's also assumed that four RRHs are connected to a multi-port ONU.

The proposed optimization problem is evaluated in three scenarios, i.e., very low, low and high fronthaul latency values.

A. Very low latency values

The impact of wireless interface delay on the required number of BBU pools at cell radius $r = 6\text{km}$, and very low latency values is given in fig 5 and from the figure we can see that for the same fronthaul latency values, one additional BBU pool is required when the wireless interface delay is considered in the planning process. On the other hand, at very low fronthaul latency values decreasing or relaxing the number of wavelengths used per fiber has no impact on the required number of BBU pools, however, a small variation in the fronthaul latency values can lead to a different maximum number of BBU pools. Therefore, for very small fronthaul delay values, it is recommended to use fewer wavelengths per fiber.

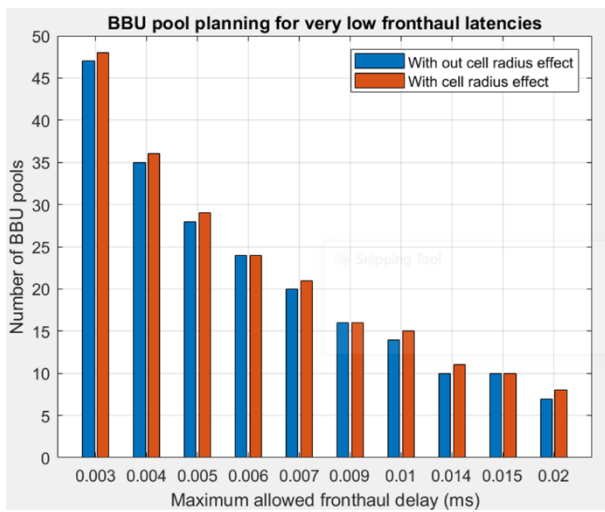


Fig 5. Impact of wireless interface delay on BBU centralization for very low latencies

B. Low latency values

For low fronthaul latency values [25 μs to 100 μs], a slight impact of wireless interface delay on BBU centralization is shown at 35 μs and 70 μs latency values, and when relaxing the number of wavelengths more BBUs can be centralized both in the case of considering and neglecting the cell radius impact. The higher BBU consolidation achieved in this scenario is 2 occurred at $W=36$ and fronthaul latency values above 80 μs . However, for $W=10$ the maximum BBU centralization achieved is 4, this is due the fact that minimizing the number of wavelengths per fiber will lead to a decrease in the overall capacity of the optical network that couldn't handle the mobile and fronthaul traffics passing through the link. Therefore, as the allowable fronthaul delay increased minimizing the number of wavelengths per link has negative impact on BBU centralization.

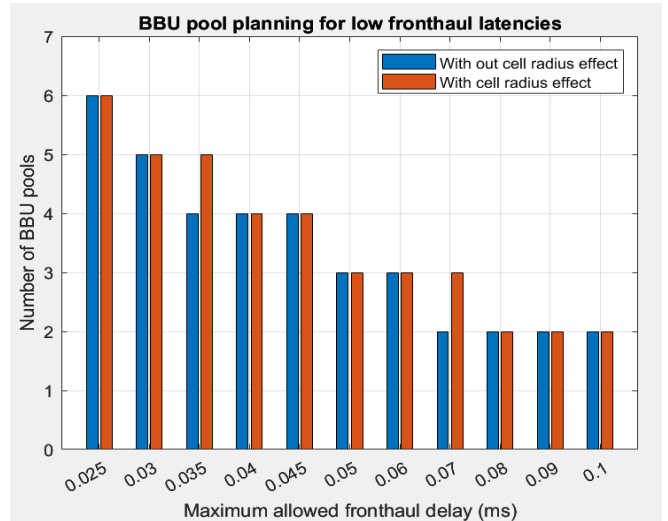


Fig 6. Impact of wireless interface delay on BBU centralization for low latencies

C. High latency values

For high fronthaul latency values a slight impact of the wireless interface delay on BBU centralization is shown at $L=140\mu\text{s}$. Moreover, considering higher delay values will also reduce the required deployment CAPEX. For higher values of W , where there is no capacity constraint in the link, and relaxed FH latencies the BBU pools can be placed at longer distances from their respective cell sites, therefore, a significantly higher BBU centralization is achieved for $W=36$ and with a latency above 150 μs . on the other hand, minimizing the number of wavelengths used per fiber will lead to an increase in the BBU pool requirement.

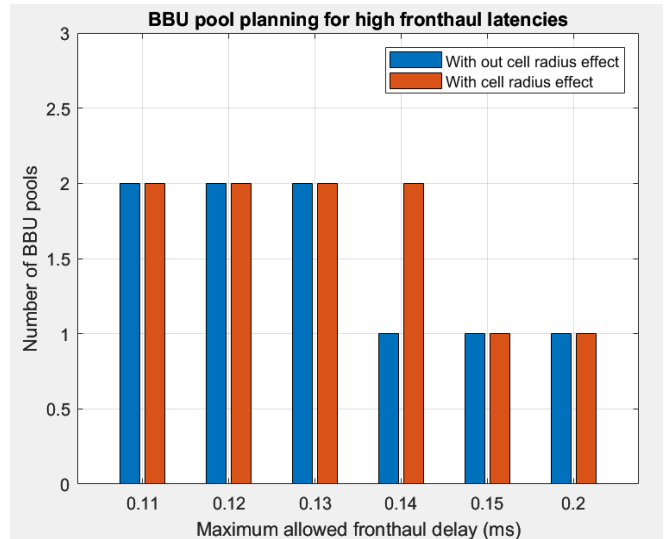


Fig 7. Impact of wireless interface delay on BBU centralization for higher latencies

D. Result for different Use cases

The end-to-end latency for 5G networks varies depending on the type of application being used. For example, URLLC applications require an end-to-end latency of less than 0.5 milliseconds for both UL and DL. Tactile internet, industrial networking or smart cities, and factory automation applications require an end-to-end latency of less than 1 millisecond for both UL and DL, on the other hand, eMBB applications have a relaxed latency requirement of 4 milliseconds for both UL and DL.

The fronthaul latency is a critical performance metric for URLLC and critical machine type communication services, because it can directly impact the end-to-end latency of these applications, hence, latency-sensitive applications require fronthaul latency below 75 microseconds. In order to support this latency critical applications and to maintain the latency requirement under 75 μ s, the fiber length in the fronthaul should not be longer than 15 kilometers. This is because the latency of the fronthaul link is proportional to the length of the fiber. Table 1 summarizes the required number of BBU pools for different service categories.

TABLE II. REQUIRED NUMBER OF BBU POOLS FOR DIFFERENT USE CASES

Use cases	FH latency (μ s)	No. of BBU pools
Ultra low latency performance	25	6
URLLC	35	5
Real-time functions:- voice over LTE, IoT, tactile applications	50-70	3
For full E-UTRA or NR performance	100	2
-For installations where the lengths of fiber links are in the 40 km range -Non real time functions: web browsing and email.	200	2

V. CONCLUSION

C-RAN splits the traditional base stations into two physical entities, i.e., the radio unit and central unit, following this separation a new interface called fronthaul is introduced. As the centralization of functions varies, split option 7.2 is selected for the research as it offers the best trade-off between key centralization benefits, required fronthaul bandwidth, RU complexity, and inter-cell cooperation. An ILP optimization model is evaluated in three different scenarios: very low, low, and high fronthaul latency values. Simulation results reveal that for very low fronthaul latency values the wireless interface delay has a higher impact on BBU centralization because for the same fronthaul latency values, one additional BBU pool is required when wireless interface delay is considered in the planning process. On the other hand, it has a slight impact on low and high fronthaul delay values, therefore wireless interface delay must be considered when planning for BBU pools, especially for very low latency values. This is because one additional BBU pool is required when the wireless interface delay is considered in the planning process.

Another important consideration when designing a fronthaul network is the trade-off between the degree of centralization, the tight latency requirement (L), and available link capacity (W), because at a higher latency with no wavelength constraints higher degree of BBU centralization or even complete centralization can be achieved for $W = 36$ and $L > 150\mu$ s. However, deploying a single BBU pool for the entire area may create a single point of failure which can cause service outages for a large serving area with a significant number of users, hence, we assume that each RRH in the cluster is connected to two BBU pools, where one BBU pool served as a primary baseband processing unit, while the other

will be used as a backup. This configuration provides redundancy and improves the overall system reliability.

On the other hand, cost is related to latency variation, and fronthaul bandwidth, where the lowest fronthaul latencies require additional CAPEX given the higher number of required BBU pools, and a small variation is related to the different maximum number of BBU pools. Furthermore, considering higher delay values until the processing capacity limitation of the BBU pool will reduce the required deployment CAPEX, given fewer BBU pools are required to serve all the RRHs. Therefore, choosing lower delay values in the fronthaul requires a higher cost for MNOs, however, it makes the deployment ready for the future evolution of technologies.

Since, the end-to-end latency for 5G networks depends on the type of application being used, and the latency in the fronthaul can directly impact the end-to-end latency, use cases such as URLLC services require 5 BBU pools, real-time functions such as voice over LTE, tactile applications require 3 BBU pools while for latency insensitive applications 2 BBU pools are required for the chosen area to meet the required performance requirements.

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