Addis Ababa University;

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School of Electrical and Computer Engineering

Techno-economic analysis of open RAN deployment scenario: in the case of Ethiotelecom

By: Seada Endris

Advisor: Dr. Beneyam Berehanu

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Thesis Title

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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September 26, 2023

This thesis has been submitted for examination with my approval as a university advisor.

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Dr. Beneyam Berehanu Haile

September 26, 2023

Abstract

The telecommunications industry is characterized by the collaboration of multiple vendors to provide mobile network communication services. However, the heterogeneous integration of hardware and software from multiple vendors presents a considerable challenge. Hence, operators typically rely on a single vendor for their radio access network (RAN) requirements. Furthermore, the increasing demand for data services adds to the complexity.

In response to these challenges, the introduction of open Radio Access Network (Open RAN) emerges as a solution, offering an ecosystem that is open, flexible, intelligent, efficient, and cost-effective. In the context of Ethiotelecom, an assessment of the viability of implementing Cloud RAN incorporating Layer 1 (L1) and Layer 2 (L2) functionalities alongside the physical network function (PNF) and the virtualization of Layer 3 (L3) functionalities has been conducted. In C-RAN the HW components and SW are all proprietary. This study focuses on the virtualization of all baseband functionalities and based on open RAN COTs HW and SW.

This thesis assesses the viability of deploying Open RAN network architecture in Addis Ababa, Ethiopia. A thorough techno-economic analysis (TEA) with a study period of five years was conducted by using modified TERA model. The analysis encompassed an investigation of deployment scenarios of Open RAN Distributed Unit (DU) pooling to edge cloud and Central Unit (CU) pooling to regional cloud. The selection of optimal locations for vDU and vCU components entailed an array of factors, including available bandwidth, fiber accessibility, and latency considerations. Inputs such as cell site data, network configurations, hardware-software specifications, and financial parameters were used.

The analysis involved network dimensioning, cost modeling and assessing using economic metrics for each architecture. Metrics such as Net Present Value (NPV), Payback Period (PP), and Internal Rate of Return (IRR) were employed as decision-making tools. These metrics were computed using MS-Excel and MATLAB. The results indicate that D-RAN was more favorable than Open RAN, with PP of 2.4 and 3.5 years, respectively because D-RAN CAPEX cost of initial investment are taken by considering depreciation rate of RAN component. Also both architectural approaches exhibited positive NPV and IRR that exceeded the assumed discount rate of 10%. The findings of this study indicate the profitability of existing RAN architecture within the study period.

Keywords: *RAN, Open RAN, virtualized RAN, TERA model, TEA, Cost modeling*

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Contents

List of Figures

List of Tables

Acronyms

2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
APRU	Average Revenue Per User
BB	Baseband
BBM	Baseband Module Unit
BBU	Baseband unit
BH	Busy Hour
CAPEX	Capital Expenditures
CF	Cash Flow
CNFs	containerized network functions
COTS	commercial off-the-shelf
CP	Control Plane
CSPs	Communications Service Providers
CUE	Connected User Equipment
O-CU	Open Central Unit
DCF	Discounted Cash Flow
D-RAN	Distributed Radio Access Network
DU	Distributed Unit
gNB	Next Generation Node Bases
eCPRI	enhanced Common Public Radio Interface
eNB	Evolved NodeB
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HW	Hardware
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IRR	Internal Rate of Return
ITU	International Telecommunication Union

LTE	Long Term Evolution
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output
MNOs	Mobile network operator
NFV	virtual network functions
NPV	Net present value
NR	New Radio
NRT	Non-Real-Time
OAM	Operation and Management
ORAN	Open Radio access network
OPEX	Operational Expenses
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PP	Payback Period
PSU	Power Supply Unit
QoE	Quality-of-Experience
QoS	Quality-of-Service
RACE	Research into Advanced Communications for Europe
RAN	Radio access network
RAT	Radio Access Technology
RF	Radio Frequency
RLC	Radio Link Control
RNC	Radio Network Controller
ROI	Return on Investment
RRU	Remote Radio Unit
RU	Radio Unit
SDN	Software Defined Networking
SDOs	Standards development organizations
SMS	Short Message Service
SW	Software

TCO	Total cost of ownership
TEA	techno-economic analysis
TERA	Techno-Economic Results from ACTS
UE	user equipment
UL	Uplink Link
UP	User Plane
vBBU	virtualized Baseband Unit
vCU	Virtual Central Unit
VM	virtual Machine
VNFs	virtual network functions
vRANs	Virtual RAN
WCDMA	Wideband Code-Division Multiple Access

Chapter 1

Introduction

1.1 Background and Motivation

The growth of mobile data traffic has been sustained and uninterrupted in recent years. This can be attributed to the widespread use of mobile smartphones, smart devices for homes and offices, and the advancement of 5G technology [1]. This growth in data demand within the mobile communication market continues its rapid pace, driven by the increasing popularity of high-quality video streaming, augmented reality (AR), virtual reality (VR), and the emergence of diverse vertical services that leverage the capabilities of 5G's new radio (NR) technology.

The growth of mobile data traffic can be highly variable across different years and countries, heavily influenced by local market dynamics. Globally, it is projected that the average monthly data usage per smartphone will surpass 20 GB in 2023 and is anticipated to reach 47 GB by the close of 2028. Also, in the Sub-Saharan Africa region, the average monthly mobile data usage per smartphone was 4.7 GB by the end of 2022 [1].

Ethiotelecom serves as a notable example, boasting 72 million subscribers during the budget year, surpassing 98% of its subscriber base target and demonstrating an 8% growth from the preceding year. This subscriber base encompasses various service types, including Mobile Voice customers, Data users, Fixed Services subscribers, and Fixed Broadband subscribers. The density of telecom services has achieved 66.8%, positioning Ethiotelecom as the second-largest operator in Africa and the 21st globally out of 774 operators [2].

Figure 1.1.2 shows the growth of total mobile data traffic in Ethiopia, Addis Ababa. As can be seen, the traffic is expected to continue to grow exponentially in the coming years. This growth will put even more pressure on the RAN, and innovative solutions will be needed to meet the demand.

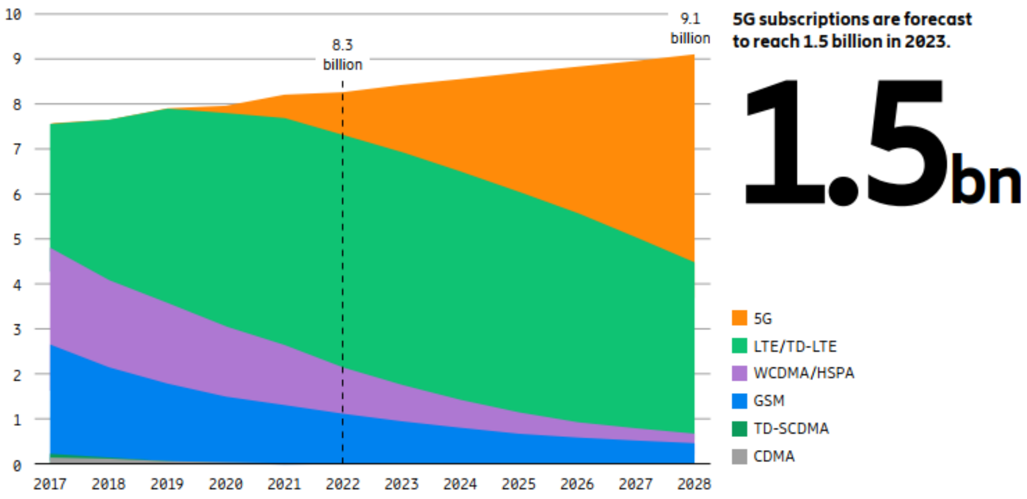

Figure 1.1.1: Mobile subscriptions by technology [1].

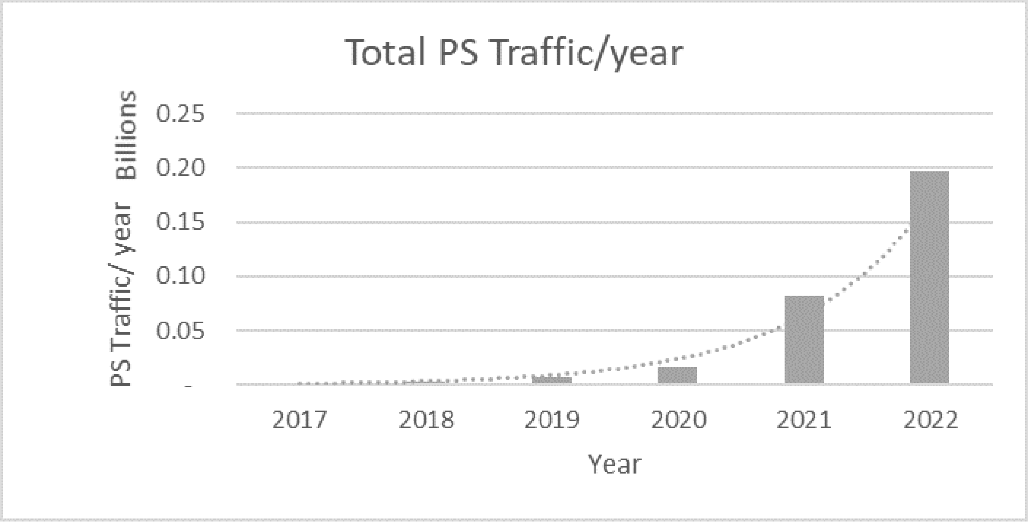

Figure 1.1.2: Total Mobile data traffic growth [3].

However, despite this surge in data consumption, forecasts indicate that the growth rate of annual revenue per user is trailing behind the growth rate of traffic demand. This puts significant pressure on mobile network operators (MNOs) to find ways to minimize network costs while upholding service quality standards [2].

One integral element of a mobile network is the radio access network (RAN), responsible for more than half of an MNO's expenditure. It is responsible for providing the radio connectivity that bridges the user equipment (UE) and the core network in wireless communication systems. This component's performance directly impacts the quality of service that subscribers experience. This has led MNOs to continually enhance the cost efficiency of RAN performance and operations, aiming to cut costs without compromising the quality of service (QoS) provided to subscribers. On the other hand, the inflexibility of existing telecom network infrastructures has hindered the ability of telecom service providers to effectively expand their networks, introduce innovative services, and capitalize on opportunities presented by the new digital economy [2],[4].

During 3G era, the introduction of Wideband Code-Division Multiple Access (WCDMA) technology led to a notable restructuring of the network. This transformation encompassed a division of the RAN into two distinct components: the Radio Network Controller (RNC) and the base station, also referred to as NodeB. This partitioning enabled the establishment of one-to-many connections among these entities.

Advancing to the Fourth Generation (4G) Long Term Evolution (LTE) networks, implements sophisticated technologies that facilitate cross-vendor connections between RAN base stations, denoted as eNB, and core networks. These connections are facilitated through standardized interfaces, ensuring a seamless alignment of compatibility and interoperability. Despite these strides in network technology, it's important to acknowledge that the interfaces within the RAN infrastructure, specifically among various nodes, remain proprietary. This signifies that the specific protocols and communication methods employed within the RAN are tailored to individual vendors or network operators, without universal standardization [5].

The growth in wireless capacity demand has led to the exploration of innovative solutions. One such solution is the densification of the RAN, which involves the installation of more base stations to accommodate the proliferation of user devices and enhance network coverage and capacity. However, this expansion requires significant financial investment from network providers.

To minimize capital and operating expenditure, various network architectures have been proposed, such as centralized RAN (C-RAN), virtualized RAN, and the Open RAN framework. C-RAN centralizes the processing and intelligence of the RAN, while virtualized RAN further virtualizes the RAN functions. The Open RAN framework is an open architecture that allows for the interoperation of different RAN vendors.

As Mobile Network Operators (MNOs) transition to the 5G era, the concept of Open RAN emerges as a solution that offers an open network, adaptable to emerging wireless technologies across all generations. Open RAN encapsulates the notion of interoperable open hardware, open software, and open interfaces. This approach not only fosters interoperability but also incorporates virtualization through technologies like Network Function Virtualization (NFV) and containers. These advancements enable RAN workloads to operate on commercially available servers as Virtual Network Functions (VNFs) or Containerized Network Functions (CNFs) [6].

The implications of these open and disaggregated technologies extend beyond immediate benefits such as cost efficiency and expedited deployment of new network functions. They also hold potential downstream advantages for both service providers and consumers, as outlined [7]:

- Increasing connectivity
- Innovating in local manufacturing, developing software, and enhancing the workforce
- Allowing for greater economic growth and a faster-developing digital economy

Open RAN uses split architecture between central and distributed units. This split contribute performance attributes, load management, and real-time optimization. This allows for adaptability to diverse use cases and quality of service requirements, which vary based on latency tolerances, transport dependencies, and deployment scenarios, influenced by factors like access to transport mediums such as fiber [8]. In densely populated urban zones, optimal functional splits tend to be higher for capacity-centric applications, whereas coverage-centric applications favor lower functional splits. The significance of front haul performance heightens with higher functional splits, as opposed to lower splits that rely on less robust front hauls. Detaching baseband functions from hardware through approaches like NFV Infrastructure (NFVI) or containerization emerges as an effective strategy to meet latency demands. MNOs can enact these functional splits while adhering to various Virtual Machine (VM) requirements.

Hence, for telecommunications operators to identify and evaluate feasibility of new technology, a comprehensive analysis is necessary. Different technologies vary in terms of their technological attributes, maturity levels, and associated costs. This thesis undertakes a thorough exploration of the feasibility of Open RAN deployment, coupled with a thorough investigation into the techno-economic viability of the selected scenarios. The insights gained from this techno-economic analysis of deployment strategies can help to optimize resource utilization, enhance network efficiency, and understand the cost dynamics of different RAN architectures. This techno-economic analysis (TEA) is essential for informed decision-making and strategic planning.

1.2 Statement of the Problem

The growing demand for cellular data is driving the need for RAN architectures that can support higher data rates, greater capacity, more flexible and cost effective. Various technologies like massive MIMO, mmWave transmission, software-defined network (SDN), cloud RAN (C-RAN), virtual RAN (vRAN), and open RAN have been proposed to address these requirements.

Open RAN is a cost-effective approach to RAN deployment that is gaining popularity in the 5G era. It separates the hardware and software components of the RAN, allowing operators to choose from a wider range of vendors and solutions. Open RAN is made possible by standardized open network interfaces defined by 3GPP (Third Generation Partnership Project), the O-RAN Alliance (Open-RAN Alliance), IEEE (Institute of Electrical and Electronics Engineers), and other SDOs (standards development organizations) and industry fora. The standards define multiple NG-RAN architecture options and the associated open network interfaces to cater to the diverse 5G use cases and operator deployment constraints [9]. This can lead to cost savings, flexibility, and innovation.

Telecommunications operators is conducting a feasibility study on open RAN as a potential solution for its network deployment. It is important to thoroughly analyze the feasibility of new technology before implementing. Also it is important to consider a number of factors, such as the number of subscribers to be supported, the amount of traffic data to be handled, the RAN architecture, the environmental conditions,throughput data rates and front haul capability.
Hence this research addressed the following question::

1. Which RAN deployment scenarios are feasible techno-economically?
2. What are the costs and benefits of deploying Open-RAN?
3. When will the return on investment (ROI) be achieved?

1.3 Objective

The objective of this thesis is described below as general and specific objective.

1.3.1 General Objective

The objective of this thesis is to assess the techno-economic feasibility of Open RAN deployment scenario in the context of Ethiotelecom by combining technical with economic evaluation methods.

1.3.2 Specific Objectives

The specific objective of this thesis are described below,

- To identify the suitable deployment area in Addis Ababa based on densification of the network and availability of fiber.
- To perform network dimensioning and assess the required number of network devices.

- To investigate the existing TEA frameworks, select a suitable framework for this research work, and adapt the selected framework to meet local context.
- To implement cost modeling analysis and estimate CAPEX cost, OPEX cost and TCO.
- To evaluate the techno-economic feasibility of the Open-RAN deployment scenarios by applying key economic indicators.
- To evaluate the return on investment.

1.4 Literature Review

The literature on open RAN is wide and constantly evolving, with research papers covering a wide range of topics, including the architecture, use cases, and deployment scenarios of open RAN and related technologies. This section provides the findings of relevant literature.

[10] presented the economic benefits of using open RAN technology for deploying 5G networks. It compares the costs and advantages of different options and highlights the savings that can be achieved through open RAN architectures. The findings are based on interviews with mobile network operators who are currently implementing open RANs in their networks. Open radios are found to be 30% cheaper than proprietary radios, and significant savings can also be achieved through software and pooling efficiencies.

[11] discusses the value and cost of vRANs in comparison to traditional RANs. It presents a TCO model that using cost of different components of the RAN, such as radio, baseband, transport, site rental, and OAM. The results show that vRANs offer cost savings of around 30% in terms of CAPEX and 25% in terms of OPEX compared to traditional RANs. However, there is a slight increase in transport CAPEX due to the higher bandwidth requirements of vRANs.

[12] presented development of a cost model for comparing different RAN architectures in terms of costs. The research used literature analysis, interviews, and internal company documents as methods. Microsoft Excel and draw.io were used as tools to create the cost model. The model evaluates the cost positions of various RAN architectures and helps determine the most economical deployment option based on subscriber traffic and network configuration in different scenarios. The procedure for calculating total cost of ownership includes input data, network dimensioning, and cost calculation.

[13] summarized O-RAN Alliance RAN architecture and its primary components. O-RAN Alliance is a carrier-led initiative that aims to create vRAN for multi-vendor deployments. It promotes the

use of software-defined AI-assisted control in these networks, which allows for different degrees of openness. The article summarizes six different deployment scenarios and discusses the use of AI-assisted orchestrators to manage radio and computing control policies in these networks. The author focuses on the proposed architecture and building blocks of O-RAN and highlights the innovations made possible by this technology.

[14] discusses the negative effects of using a proprietary RAN on the QoS and QoE in wireless networks. The author suggests using Open RAN, a software defined RAN architecture that utilizes virtualization to improve the efficiency of the network. This architecture allows for complete virtualization and programmability, resulting in a more open, controllable, flexible, and adaptable RAN. The article also briefly touches on the use of SDN for network virtualization.

[15] aims to demonstrate how Open RAN network components can be designed and sized to meet the needs of operators, such as Telefonica, who require a wide range of radio units, site capacities, and synchronization options. The article outlines a complete portfolio of radio units and baseband equipment that can be used for a full 4G/5G RAN rollout in any market. It also discusses the architectural components, design criteria, technology choices, and major chipsets used in creating this portfolio. Additionally, the article explores the virtualization of 5G open RAN, with the ability to deploy virtual instances of vCU, vDU, and vEMS over a scalable cloud-based platform managed by a Service Management and Orchestration Framework. The article also covers the integration of open RAN with legacy Ran systems.

[16] discusses how Indonesian operators are testing open, disaggregated RAN technology to improve mobile broadband. The TIP (Telecom infra project) Community lab activities aim to accelerate the deployment of viable solutions and nurture an innovative ecosystem. The challenges of separating the network from traditional networks are addressed through testing and validating open and disaggregated networks. The results show that with 5MHz and 10MHz bandwidth, average download speeds are 38 Mbps, with a maximum of 60 Mbps, and average upload speeds are 14 Mbps, with a maximum of 16.4 Mbps.

[17], presented a field trial conducted to test Open RAN technology and its potential for expanding mobile broadband connectivity in Africa. The trial aimed to determine whether Open RAN could be commercialized in rural markets. Amdocs' Open RAN solution successfully transformed networks into cloud-based, intelligent, and open systems. The trial achieved various accomplishments, including the ability to make voice and video calls using Open RAN hardware and connect to existing networks. The successful trial suggests that Open RAN may be deployed across Africa in the future.

[18], discussed the challenges and opportunities associated with the implementing an open RAN architecture. Samsung gave a demonstration of the O1 interface's multi-vendor compatible Configuration, Performance, and Fault Management features. Also demonstrated their implementation of the Open Fronthaul Management Plane specification on the O1 interface.

[19], highlighted that active involvement by policy makers and industry initiatives in facilitating the development of a vibrant open network supply chain ecosystem would help to unlock economic benefits. Also discussed is how a lack of co-ordination on issues such as adoption of open standards, and refragmentation leading to poor interoperability of solutions could reduce the potential for open and disaggregated technologies to deliver economic and supply chain benefits. In general all the studies quantified that as TEA is an essential tool for operators specially to evaluate a new and evolved emerging technology in a different network environment. Each author follows a different approach in a different perspective to evaluate techno-economic in each of their studies. In addition, most of the studies only considered the geographical scenarios and technology comparison mainly focused on input data assumption.

1.5 Methodology

The methodology employed in this thesis is depicted in the flow diagram provided in fig 1.5.1. This work started with extensive study on RAN and TEA of different RAN architecture by reviewing relevant literature from various sources such as books, IEEE journals, conferences, and 3GPP documentation. Additionally, valuable data on the existing RAN infrastructure of Ethiotelecom in Addis Ababa was collected, including cell site information, network configurations, as well as hardware and software specifications.

In this thesis, Scenario C, which involves pooling the DUs to the edge cloud and the CUs to the regional cloud, is the primary focus area among the various deployment scenarios of Open RAN. This scenario support deployments in locations with limited front-haul capacity[20], [21], [13]. This deployment scenario can be implemented by utilizing the existing fiber front haul, thereby meeting the latency requirements of both 5G and 4G networks. The functional split utilized in the modeling of Open RAN were split 7.2x. This functional split is recommended by O-RAN alliance and 3GPP also it is widely adopted and implemented by different operators [22], [23].

The D-RAN architecture, which is currently utilized by the majority of MNOs, is considered as the existing RAN architecture. Also deployment area was selected based on the availability of fiber and densification of the network. Based on this Bole sub city with in 4km2 area were selected.

Then after reviewing different TEA frameworks, TERA framework was selected for its relevance to the wireless telecommunications sector, and adapted it to the local context. By following modified TERA model Network dimensioning is done to estimate the necessary gNB equipment like BBU, RRU, server, fronthaul capacity, necessary software [24].

Following network dimensioning, cost modeling, revenue modeling, and economic analysis were conducted [12], [25]. Mathematical models were used to calculate the costs, and economic metrics such as NPV, IRR, and PP were analyzed. The implementation of these metrics was carried out using MS-Excel and MATLAB. As an input to the system model study period assumed to be five years and a discounted rate of 10%.

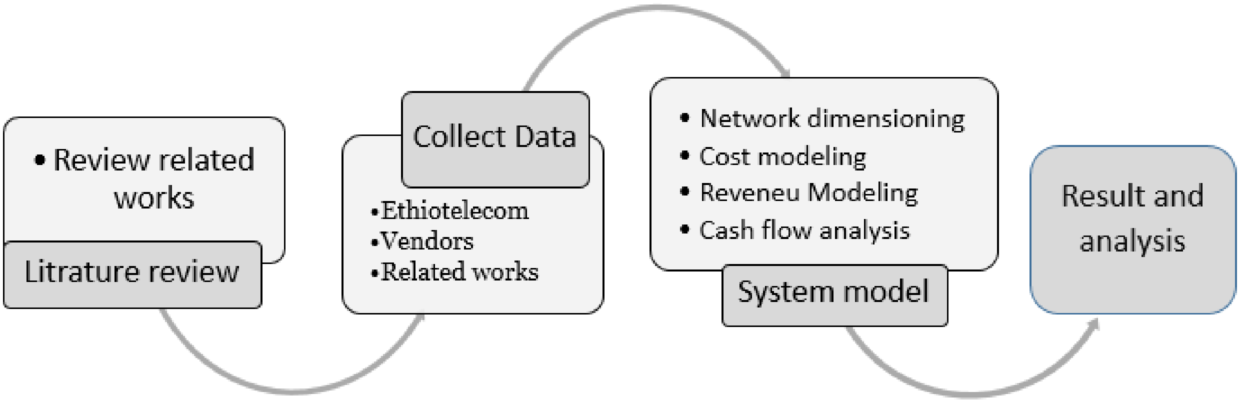

Figure 1.5.1: General methodology Flow chart.

1.6 Scope and limitation

This thesis focuses on study and evaluate the advantages of deploying Open RAN scenarios, with a specific focus on its techno-economic feasibility. To achieve this goal, a comprehensive techno-economic analysis will be conducted, taking into account both the technical and economic aspects of Open RAN deployment scenarios. The examination will primarily concentrate on deployment scenarios utilizing Open RAN vDU and vCU. However, this study is limited in scope to the RAN, and does not encompass the core network.

1.7 Deliverables

The open RAN TEA model developed in this thesis can be used to understand its economic benefits by providing an estimated cost comparison across different RAN architectures. A comprehensive evaluation of these scenarios will provide valuable insights to MNOs, enabling them to optimize their network infrastructure, enhance resource allocation and gain a clear understanding of the costs associated with different RAN architectures.

1.8 Thesis Layout

This paper is organized in the following manner: In Chapter 2, an extensive overview of mobile networks and the development of the RAN in the cellular network is provided. Additionally, the chapter delves into the background of RAN, its main components, and the challenges and opportunities it presents. Chapter 3 provides an overview of the TERA model and techno-economic modeling, as well as the implementation of the Open RAN TEA framework, its associated inputs and cost modeling and evaluation methods, and the various mathematical models used in this thesis. Chapter 4 then delves into discussion of the results obtained from the techno-economic modeling conducted. Finally, Chapter 5 contains as the conclusion to the thesis and explores potential future research directions.

Chapter 2

Open Radio Access Network (Open RAN)

2.1 Overview of mobile networks

The enduring fascination with instant long-distance communication became a reality with the emergence of the electric telegraph in the mid-nineteenth century. Initially, electromagnetic radiation was harnessed for ”wireless telegraphy,” primarily connecting distant points where conventional telegraph lines proved unreliable or impractical. As radio technology progressed, it facilitated simultaneous message broadcasts to multiple locations, initially utilizing telegraphic code (dots and dashes) and eventually advancing to full audio transmission [26].

Cellular networks, conceived in the 1980s and rapidly embraced in the mid-1990s, were the driving force behind the subsequent communication revolution following the telephone’s invention [27]. These networks underwent a series of evolutions, commencing with the first-generation (1G) analog voice service, boasting speeds of up to 2.4 kbps.

The second generation (2G) introduced digital technology and supported text messaging, resulting in increased demand and success. Within the GSM network architecture, key elements included the Mobile Station (MS), Base-Station Subsystem (BSS), Network and Switching Subsystem (NSS) or Core Network, and External Network [28]. The transition to 2.5G, commonly referred to as GPRS, saw enhancements in the GSM system, offering both circuit and packet-switched services. This evolution permitted users to occupy up to five time slots, achieving respective downlink and uplink speeds of 114 kbps and 20 kbps. Supported by Packet Data Protocol (PDP) and GPRS Tunneling Protocol (GTP), end-to-end IP services were made available [29].

In 1998, 3G networks were introduced, enabling information transmission at speeds of at least 200 kbits per second. A UMTS network encompassed three interconnected domains: Core Network, UMTS Terrestrial Radio Access Network (UTRAN), and User Equipment (UE). These networks facilitated both circuit-switched and packet-switched connections, with data services like web browsing via HTTP and file transfers via FTP conducted over packet-switched connections, while voice services relied on circuit-switched connections. Subsequent releases such as 3.5G and 3.75G emerged, driven by packet-switched advancements in 3G technologies, eventually leading to the birth of 4G networks [30], [28]. Figure 2.1.1 illustrates the network architectures of both 2G and 3G.

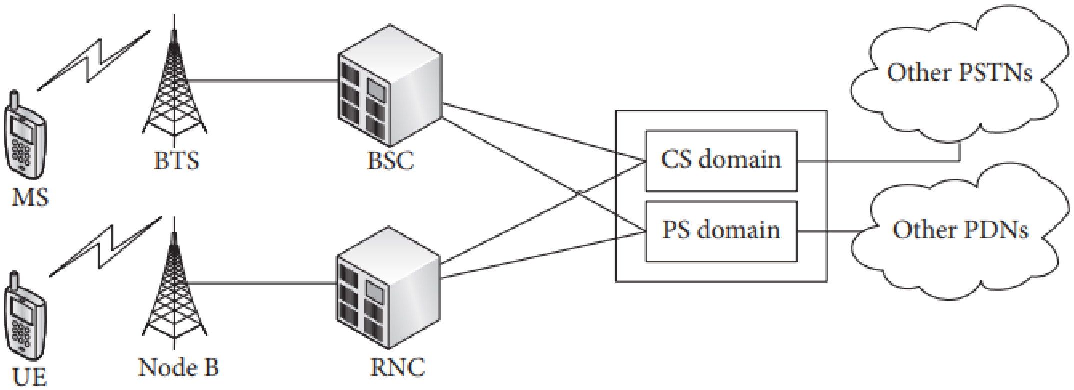

Figure 2.1.1: 2G & 3G network architecture [31].

Long Term Evolution Standard (LTE) introduced a wireless communication standard for mobile phones and data terminals, building upon GSM/EDGE and UMTS/HSPA technologies. LTE simplified the core network and employed a distinct radio interface, resulting in increased capacity and higher speeds.

4G networks operated as all-IP, packet-switched networks, achieving data rates of at least 100 Mbit/s between any two points worldwide. They featured seamless handoffs across various networks, global roaming capabilities, high-quality services for multimedia support, and interoperability with existing wireless standards. LTE, UMB (ultra-mobile broadband), and IEEE 802.16 (WiMAX) were recognized as 4G standards [5], [32]. Figure 2.1.2 presents the architecture of a 4G network.

5G was designed to efficiently handle extensive traffic from numerous devices and deliver real-time services, including mission-critical applications, with a flexible, customer-tailored architecture. 5G aimed to offer a significantly higher capacity than its predecessor, surpassing 1 Gb/s [34]. This enhanced capacity promised more efficient communication, increased reliability, and support for a higher density of mobile users [30], [27]. Table 2.1.1 provides an overview of cellular technologies, considering various parameters.

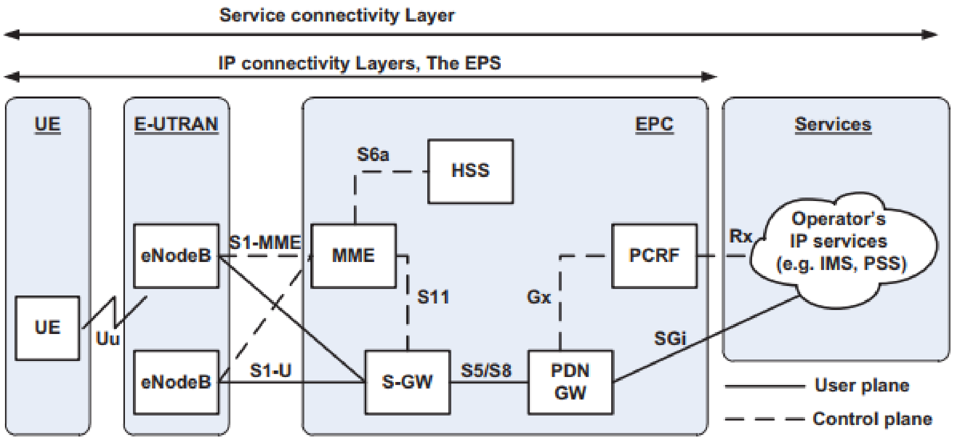

Figure 2.1.2: LTE network architecture [33].

	1G	2G	3G	4G	5G
Introduced Year	1980	1993	2001	2009	2020
Technology	AMPS	IS-95, GSM	IMT2000, WCDMA	LTE, WiMAX	Unified IP and seamless combination of broadband(WWWW)
Speed of Data Rates	2.4Kbps-14.4Kbps	14.4Kbps	3.1Mbps	100Mbps	Higher than 1Gbps
Internet services	No Internet	Narrowband	Broadband	Ultra Broadband	Ultra Broadband mission critical communications and connecting the massive IoT
Band-width	Analog	25MHZ	25MHZ	100MHZ	Sub band & millimeter wave
Band type	Narrowband	Narrowband	Wideband	Ultra wide band	low, mid, and high
Carrier Frequency	30Khz	200Khz	5Mhz	1.4Mhz,5Mhz, 10Mhz, 15Mhz, 20Mhz	Sub-6 GHz and mmWave Band
Multiplexing	FDMA	TDMA/CDMA	CDMA	CDMA,OFDMA	CDMA & BDMA
Core Network	PSTN	PSTN	Packet Networking	Internet	Internet
Switching	Circuit	Circuit Packet	Packet	All Packet	All Packet

Table 2.1.1: cellular network technology [35].

2.2 Evolution of Radio access network

Mobile cellular networks have three main components: User Equipment (UE), RAN, and Core Networks [36].

- **UE** encompasses a broad range of devices like mobile phones, smartphones, tablets, as well as diverse devices such as cars, drones, industrial machines, robots, home appliances, and medical devices.

- **RANs** play a pivotal role in wireless communication systems by establishing radio connectivity between UE and the core network. This network segment comprises a base station and antennas that provide coverage based on factors like capacity, design, and propagation characteristics.
- **core network** coordinates the various sections of the access network and also connects to the internet.
- **Transport network** connects the RAN and the Core Network.

Within RANs, there are two primary components: the radio unit (RU) and the baseband unit (BBU).

- **RU:** is responsible for handling the transmission and reception of wireless signals within the mobile network. It deals with the actual wireless communication between the user devices (such as smartphones) and the mobile network infrastructure. It manages the physical layer of the wireless connection, ensuring that data is transmitted accurately and received efficiently. Over the years, advancements in RU technology have allowed for higher data rates and improved signal quality, contributing to better overall network performance.
- **BBU:**plays a critical role in managing the radio resources within the RAN. It is responsible for tasks such as radio resource allocation, power control, modulation and demodulation, error correction, and various operational functions. The BBU is essential for optimizing the use of available radio spectrum and ensuring that network resources are efficiently distributed to provide the best possible service to users.

MNOs have various methods to enhance their coverage, capacity, and services, driven by the rapid advancements in wireless network broadband. This evolution has been particularly notable in the RAN. Over time, the RAN has adapted to accommodate more users, faster data rates, and improved Quality of Service (QoS).

One pivotal transformation in the RAN involves its shift towards virtualization, where base station functions are distributed across different physical devices. This not only simplifies RAN management and scalability but can also enhance overall performance. Furthermore, the adoption of innovative technologies like millimeter wave (mmWave) and massive MIMO plays a crucial role. These technologies offer superior data rates and broader coverage, addressing the contemporary demands of users.

The RAN remains a critical component of mobile networks, continually evolving to meet users' ever-changing needs. Through the integration of new technologies and virtualization, mobile network operators can enhance network performance, scalability, and satisfy even the most demanding users.

There are different types of RAN [37], the mains are listed as the following:

- GRAN: The 2G GSM network was built on GRAN, which stands for GSM radio access network.
- GERAN: GERAN stands for GSM EDGE Radio Access Network. In 2003, there was another improvement in GSM systems with the deployment of Enhanced Data rates for GSM Evolution (EDGE) networks.
- UTRAN: Radio access networks for 3G UMTS were known as UTRANs, which stood for UMTS RANs.
- E-UTRAN: The E-UTRAN was developed along with 4G LTE and stands for Evolved UTRAN.
- C-RAN: It is sometimes referred to as centralized RAN or cloud RAN. Unlike traditional RAN, C-RAN consists of separate elements and the remote radio heads remain in place as usual. However, the base band processing units are centralized, allowing the resources to be shared and the RRHs to be more effectively controlled, especially users are handing over from one cell to the next
- O-RAN: One of the major issues with RAN technology is that it consists of many different elements. There are the radio heads containing the RF transmitter and receiver and the base band units containing the control and processing. Traditionally there has been no standardization of the links between the two main units, as well as other elements within the overall RAN.

Table 2.2.1 described components across different mobile network generations, [36],

Generation	Base station	Controller	Backhaul interface	Backhaul aggregation
2G	BTS	BSC	Abis	TDM
3G	NodeB	RNC	lub	ATM/IP
4G	eNodeB	eNodeB, MME, and SGW	S1	IP

Table 2.2.1: RAN component.

2.2.1 Traditional RAN

In a traditional RAN, a single base station integrates both radio and baseband functions. These base stations typically comprise one or more equipment racks, housing both baseband and radio equipment, usually situated at the base of a cell tower. These stations then transmit signals to passive antennas mounted at the tower's apex. As depicted in Figure 2.2.1, coaxial cables (referred to as feeders) connect these antennas to the equipment racks. However, this approach presents several challenges, including the need for substantial shelter space, robust structural support, high acquisition costs, and significant energy consumption.

Furthermore, within this architecture, base station racks experience an approximate 3 dB loss when transmitting signal power to antennas. To overcome these challenges, a distributed Base Station (BS) architecture comes into play. This distributed BS architecture was prevalent during the 1G and 2G eras of mobile network deployments [36].

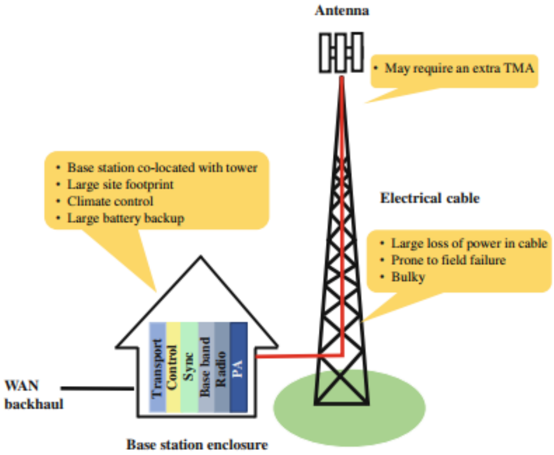

Figure 2.2.1: Traditional RAN [36].

2.2.2 Distributed RAN (D-RAN)

In Distributed RAN, the traditional RAN base station is separated into a radio unit or Remote Radio Unit (RRU) or Remote Radio Head (RRH) and a signal processing unit (BBU). BBUs handls higher-layer processing tasks, dynamically allocating resources to RRUs based on the network's requirements. RRUs, on the other hand, handle RF (radio frequency) functions and incorporate components like power amplifiers (PAs), duplexers, low noise amplifiers (LNAs), as well as analog-to-digital converters (ADCs) and digital-to-analog converters (DACs).

The communication interface connecting the BBU and RRU is typically referred to as the Common Public Radio Interface (CPRI) [38]. One significant advantage of D-RAN is its simplicity of implementation, notably due to the absence of a high-speed interface requirement between the RU and BBU. This autonomy allows each RAN to function independently. However, the increasing proliferation of UEs has led to a higher density of cellular networks, necessitating the construction of additional Base Stations (BSs).

Consequently, cellular network providers face substantial expenditures, including rental costs for BS placement and investments in cooling systems to maintain network efficiency. In response to these challenges, there has been a growing imperative to identify solutions that reduce OPEX. D-RAN can be used with a variety of radio access technologies, such as 2G, 3G, 4G, and 5G.

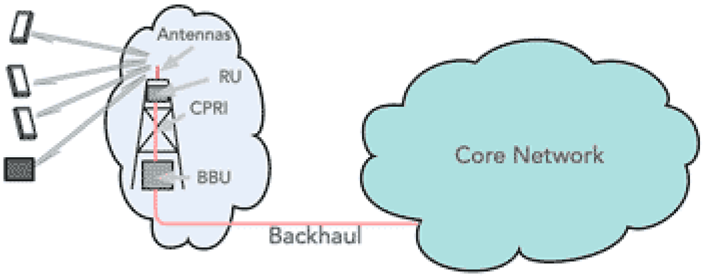

Figure 2.2.2: Distributed RAN [39].

2.2.3 Centralized RAN

C-RAN is a revolutionary network architecture that comprises two fundamental components: the BBU pool and RRHs. In this architecture, numerous RRHs, often numbering in the hundreds or even thousands, are interconnected with a central pool of BBUs through a front haul network, as visually depicted in Figure 2.2.3.

A major advantage of C-RAN architecture is its ability to establish significantly lower costs, greener communication, and capability of supporting advanced wireless technologies such as coordination multi-point due to the centralized processing of the radio signal. C-RAN brings about significant cost savings by centralizing the processing and intelligence of the network. Sharing of BBUs among multiple RRHs reduces the need for redundant equipment at each cell site, cutting down on capital expenditure. Additionally, Centralized processing allows for optimized resource utilization, leading to lower power consumption and reduced environmental impact. [40].It is a vital enabler for the evolving needs of modern telecommunications and the deployment of future wireless technologies.

2.2.4 Virtualized RAN (vRAN)

RAN virtualization heavily relies on concepts such as SDN and NFV. With vRAN, the proprietary radio hardware remains as it is, but the BBU gets replaced by a COTS server rather than being proprietary BBU hardware. In the cloud server, multiple virtual BBUs (vBBUs) are deployed. vBBU can be deployed on either a VM or container. The software that runs on the BBU is virtualized to run

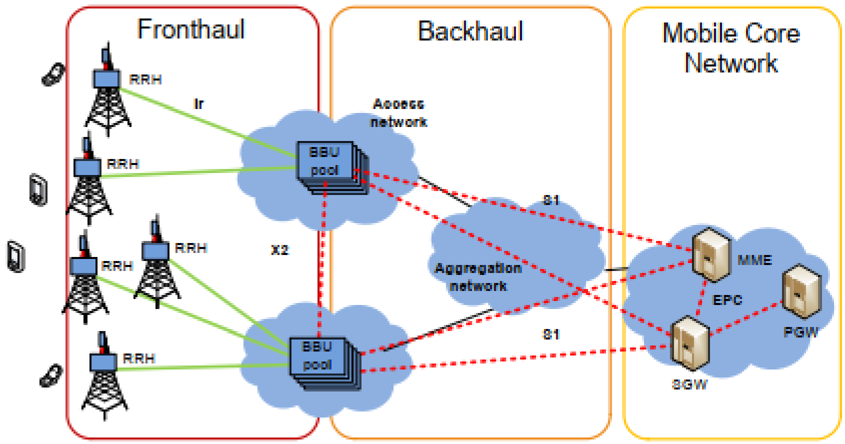

Figure 2.2.3: Centralized RAN [40].

on any COTS server. But the proprietary interfaces between radios and COTS-based BBU remain as they are [41], [42].

Virtualization is an abstraction of physical resources that enables multiple VMs to run on the same physical server. VM applications are isolated from each other. Hypervisors or virtual machine monitors (VMMs) provide an abstraction of physical resources. The hypervisor manages the physical resources and schedules between the VMs. The VMs are configured with virtual resources such as virtual CPU (vCPU) and does not own physical resources (e.g., physical CPU) [4].

The implementation of network function virtualization and cloudification in vRAN, along with its deployment across different scales such as site, far edge, edge, and core clouds, allows for a more flexible and adaptable approach to capacity management. This flexibility and adaptability provide various advantages, such as preventing the need for over-provisioning RAN capacity based on peak traffic demand. Additionally, it offers a practical and cost-effective solution for scaling capacity without the need for unnecessary investments in vDU servers.

Advantage of current RAN

The current RAN architecture offers various benefits [43], [44].

- Lower front haul requirements: The D-RAN architecture eliminates the dependence on front haul connections that have high capacity and low latency, as it adopts a co-location approach where the BBUs and RF components are situated together at the cell sites. Consequently, this significantly reduces the requirement for a complex fiber infrastructure and streamlines the process of deploying the network.
- Network resiliency: In D-RAN, each cell site functions autonomously. In the event of a failure in one cell site, the functioning of other cell sites remains unaffected, thereby ensuring the overall performance and efficiency of the network.

- System integration: the purpose-built RAN solution is a thoroughly tested and fully integrated system that covers all aspects, from start to finish. On the other hand, in numerous scenarios, a virtualized system, especially if it is not purchased from a single vendor, will necessitate extra efforts and expenses for system integration, which must be taken into account.
- When using a pre-integrated end-to-end solution provided by a single supplier, the responsibility for system performance is easily identifiable. However, in the case of a virtualized solution where different suppliers contribute hardware, software, and services, it becomes essential to clearly allocate accountability.

Drawback of current RAN

There are several concerns and challenges associated with implementing current RAN Architecture [45], [44].

- Excessive Cost of D-RAN: The installation, expansion, and maintenance of D-RAN architecture incur substantial costs that significantly affect the capital and operational expenditure of telecom companies. These expenses are attributed to various factors.
  - Independent towers require a significant amount of space, resulting in a considerable ”footprint,” which necessitates telecom companies to lease space for each tower. This can lead to substantial expenses, particularly in urban areas.
  - Because of the extensive amount of data and processing tasks they are engaged in, they require a significant amount of electricity to function. This high demand for power is a direct result of the extensive data handling and computational operations they perform.
  - It is crucial to ensure that the base station equipment is adequately safeguarded from any adverse weather conditions.
- Inefficient use of equipment: investments in D-RAN can often be considered highly inefficient due to the specific construction and configuration of the network. This inefficiency stems from the fact that each base station within the network operates independently, and is consequently designed to handle the maximum demand of a particular region.
- Inefficient use of radio frequency: One of the challenges faced by independent cells is the absence of coordination, which leads to antennas having to vie for the limited radio frequencies that are available. This competition among antennas can result in interference between radio signals, thereby complicating the operation and expansion of D-RAN.

2.3 Open RAN network

Open RAN was first proposed in May 2002 and has gained traction in recent years due to the challenges faced by traditional RAN deployments, such as the high cost of proprietary hardware and software, the lack of interoperability between different vendors, and the difficulty of upgrading and scaling networks. It is a concept that aims to define and build 2G, 3G, 4G, and 5G RAN solutions based on general-purpose, vendor-neutral hardware and software-defined technology with open interfaces between all the components. Also It is a movement to drive the mobile industry towards an ecosystem of innovative, multi-vendor, interoperable, and autonomous RAN, with reduced cost, improved performance, and greater agility. [46], [42], [41].

RAN equipment must be deployed efficiently and rapidly to handle the growth in cellular data traffic, high data rates, and large server storage capacities. But in traditional RAN deployments, Hardware, software and interfaces is proprietary or “closed” by the individual vendor and are often tied to the underlying hardware by the same vendor. Moreover, dense base station deployment causes severe co-channel interference at cell edges, which negatively impacts user experience. These challenges were addressed with the development of the Open RAN.

2.3.1 Architecture of open RAN

The open RAN paradigm will dramatically change the design, deployment and operation of next-generation cellular networks (gNB). gNB is split into CU, DU, and RU. The CU is further split into two logical components, one for the Control Plane (CP), and one for the User Plane (UP). This logical split makes it possible to deploy different functionalities in different places on the network, as well as on different hardware platforms.

The functional decomposition of the RAN is necessary to meet different transport needs in terms of different performance requirements and to adapt to different types of traffic of different performance goals, for example, very high throughput compared to extremely low latency [47].

As shown figure 2.3.1 the open RAN architecture is composed of two main groups: the radio group and the management group. The radio group is comprised of various components such as Near-Real Time RIC (Near-RT RIC), Next Generation RAN (NG-RAN) which includes O-RU, O-DU, O-CU, and O-RAN eNodeB (O-eNB) [48]. These components are responsible for facilitating radio communications within the system.

On the other hand, the management group consists of the Service Management and Orchestration (SMO) framework and the Non-Real Time RIC (Non-RT RIC). This group is responsible for managing the system’s performance. Additionally, the Open RAN Cloud (O-Cloud) is a cloud computing platform that serves as the host for various Open RAN functions and software. The Open RAN concept involves the use of COTS servers for the software components of the DU and CU, while RU can be sourced from any vendor. The DU works closely with the RU and is controlled by the CU. The CU

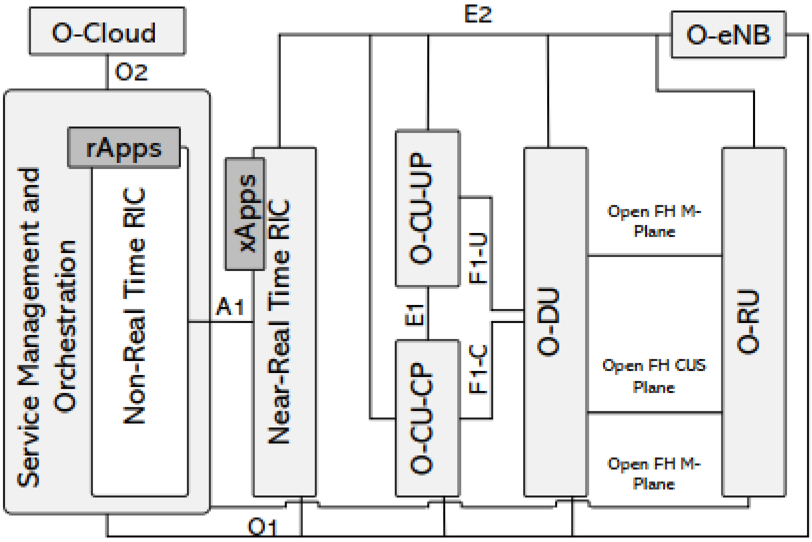

Figure 2.3.1: Open RAN architecture [48].

is connected to the DU and controls its operation. It can also support multiple DUs and control their operation over the midhaul interface. Additionally, the CU can be co-located with the DU software on the same server at the site.

2.3.2 Open RAN functional split

Many well-known operators have opted open RAN as their preferred choice for implementing 5G networks. Open RAN is enabled by the use of standardized open network interfaces, which are outlined in various organizations such as 3GPP, O-RAN Alliance, IEEE, and other industry fora and standards development organizations (SDOs).

Open RAN works by distributing the processing of baseband functions across different logical nodes, which in turn determines the attributes of the links, especially in the front haul. 3GPP has established various options known as functional splits, which outline the relationships between these logical nodes and detail the specific tasks that each node is responsible for. In addition to the traditional ”monolithic” NG-RAN architecture, 3GPP have defined the following two split architectures [9]:

- Split option 2 which is high-level CU/DU split,
- NG-RAN architecture with separated control and user plane functions.

Small Cell Forum has adapted its functional application platform interface (FAPI) specification for option 6 to accommodate the advancements in 5G technology. Similarly, the O-RAN Alliances have defined the low-level split, known as option 7. The CPRI specification has been improved and is now referred to as eCPRI, enabling support for not just option 8 but also higher splits.

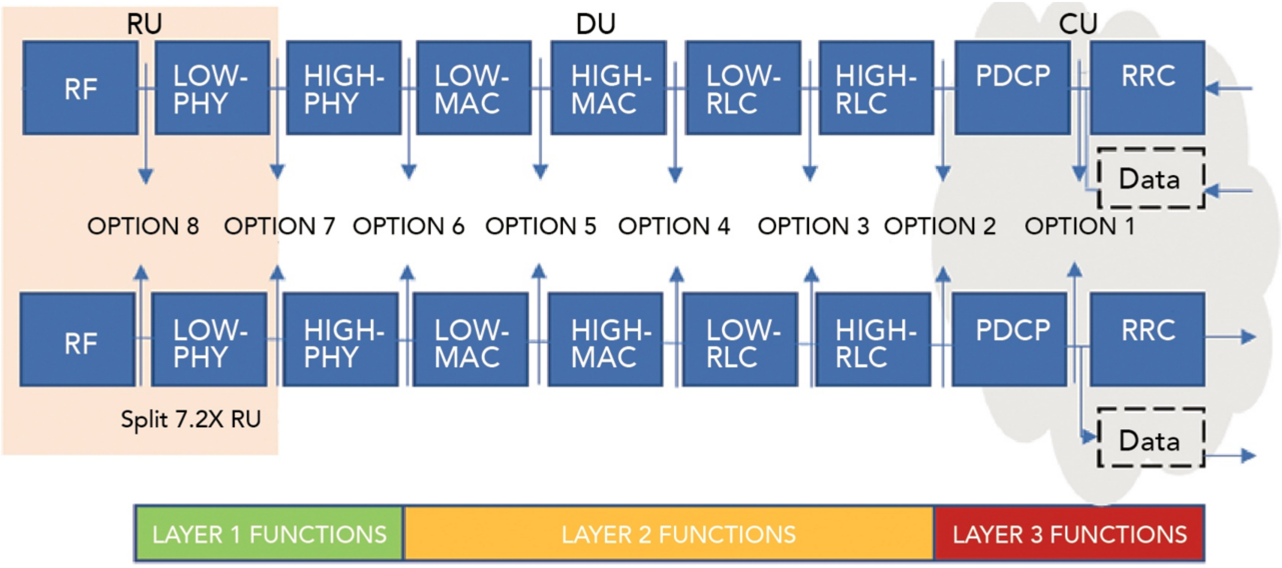

Figure 2.3.2: Functional Splits [49].

As can be observed from the figure 2.3.2; Different RAN functional splits work for different use cases. Split 8 will be the best option for 2G and 3G whereas Split 7.2 is the best for 4G and 5G so in case of requirements for more delay-sensitive service, based on appropriate front haul availability, the MAC-PHY split will be the preferred solution. Open RAN architectural component function are described below based on split 7.2 [48].

- **RU:** is Deployed on site near to the antenna, the RRU converts radio signals sent to and from the antenna into digital data for transmission. It controls the digital front end (DFE), the lower layer 1 (L1, physical layer) baseband processing, as well as front haul transport.
- **DU:** is physically closer to the RU and it connected to multiple RUs and the CU. The DU handles real-time layer 1 (higher L1, physical layer) and lower layer 2 (L2, Data Link Layer) functions including MAC (Media Access Control) and RLC (Radio Link Control).
- **CU:** controls DU operation, connects to the cellular network, and communicates with other base stations. It is responsible for performing non-real time, higher L2 and L3 (network layer) protocol stack workloads, such as the functions of RRC (Radio Resource Control) and PDCP (Packet Data Convergence Protocol). One CU can manage one or more DUs over the midhaul interface.

The split architecture of open RAN enables the coordination of performance features, load management, and real-time performance optimization. This allows for adaptation to various use cases and QoS requirements, which have different latency tolerances and depend on the transport network and deployment scenario (e.g., rural or urban) [8].

Suitable functional splits for dense urban areas are higher functional splits are typically used for capacity applications, while lower functional splits are used in rural areas for coverage applications. The performance of the fronthaul network is more important for higher functional splits, as lower functional splits rely on less-than-perfect fronthaul networks. Hence, Open RAN enables the distribution of protocol stacks between the CU and DU based on network design, fronthaul & midhaul availability [49].

Open RAN use cases

As defined by the O-RAN Alliance, Open RAN Use Cases leverage the RAN architecture by utilizing artificial intelligence and machine learning to control the real time behavior of the RAN and by focusing on optimizing RAN with configurations in order to improve its performance. The use cases are prioritized as per MNOs' requirements. Open RAN use cases include [21]:

Open RAN Key Use Cases for Phase I:

- White-box Hardware Design
  - **Low Cost RAN White-box Hardware:** is a key use case of open RAN. which refers to the use of COTS hardware for RAN base stations. COTS hardware is typically much less expensive than proprietary hardware, as it is designed for a wider market and can be mass-produced. Additionally, COTS hardware can be customized to meet the specific needs of each operator, as it is not tied to a specific software platform. Finally, COTS hardware can help to accelerate innovation in the RAN market, as it is open and accessible to a wider range of players. Some specific examples of the benefits of white-box hardware design in open RAN [21]:
    - Cost savings: COTS hardware is typically much less expensive than proprietary hardware, which can save operators significant costs.
    - Flexibility: COTS hardware can be customized to meet the specific needs of each operator, which can give operators more control over their networks.
    - Innovation: COTS hardware can help to accelerate innovation in the RAN market, as it is open and accessible to a wider range of players.
- AI-enabled RAN and Open RAN Interfaces (O1/A1/E2)
  - Traffic Steering

  - QoE Optimization
  - QoS Based Resource Optimization
  - Massive MIMO Optimization

Open RAN Key Use Cases for Phase II:

- AI-enabled RAN and Open RAN Interfaces (O1/A1/E2)
  - RAN Slice SLA Assurance
  - Context Based Dynamic Handover Management for V2X
  - Flight Path Based Dynamic UAV Resource Allocation
  - Radio Resource Allocation for UAV Applications
- Virtual RAN Network
  - RAN Sharing

2.3.3 Open RAN Deployment scenario

One major option for operators to improve their RANs is to disaggregate the architecture, modularize, and virtualize the deployments. Disaggregating software from hardware is one method of implementing Open RAN, allowing RAN software to run on any popular hardware platform such those based on Intel x86 and ARM architectures [46]. Different deployment scenario are described in fig 2.3.3 and discussed as folows[21],[13].

Scenario A: A single edge cloud is used here to centralized all near-RT RIC, virtual O-CU, and O-DU functions, enabling the deployment of a high-capacity front haul network in dense urban areas. An edge cloud with substantial hardware acceleration capabilities is expected for this type of deployment.

Scenario B: With this scenario, virtual O-CUs and O-DUs are separated from near-RT RICs, which can be placed in a regional cloud and are interfaced with through E2. For near-RT RIC, this gives a global view of optimization.

Scenario C: In a regional cloud, virtual O-CU network services can be co-located with the near-RT RIC to reduce latency and meet the latency criteria of the 3GPP-defined F1 interface. This allows for deployment in areas with limited front haul capacity and O-RUs.

Scenario D: This example is the same as of Scenario C, except it uses a PNF that is capable of

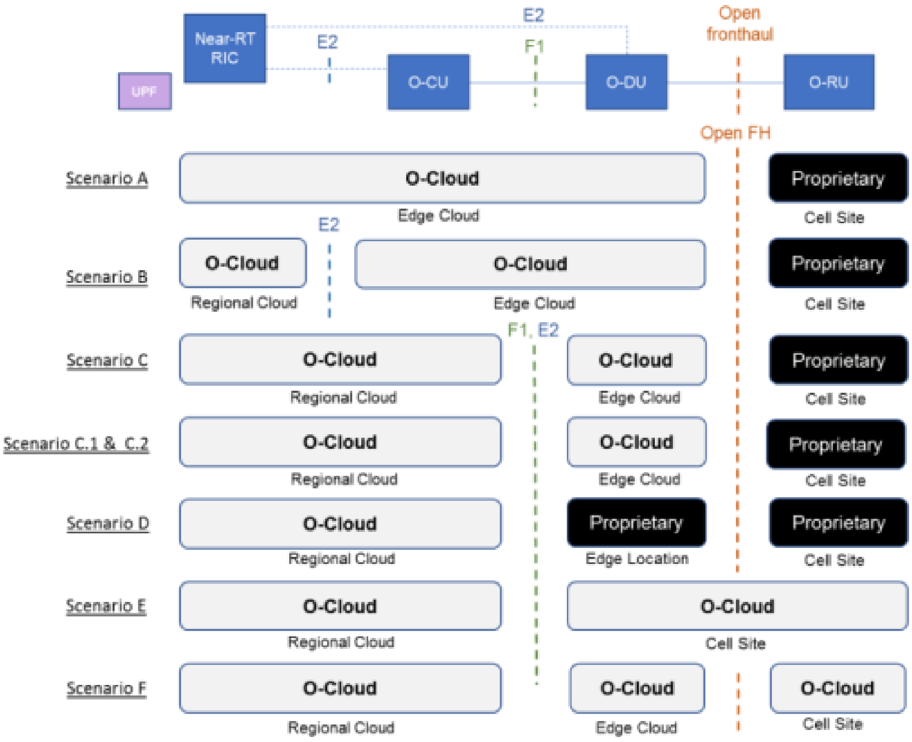

Figure 2.3.3: Open RAN deployment scenario [21].

supporting O-RAN, rather than a virtualized O-Cloud. Scenario E: It is replica of Scenario C, in which both O-RU and O-DU functions are virtualized into a common O-Cloud

Scenario F: This example is the same as of Scenario E. The O-DU and O-RU functions are virtualized into separate O-Clouds in this scenario.

2.3.4 Benefits of Open RAN

Open RAN creates a unified architecture through the disaggregation of hardware and software, bringing several benefits such as low latency and network slicing. In addition to facilitating network automation, Open RAN provides the following benefits:

- Open standard interfaces increase interoperability between different equipment and help create a diverse supplier ecosystem by engaging a broader participation of vendors in 5G development.
- Using multi-vendor COTS hardware prevents proprietary vendor lock-in risk and provides solution agility and new capabilities leading to further innovation, giving operators more deployment options and partnership resources to quickly address 5G issues and deliver the best possible customer experience.
- Increased virtualization of network functions extends cloud capabilities to the edge of the net-

work, minimizing physical deployment limitations and costs to accelerate 5G penetration.

- One of the key benefits of network automation is the significant reduction in OPEX. This is achieved through the implementation of plug-n-play configuration and hands-free optimization, which greatly diminishes the need for professional services to handle deployment or maintenance tasks [50].

2.3.5 Challenge of open RAN

When planning the deployment and management of Open RAN networks, operators are primarily concerned with ensuring interoperability, manageability, optimization, and end-to-end performance, especially in a multi-vendor environment.

Today, networks must support multiple technology generations, such as 3G, 4G, and 5G, while also scaling up to meet the ever-increasing demand for data. The design of a 5G RAN must carefully consider features such as multiple-input, MIMO antennas and multi-band carrier aggregation. However, incorporating these features poses a significant challenge to the successful growth and maintenance of networks. This further highlights the complexity and difficulty that operators face in effectively managing and expanding their networks.
Some challenges regarding the implementation of open RAN include [51]:

- It is challenging to deploy policies for the RIC, near-RT and non-RT control loop meeting the economical and ecological aspects.
- Coordination, updation and training is difficult with the modern learning techniques.(i.e., ML and AI).
- It is challenging to handle data (specifically cross layer data) to support the intended operation while protecting other internal operations.

Orchestration & Performance challenges: this challenges include on service management and intelligence management challenges. The Open RAN faces significant challenges in terms of deploying and managing various hardware and software components due to its multi-vendor ecosystem.

While the Open RAN Software Community has established standard interfaces to ensure interoperability between different vendors, there are still lingering concerns surrounding the operations, administration, and maintenance aspects [48]. Also intelligence plays a crucial role in Open RAN as it assists in tackling the escalating intricacy of mobile networks, which stems from the rising user demand and data consumption. This is achieved by incorporating intelligence at both the network and component levels, enabling efficient resource management and optimization [52],[41].

Security challenges: Open RAN harnesses the power of network softwarization and Artificial Intelligence to optimize the functioning of RAN devices and operations. By creating an open ecosystem, Open RAN facilitates the development of diverse RAN solutions by various stakeholders. Nonetheless, while Open RAN brings about numerous advantages, it also introduces novel security and privacy concerns. Given the significant departure from traditional RAN configurations, mismanagement of Open RAN could potentially result in grave security and privacy ramifications [53].

2.3.6 Related technologies

Open RAN is a new radio access network architecture that uses a variety of technologies and approaches to create a more open and intelligent network. These technologies include disaggregation, SDN, NFV, functional split, cloudification, automation, intelligence, network slicing, open source, and mobile edge computing (MEC). The specific technologies and approaches that are used will depend on the specific requirements of the network.

Cloudification

Cloudification is the process of moving network functions to the cloud. This makes it possible to scale the network more easily and efficiently, as well as the ability to take advantage of the latest cloud-based technologies. Also Containerization is a virtualization technology that allows multiple applications to run on the same operating system instance. This makes it more efficient to utilize hardware resources and simplifies the deployment and management of applications [54]. This offers a number of advantages over traditional RAN architectures, including:

- Scalability and flexibility: Cloud RAN can be easily scaled up or down to meet changing traffic demands. It also offers greater flexibility in deploying and managing RAN functions.
- Cost savings: Cloud RAN can help to reduce the cost of RAN infrastructure and operations.
- Innovation: Cloud RAN makes it easier to introduce new features and services into the network.

MEC

MEC ais a technology that brings computing resources closer to the end users. This can be used to improve the performance of applications and services, as well as to reduce latency. It is a key enabler of the 5G network, providing ultra-low latency and high bandwidth capabilities at the edge of the network. This makes it ideal for hosting and delivering applications and services that require real-time data processing and response.

In the past, Communications Service Providers (CSPs) have primarily focused on providing connectivity services to consumers. However, the increasing demand for new and innovative applications and services is driving CSPs to look for new ways to monetize their networks. MEC provides CSPs with a new opportunity to do this by opening their networks to third-party developers and businesses.

Moving network functions to the edge is a crucial way to improve the performance of mobile networks. This is especially important in virtualized networks, where the location of network functions is more flexible. MEC allows software applications to take advantage of local resources and conditions, which can reduce latency, improve performance, and reduce bandwidth usage. By deploying services and caching content at the edge, MEC can also help to relieve congestion on the mobile core network [55].

Disaggregation

Disaggregation is the process of separating the different components of the RAN. This allows for greater flexibility and choice in the selection of components, as well as the ability to upgrade or replace components more easily.

SDN

SDN is a networking technology that decouples the control plane from the data plane. This allows the network to be more easily managed and controlled, and it also makes it possible to create more flexible and dynamic networks.

NFV

NFV is a technology that allows network functions to be virtualized and run on general-purpose hardware. This makes it possible to create more agile and cost-effective networks, as well as the ability to deploy new services more quickly.

Functional split

Functional split is the process of dividing the functionality of the RAN into different components. This allows for greater flexibility and choice in the selection of components, as well as the ability to optimize the performance of the RAN for different use cases.

Automation

Automation is the use of software to automate the operation and management of the network. This makes it possible to reduce costs and improve efficiency, as well as the ability to respond to incidents more quickly.

Intelligence

Intelligence is the use of artificial intelligence (AI) and machine learning (ML) to improve the performance of the network. This can be used to optimize the performance of the network for different use cases, as well as to detect and mitigate threats.

Network slicing

Network slicing is the process of dividing the network into logical networks, each with its own dedicated resources. This allows for the creation of different types of networks, such as private networks and public networks, as well as the ability to support different use cases.

Open source

Open source is the practice of developing software with open access to its source code. This allows for greater collaboration and innovation, as well as the ability to customize the software to meet specific needs.

Chapter 3

Techno-economic Modeling and Evaluation Method

3.1 Techno-economic Result from ACTS (TERA) Model

The TERA (Techno-Economic Results from ACTS) model is a comprehensive techno-economic analysis tool that was developed by the European Union's Advanced Communications Technologies and Services (ACTS) program to assess the economic feasibility of different telecommunications technologies and architectures. As shown in figure 3.1.1 the model integrates various factors, such as technical aspects, market conditions, economic considerations, and costs associated with network elements, to provide a holistic assessment of the economic viability of a new technology or service [56],[57].

The TERA model is a valuable tool for decision-makers who are considering investing in new telecommunications technologies and services. The model can be used to evaluate the economic feasibility of different technologies and architectures, and to identify the risks and uncertainties associated with a particular project.

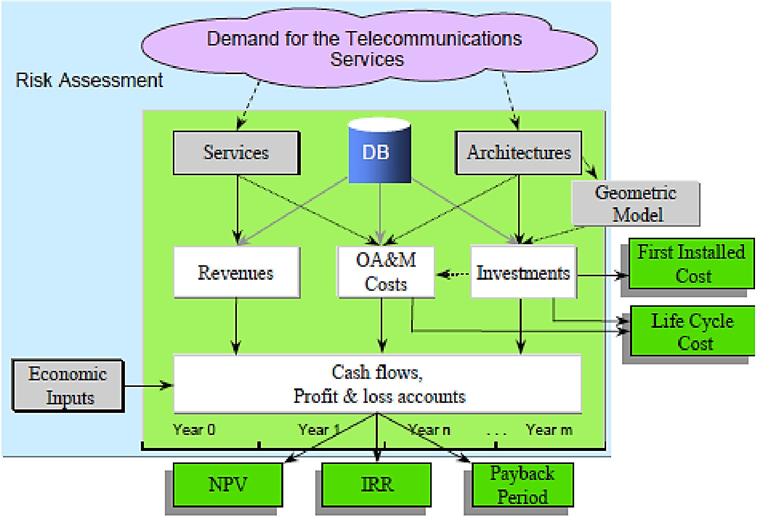

Figure 3.1.1: TERA framework [58].

3.2 Open RAN TEA Model

The TERA model is used in this thesis to conduct a techno-economic analysis of the deployment of Open RAN. The inputs to the model include the marketing, technical, and economic parts. The model is based on network dimensioning, mathematical modeling and cost calculations. The outputs of the model include the revenues, costs, cash flows, and other economic indicators for the network. The implemented TERA model are presented in the figure 3.2.1.

3.3 Input data

The open RAN TEA model can be used to evaluate the cost and performance of open RAN. The model requires a variety of data sets, including cell site data, network configuration data, hardware and software data, and financial data. By using this data, the model can provide operators with valuable insights into the potential benefits of deploying open RAN. Each input data set can be described and explained in the following way:

3.3.1 Cell site data

Cell site data is essential for network planning, optimization, and troubleshooting. By analyzing cell site data, operators can gain insights into the performance of their networks and identify areas where improvement is needed. This data includes information on the configuration of the cell site, data throughput, and C-plane traffic.

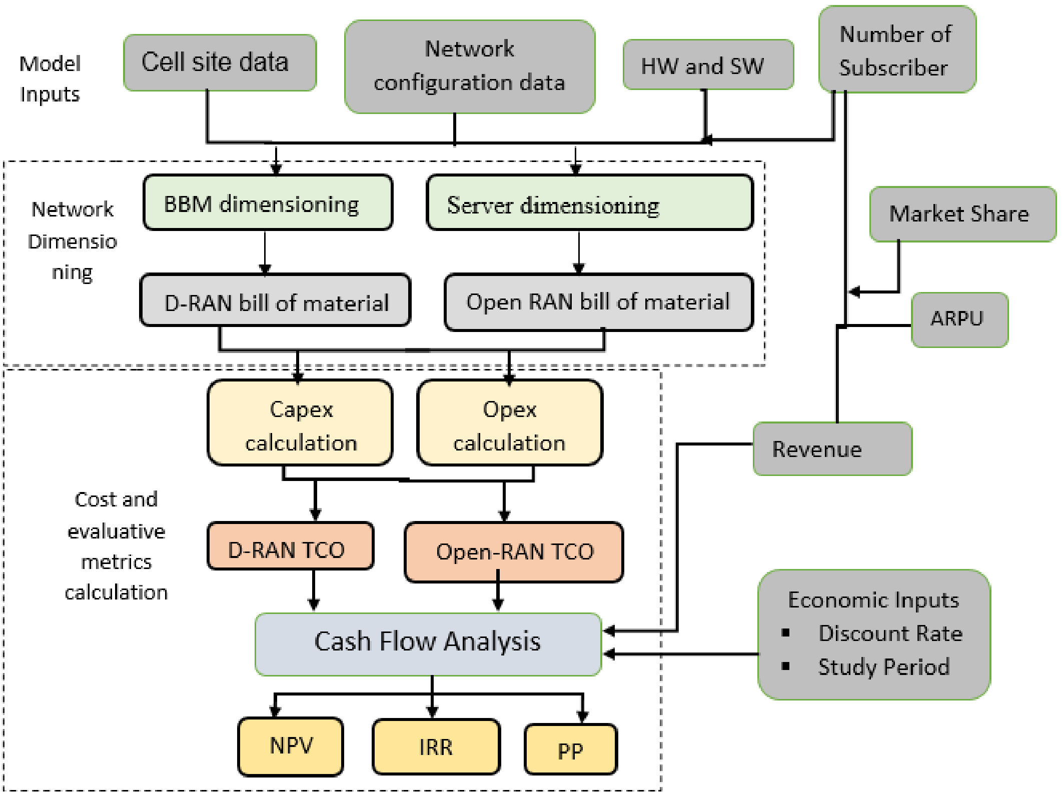

Figure 3.2.1: Implemented TEA model.

1. **Cell configuration:** is the physical and logical parameters of a cell site, such as the carrier frequency, bandwidth, and MIMO configuration. Cell configuration has a significant impact on the performance of a cellular network, including the capacity, coverage, and data throughput.
   - It determines how many cells are in a network, as well as peak throughput in downlinks and uplinks. Also used to design cell size limitations and cell connectivity in network dimensioning.
2. **Data throughput:** is the amount of data that is transferred over a network over a period of time. It is typically measured in bits per second (bps). It is an important metric for measuring the performance of a cellular network, as it indicates how much data the network can support. This data includes the number of calls, the amount of data traffic, and the type of traffic (voice, video, or data) that is being carried by the cell site.
   - Includes Average busy hour (BH) throughput per site and Traffic share per day on the site for BH.
   - Used for throughput requirement calculations in the server dimensioning.
3. **Control plane traffic:** is essential for managing and controlling the cellular network. It is used to manage and control the network, including establishing and maintaining connections

between UEs, managing the network's resources, and ensuring that the network is operating efficiently.

- Includes Maximum connected user per site, Average connected user per site, Control plane load per connected user
- The CUE per site parameter provides information about the number of devices connected to a specific site. It is also used to determine the signaling frequency of these devices, known as the C-plane load per CUE. Additionally, the CUE per site plays a role in calculating the number of RRC connected users within the network. These parameters are crucial in the process of network dimensioning requirement calculations.

3.3.2 Network configuration data

Network configuration data includes information on the topology of the network, the types of equipment that are used, and the configuration of those devices. This data is needed to model the network and to understand how RAN architecture would impact the performance and cost of the network. It is used to quantify the overall quantity of networking hardware and networking software licenses needed.

1. It includes information on the type and number of network elements, such as base stations, routers, and switches. It also includes information on the software used by each network element. This data can be used to calculate the number of licenses needed for each software application.
2. It can also be used to estimate the overall cost of networking hardware and software for each RAN architecture.

3.3.3 HW and SW data

Hw and SW data includes information on the hardware and software used in a network, as well as their specifications, performance, capabilities, and limits. This data includes information on the type, model, and specifications of the hardware used in the network, such as base stations, routers, and switches. The software data includes information on the type, version, and specifications of the software used in the network, such as operating systems, network management software, and applications. This data can be obtained from different sources, including operators, books, literature, and other relevant sources.

1. BBM data: includes Cell connectivity and control plane capacity per BBMs, BBM energy consumption and BBM maximum and minimum configurations per cabinet
    - Used for BBM dimensioning and to calculate energy consumption of the network.
2. vRAN server data: is essential for dimensioning VNFs, vRAN servers, and VMs. It includes, CPUs per server, CPUs requirement per VMs, capacity limit of VM and VNF
    - used for VNFs, vRAN servers, and VMs dimensioning.
3. Software licenses: includes BB and cloud software licenses
    - To estimate the cost of the network software licenses required.

3.3.4 Financial data

Financial data includes information on the cost of previously owned hardware and software licenses, which is crucial for determining CAPEX. It also encompasses various expenses associated with network operations, such as energy prices, rental fees for cell sites and data centers, and costs of hardware upgrades and installations. These expenses are essential for calculating the OPEX of the network. This data can be obtained from a different sources, including operators, books, literature, and other relevant sources.

3.4 Network Dimensioning

Network dimensioning is the process of determining the number and type of network equipment that is needed to support a given level of traffic and service quality. It is a critical process for both D-RAN and Open RAN networks, as it ensures that the network is able to meet the needs of its users without over-provisioning or under-provisioning resources.

The network dimensioning approach in this thesis is adapted from the papers [12], [25] and customized to the local context. The general principles of network dimensioning from those papers are taken and applied them to the specific conditions. Network dimensioning requirements can vary depending on a number of factors, such as the type of network, the traffic load, and the regulatory environment.

The result of network dimensioning is a comprehensive bill of materials (BoM) of all the necessary baseband processing hardware and software licenses for both D-RAN and Open RAN architectures. This BoM is an essential tool for operators who are planning to deploy a new D-RAN or Open RAN network. It provides a clear understanding of the hardware and software that is required to support the desired network capacity and service quality. The BoM includes the following information:

- The type and quantity of hardware required, such as baseband units and servers.
- The type and quantity of software required, such as operating systems, network management software, and applications.
- The cost of the hardware and software.

Network dimensioning includes:

- Baseband module dimensioning
- Server dimensioning

3.4.1 Baseband module dimensioning

In D-RAN, the dimensioning process focuses on the number and capacity of BBUs required to support the desired network capacity. The number of BBUs is determined by the number of cell sites in the network, while the capacity of each BBU is determined by the traffic load expected at each cell site.

BBM hardware is a critical component of D-RAN architectures. It is responsible for processing the radio signals from the base station antennas and performing functions such as modulation, demodulation, coding, scheduling, routing, and quality of service control. Within D-RAN architectures, the hardware for the BBM is situated at individual cell sites, making the dimensioning process specific to each site. It is comprised of three distinct units: the capacity plug-in unit (CAP), the main processing unit(MPU), and the cabinet unit (CBN)[59]. BBM unit are described below:

- **Capacity plug-in unit (CAP):** responsible for processing the radio signals from the antennas. The number of CAPs required depends on the traffic load at the cell site.
  - The capacity of a single CAP unit to accommodate cells is determined by the bandwidth and MIMO configuration of the cell.
- **Main Processing Unit (MPU):** The MPU is responsible for controlling the CAPs and other BBM components. There is typically one MPU per cell site.
  - It handle the C-plane traffic and establish connections between multiple BBMs. COM is responsible for managing the transport and centralized control functions for various radio access technologies, as well as routing antenna data.

- **Cabinet unit (CBN):** The CBN houses the CAPs, MPU, and other BBM components. The number of CBNs required depends on the size of the cell site.
    - Additionally, it provides a backplane for internal communication and ensures that the units are properly cooled through air conditioning.

The BBM dimensioning process uses data from cell sites, network configurations, as well as the hardware and software. As illustrated in Figure 3.4.1, the BBM dimensioning process incorporates these variables to determine the necessary number of CAP, MPU, or CAB units required per cell site. Once the dimensioning for the BBM units at each cell site is complete, multiplying this figure by the total number of cell sites yields the overall number of BBM units needed for the entire network.

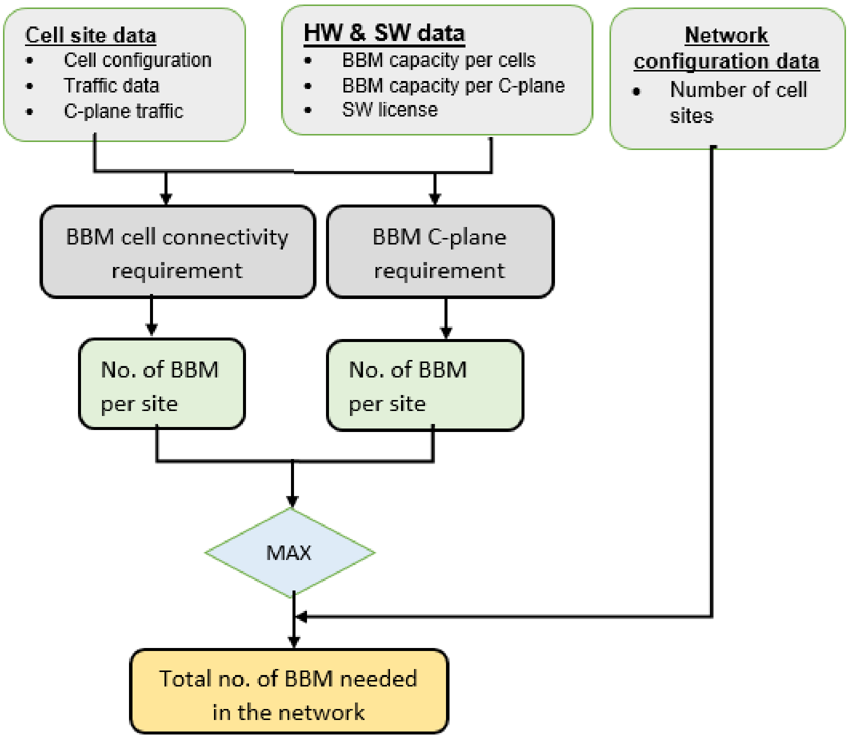

Figure 3.4.1: Baseband module dimensioning Flow chart[12][25].

BBM module dimensioning requirements are explained below:

- **Cell connectivity requirements:** refer to the number of cells that need to be connected to the BBU. This depends on the size of the network and the traffic load.
    - Capacity unit (CAP):
        - The processing requirement of cells varies depending on the bandwidth and MIMO being used. When higher bandwidth and MIMO are employed, the CAP unit needs to allocate more resources, and it is necessary to ensure that the number of CAP units

    per site is sufficient to meet the overall processing needs of the cells.

  - Main Processing Unit (MPU):
    - ∗ Used for cell connectivity requirements. The CAP unit is the primary component responsible for meeting cell connectivity requirements. Nevertheless, it is essential to have at least one MPU module for every cabinet.
  - Cabinet Unit (CAB):
    - ∗ CBN unit has the role of accommodating the other two units. The number of CBN units needed is determined by the maximum capacity for accommodating the CAP and COM units.

- **Control plane connectivity requirements:** refer to the number of control plane messages that need to be exchanged between the BBU and other network elements.
  - Capacity unit (CAP):
    - ∗ The CUE per cell and the load per CUE on the C-plane are responsible for determining the amount of C-plane traffic on sites. It is crucial to ensure that the number of CAP units meets the necessary capacity to effectively handle the processing requirements of this C-plane traffic.
  - Main Processing Unit (MPU):
    - ∗ There are two configurations for MPU units, namely single deployment and double deployment. The choice of configuration depends on the amount of C-plane traffic.
  - Cabinet Unit (CAB):
    - ∗ The determination of CAP units and MPU units in a CAB system is based on the capacity of cells that can be accommodated in each cabinet. This includes the number of cells that can be supported per CAP unit as well as the required number of MPUs to manage the control plane traffic.

3.4.2 Server Dimensioning

In Open RAN architecture, the dimensioning process focuses on the number and capacity of servers required to support the desired network capacity. The number of servers is determined by the number of VNFs that need to be hosted, while the capacity of each server is determined by the resources required by each VNF [20].

Server dimensioning is used to determine how many servers are needed by the VNFs to handle the virtualized baseband processing. NFV is a technology that enables the implementation of VNFs through software. These VNFs can be composed of multiple VMs or containers, all operating on commonly used servers, switches, and storage devices that are readily available in the market, commonly referred to as COTS hardware. Utilizing this software, the VMs or containers are able to perform the same networking tasks as their physical hardware counterparts [60].

This thesis focus virtualization of both DU and CU baseband processing. This virtualization is achieved by implementing VNFs (virtualized BBU pools) on top of COTS servers. The number of servers required by the VNFs is determined by the server dimensioning. The virtualized baseband processing functions are carried out by multiple VMs within the vRAN's VNFs. These VMs are responsible for handling both NRT and near RT baseband functions in the virtualized environment.The VM Management is typically implemented with OpenStack for VM deployments [20].

To ensure efficient processing of these baseband functions, several VMs are deployed. These include the Cell VM , User VM (UE VM), OAM VM, and Central eNB VM (CeNB VM). Each of these VMs serves a specific purpose and contributes to the overall functionality of the virtualized baseband processing system. Server dimensioning involves determining the necessary number of VMs in a network. This calculation is performed using the Cell VM and UE VM dimensioning. Additionally, it is assumed that the number of necessary OAM VMs and Central eNB VMs is equivalent to the number of VNFs, thus eliminating the need for separate dimensioning procedures. The process of server dimensioning is described figure 3.4.2.

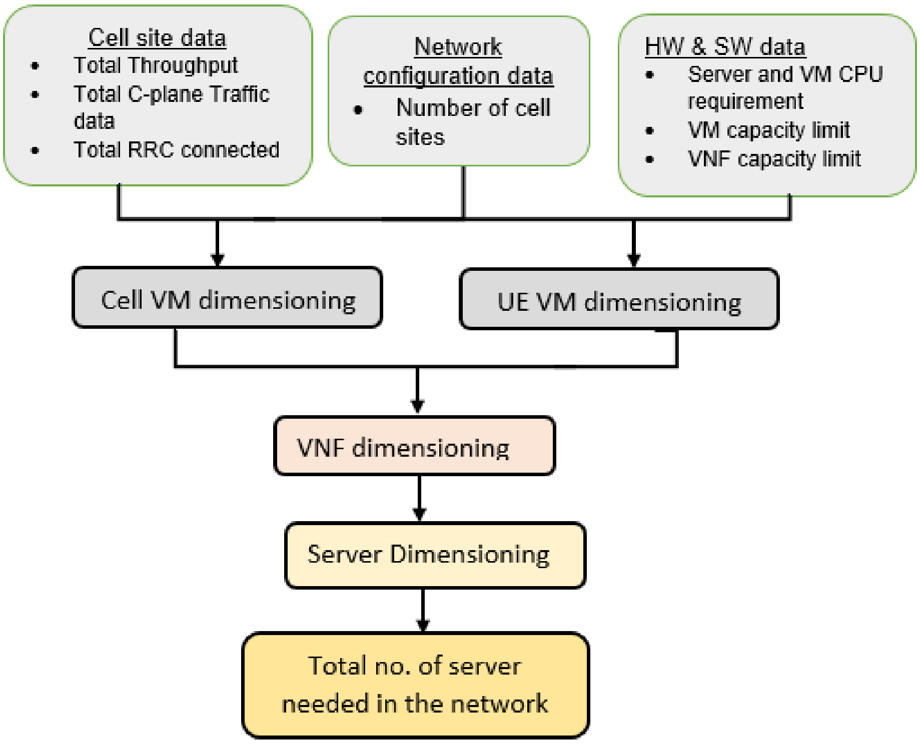

Figure 3.4.2: Server dimensioning flow chart [12][25].

The input for server dimensioning are explained below:

Cell VM dimensioning

Cell VM is responsible for running the cell related functions in the VNF. Cell VM dimensioning is the process of determining the number of Cell VMs required to support the expected traffic load at each cell site. It is based on three parameters, total number of cells, number of simultaneous RRC connected users and C-plane traffic in the network. The HW & SW data defines the Cell VM's capacity limits for each of these parameters. These capacity limits are then used to determine the Cell VM dimensioning requirements. The dimensioning process follows the steps outlined in Figure 3.4.3.

The Cell VM dimentioning requirements are explained below:

- Cell connectivity requirements
  - State the number of Cell VMs required to handle the total number of cells in the network.
- Concurrent RRC connected user Requirements
  - State the number of Cell VMs required to support the total number of RRC connected UEs in the network.
- C-plane traffic

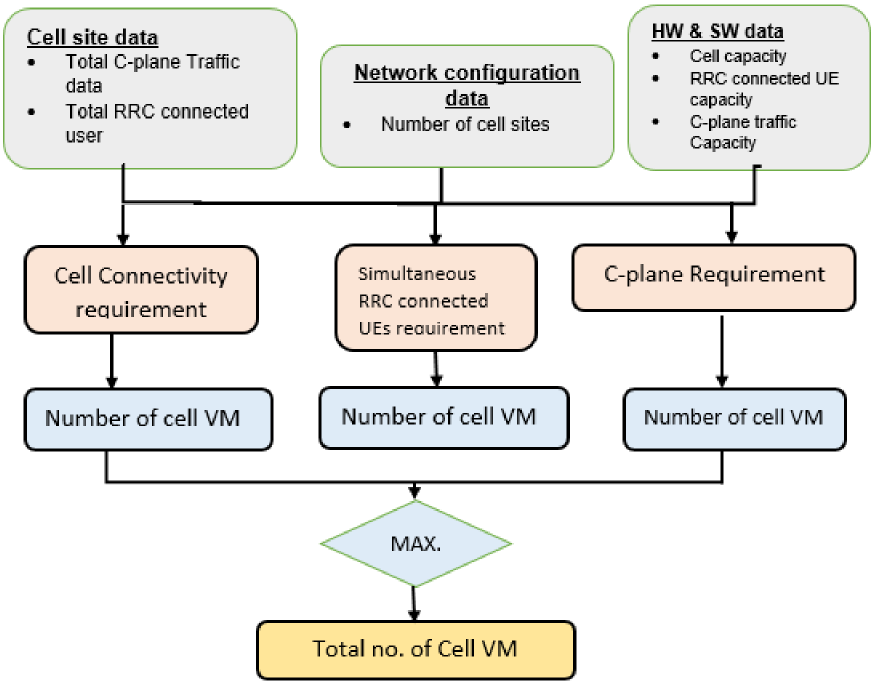

Figure 3.4.3: Cell VM dimensioning flow chart [12][25].

  - State the number of Cell VMs required to support total C-plane traffic in the network.

UE VM dimensioning

UE VM is responsible for processing the user related functions in the VNF. It hosts the UE functions for a single user. UE VM dimensioning is the process of determining the number of UE VMs required to support the expected traffic load at a cell site. It is done based on the total uplink and downlink throughput traffic, simultaneous RRC connected user, and C-plane traffic in the network. Figure 3.4.4 illustrate, in UP VM dimensioning there are different requirement to fulfil this includes Throughput requirements, Concurrent RRC connected user Requirements, Control plane traffic requirements. From the required number of VM for each requirement the maximum number of VM can be selected.

- Throughput requirement is the number of UP VMs required to handle the total downlink and uplink throughput from cell sites in the network.
- Concurrent RRC connected user Requirements is the number of UP VMs required to handle the total number of RRC connected UEs in the network.
- Control plane traffic requirements is the number of UE VMs required to support total C-plane traffic in the network.

VNF dimensioning

VNFs are composed of multiple VMs. The quantity of VNFs needed in a network is influenced by

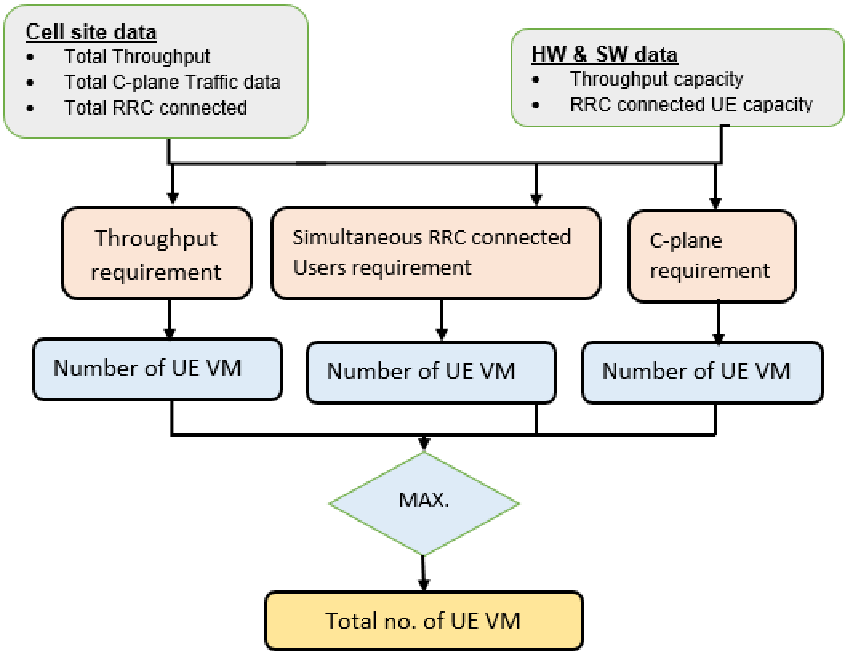

Figure 3.4.4: UE VM dimensioning flow chart [12][25].

various factors, such as the total number of cells, C-plane traffic, and the overall count of Cell VMs and UE VMs present in the network. The hardware and software specifications of the VNF determine its capacity for each of these parameters, ultimately establishing the necessary VNF dimensioning requirements. Utilizing these input values, the appropriate number of VNFs can be calculated for each requirement, allowing for a comparison of results to select the maximum number of VNFs. Figure 3.4.5 shows VNF dimensioning flowchart.

VNF dimensioning requirement are discussed below:

- Cell connectivity requirement: is the number of VNFs required to support the total number of cells in the network.
- C-plane traffic requirement: is the number of VNFs required to support the total C-plane traffic in the network.
- Cell VM requirement: is the number of VNFs required to support the total number of needed Cell VMs in the network.
- UE VM requirement: is the number of VNFs required to support the total number of needed UE VMs in the network.

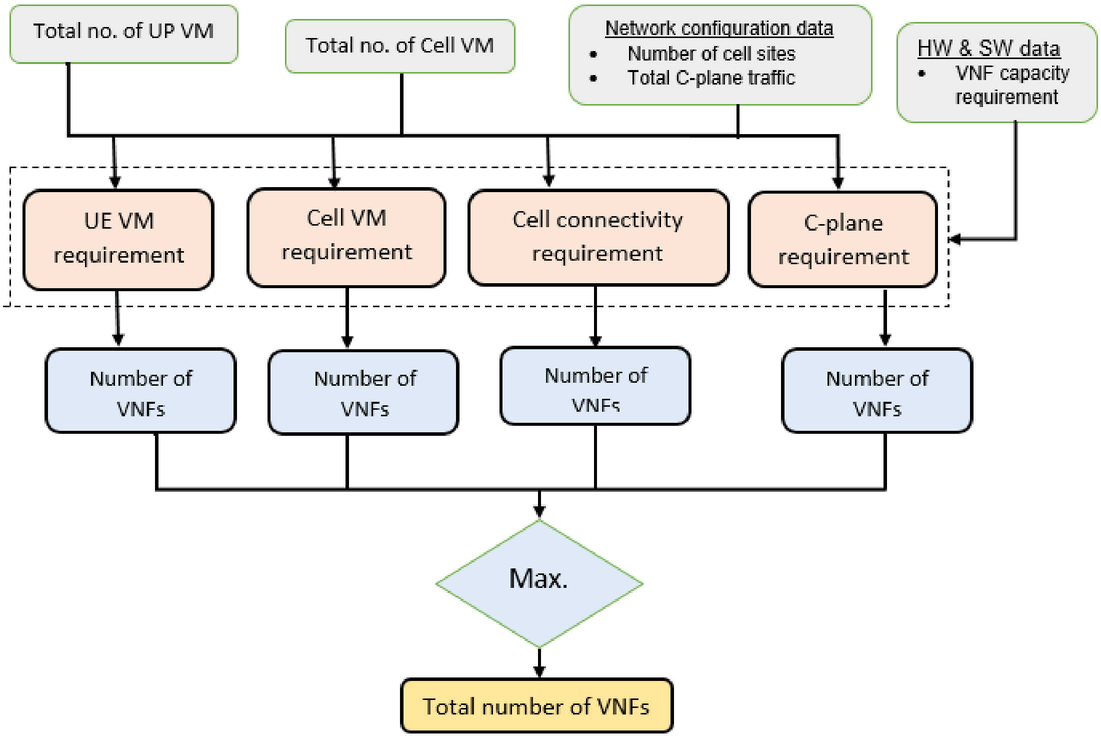

Figure 3.4.5: VNF dimensioning flow chart [12][25].

Server dimensioning

Once the number of VMs and VNFs required is known, the next step is to compute the Cell VM per VNF and UE VM per VNF. The Cell VM per VNF is the number of Cell VMs that are required to support a single VNF, while the UE VM per VNF is the number of UE VMs that are required to support a single VNF. These calculations can be performed using the following formulas, [12], [25].

$$VNF_{CP} = \frac{N_{CPVM}}{VNF_T} \tag{3.4.2.1}$$

Where VNF_{CP} is CP VM per VNF, N_{CPVM} is the total number of CP VMs in the network and VNF_T is the total number of VNFs required in the network.

$$VNF_{UE} = \frac{N_{UEVM}}{VNF_T} \tag{3.4.2.2}$$

Where VNF_{UE} is UP VM per VNF N_{UEvM} is the total number of CP VMs in the network and VNF_T is the total number of VNFs required in the network.

After computing CP VM per VNF and UP VM per VNF, server per VNF can be calculated as follows

$$S_{VNF} = \frac{VNF_{CP} * C_{CP} + VNF_{UE} * C_{UE} + C_{ceNB} + C_{OAM}}{C_{server}} \tag{3.4.2.3}$$

Where S_{VNF} is server per VNF the VNF_{CP} and VNF_{UE} are the total numbers of VMs per VNF, C_{CP} , C_{UE} , C_{ceNB}, and C_{OAM} are the required number of CPU cores per VMs and C_{server} is the number of CPUs per server. Then after server per VNF calculated, number of servers required in the network is computed as follow:

$$N_S = S_{VNF} * VNF_T \tag{3.4.2.4}$$

Where N_S is the total number of servers required in the network, S_{VNF} is the number of cloud servers per VNF, and VNF_T is the total number of VNFs in the network.

Once the optimal number of cloud servers needed for the network has been determined, the bill of material can also encompass additional essential hardware components like switches, controllers, and server racks.

3.5 Cost and Revenue Modeling

The expense associated with establishing and maintaining a network is a crucial factor in determining the practicality and viability of deploying cellular network. It plays a pivotal role in assessing the feasibility and financial viability of implementing different RAN solutions. The expenses associated with building and operating a radio access network can be divided into two categories: CAPEX and OPEX. The cost calculations are conducted by considering the required network elements, network configuration data, and cost data for each year. Cost modeling component are described below,

3.5.1 Capital expenditures (CAPEX)

Once the results from the network dimensioning process are obtained, which includes determining the necessary number of hardware components such as RU, BBM, and servers, as well as the required software licenses, the next step involves calculating the investment costs. CAPEX encompasses the investments made towards the acquisition of BBM hardware, server hardware, and software licenses. The process of calculating CAPEX involves utilizing the bill of material, which comprises all the necessary hardware and software components for study period, as well as the financial data that provides pricing information for these required items. By adding up the costs for those year, the total accumulated CAPEX for the network can be obtained [11][12].

$$CAPEX = \sum_{i}^{T} C_{BBMi} + C_{BBSWi} + C_{BBLCi} + C_{CCHWi} + C_{CSWi} + C_{CPi} + C_{BFHLi} + C_{RIUi} \tag{3.5.1.1}$$

Where, C_{BBM} is BBM cost, C_{BBSW} is BB software cost, C_{BBLC} is BB license cost, C_{CCHW} is commercial of the shelf (COTS) HW cost , C_{CSW} is cloud SW License cost, C_{CP} is cloud platform cost, C_{BFHL} is BH & FH link cost, C_{RIU} is radio interface unit (RIU) cost, T is study period.

3.5.2 Operational Expenditure(OPEX)

OPEX encompasses various costs such as energy expenses, rental fees, expenses related to upgrading baseband capacity, Operation and Maintenance (OAM) costs, as well as fees for hardware and software maintenance. This cost calculation is performed for both network architectures, taking into account a yearly basis starting from the first year. By adding up the costs for each year, the total accumulated OPEX for the network can be obtained [11][12].

$$OPEX = \sum_{i}^{T} C_{energy} + C_{siterent} + C_{CUP} + C_{OAM} + C_{maint} \tag{3.5.2.1}$$

Where, C_{energy} is Energy Cost, $C_{siterent}$ is site Rent cost, C_{CUP} is Capacity upgrade cost, C_{OAM} is OAM Cost, C_{maint} is HW & SW maintenance cost and T study period.

Operational cost components are discussed as follows.

Energy cost

The annual energy cost of the network is determined by adding up the total amount of energy used by both the BBM units and cloud servers. Energy cost can be calculated as [12][25],

$$P_T = \sum_{i} P_i * n_i + \sum_{i} P_j * n_j \tag{3.5.2.2}$$

Where i represents the total number of BBU units in the network, j represents the total number of power consuming elements in cloud servers (compute nodes, switches) and P is the power consumption of the BBM unit i or cloud server hardware element j.

The annual energy consumption (E_T) in kWh can be calculated as:

$$E_T = \frac{P_T}{1000} * \frac{Hrs}{Day} * \frac{Days}{Year} \tag{3.5.2.3}$$

Where P_T is yearly power consumed by the baseband processing hardware.

Then yearly energy cost (C_{Energy}) can be calculated as:

$$C_{Energy} = E_T * C_{kwh} \tag{3.5.2.4}$$

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

Operation and Maintenance cost

OAM costs are the expenses needed to keep a network running smoothly. This includes network troubleshooting, preventive maintenance, performance optimization, capacity analysis and planning, and software upgrades.

Capacity upgrade cost

The expenses for upgrading baseband capacity include the costs of installing baseband processing hardware at cell sites and upgrade BB capacity at virtualized hub site. In D-RAN it is necessary to install new equipment when the network traffic is anticipated to surpass the current capacity of the baseband processing hardware. The implementation costs are assumed to be lower in Open RAN due to virtualization. Baseband capacity upgrade cost for the network per year can be calculated as [12]:

$$C_{up} = CU_{D-cup} * n_{D-BBM} + CU_{hs-cup} * n_{server} \tag{3.5.2.5}$$

Where C_{up} Baseband capacity upgrade cost, CU_{D-cup} & CU_{hs-cup} represents the baseband capacity upgrade cost for D-RAN sites & vRAN hub site, n_{D-BBM} & n_{server} represents the number of new BBM units required to be installed to D-RAN sites and new vRAN servers required to be installed at hub site.

Infrastructure or Fiber Lease cost

Annual fiber lease cost per cell site is considered. Hence, the annual fiber lease cost can be calculated as [25],

$$C_{Fi} = \sum_{i}^{T} N_i * C_F^i \tag{3.5.2.6}$$

Where N_i is the number of site in the year i, C_F^i is the annual fiber lease in the year i and T is the study period.

HW & SW maintenance cost

Every year, the costs for maintaining hardware and software are determined by applying a fixed percentage to the total amount of CAPEX used for purchasing hardware and software.

Site rental cost

Operators have two choices when it comes to securing their floor space: they can either purchase or construct a building, or they can opt to lease one. If they choose the latter option, the cost of the floor space is determined by an annual rental fee paid to the data center owner in order to accommodate their equipment. The expenses associated with site rental include the yearly cost of renting cell towers for the radio hardware and antennas, the cost of renting cell site floors for each BBM cabinet in distributed architectures, and the cost of renting data center cabinets for each server rack in Open RAN architectures. Annual site rental costs can be calculated as follows,

$$C_{rent} = R_{tower} * n_{RAP} + R_{BBsite} * n_{Dcab} + R_{DC} * n_{rack} \tag{3.5.2.7}$$

Where C_{rent} is annual site rent R_{tower} represents the rental costs for the cell tower, R_{BBsite} cell site floor space rental cost per cabinet, and R_{DC} data center rental cost per server rack. And n represents the number of cell sites/radio towers, BBM cabinets in D-RAN configuration, and the number of server racks in the network.

3.5.3 Total Cost of Ownership (TCO)

The TCO model integrates the outcomes of both CAPEX and OPEX calculations for each architectural option, allowing for the computation of economic metrics. TCO can be calculated as,

$$TCO = \sum_{i}^{T} Capex_i * Opex_i \tag{3.5.3.1}$$

Where $Capex_i$ is the total CAPEX in the year i, $Opex_i$ is the total OPEX in the year i, and T is the study period.

3.5.4 Revenue Modeling

Revenue is determined by taking into account the number of subscribers, average revenue per user, and the market share. This calculation serves as a basis for determining the total revenue generated. Revenue can be calculated as [24],

$$R = N_S * ARPU * M_S \tag{3.5.4.1}$$

Where R is the revenue generated, N_S is the predicted number of subscribers, $ARPU$ is the average revenue per user, and M_S is the Open RAN market share.

3.5.5 Techno-economic Evaluation Metrics

Economic metrics provide valuable insights into the relative cost-effectiveness of different RAN architectures and the potential impact on MNOs and the solution providers involved in RAN implementation. There are different methods for assessing the profitability of a project, including the net present value, internal rate of return, and payback period. Those methods are applied in this thesis including cash flow analysis and discounted cash flow analysis. These methods allow for a thorough examination of financial aspects by taking into account the timing and value of cash inflows and outflows. By utilizing these evaluation techniques, stakeholders can gain a comprehensive understanding of the project's financial feasibility and potential profitability. Different economic metrics are discussed as follows:

Cash Flow (CF) and Discounted Cash Flow (DCF)

Cash flow analysis is a process that thoroughly investigates the inflow and outflow of cash within a company. It investigates into the origins of cash, where it is allocated, and the specific amounts involved. By utilizing the data obtained from the cost and revenue model, the cash flow is mathematically represented in equation 3.5.5.1. This analysis serves as a tool to gain a comprehensive understanding of the financial activities within the company [58], [57], [25].

$$C_F = \sum_{i}^{T} (R_T - C_T)i \tag{3.5.5.1}$$

Where: C_F is the cash flow, R_T Total revenue, C_T is TCO, T is the study period.

The discounted cash flow (DCF) approach is a technique employed to determine the value of an investment by analyzing its expected future cash flows. This valuation method is expressed mathematically through Equation 3.5.5.2 in a DCF model.

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_i}{(1+r)^i} \tag{3.5.5.2}$$

Where DCF is the discounted cash flow , CF is cash flow for the given year, i is the study period, and r is the discount rate.

Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PP)

The NPV is widely acknowledged as the most advantageous metric for assessing profitability, resulting in more informed investment choices. As per the NPV, it is advised that a company would allocate funds towards projects that exhibit a positive NPV. NPV can be computed as the difference of discounted cash flow and the initial investment Capex. This economic indicator calculated based on obtained cash flow or discounted cash flow [57][61].

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+r)^i} \tag{3.5.5.3}$$

Where: NPV is the net present value, CF_i is cash flow occurring in the year i, r is the discount rate, and T is the study period.

The IRR is an economic metric that is closely related to the NPV. IRR is calculated by determining the discount rate that results in an NPV of zero. In relation to the IRR rule, a company only consider investment opportunities that offer an IRR greater than their discount cash flow [57], [25]. IRR can be calculated as,

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+IRR)^i} = 0 \tag{3.5.5.4}$$

Where: NPV is the net present value, IRR is internal rate of return, CF_i is net cash flow in the year i, and T is the study period.

The PP refers to the number of years it will take for the company to recoup its initial cash investment according to the projected cash flow outlined in the proposal. If the calculated PP falls below a predetermined maximum duration, then the condition for accepting the PP is satisfied. PP can be calculated as

$$PP = LP + [\frac{ABS(CCF)}{CF}] \tag{3.5.5.5}$$

Where: LP is the last period of negative cumulative cash flow, CCF is value of cumulative cash flow at the end of last period, CF is the total cash flow after last period.

Chapter 4

Result and Analysis

This chapter discusses the techno-economic analysis of the Open RAN deployment scenario results and analysis. The analysis was designed to assess and compare the costs associated with the D-RAN and Open RAN architectures. The data was collected from Ethiotelecom and includes existing 4G traffic data. The study was conducted over a span of five years, starting from the initial year of 2024. Ethiotelecom currently has a RAN utilizing the D-RAN architecture. In order to determine the most cost-effective RAN architecture, both options are being evaluated based on TCO and economic metrics over a five-year study period.

The following sections present the inputs used for the analysis in the model, the deployment option chosen for the use case, the results of the network dimensioning, market analysis, and the evaluation of the techno-economic aspects. Additionally, the observations made on the obtained results will be discussed.

4.1 Open RAN Deployment Options

4.1.1 Deployment area and Implemented open RAN architecture

To select deployment area, the process entails the acquisition of the existing RAN deployment architecture details from Ethiotelecom. This data encompasses documented data, Network configuration data, data traffic, and insights gleaned from expert interviews. Once this relevant information is collected from Ethiotelecom, revealing the presence of densely populated sites across diverse locations such as Bole, Mexico, and Merkato. Within this array of options, the Bole area emerges as the most capable selection, attributed to the existence of a fiber optic infrastructure that holds the potential to serve both front haul and mid haul functionalities. The study area contains 21 macro cell site with

3 sector for each site. Also population density and increment is taken into 2.3% Annual Population growth [62]. Figure 4.1.1 depicts a specific region that has been chosen within an area measuring 4 square kilometers.

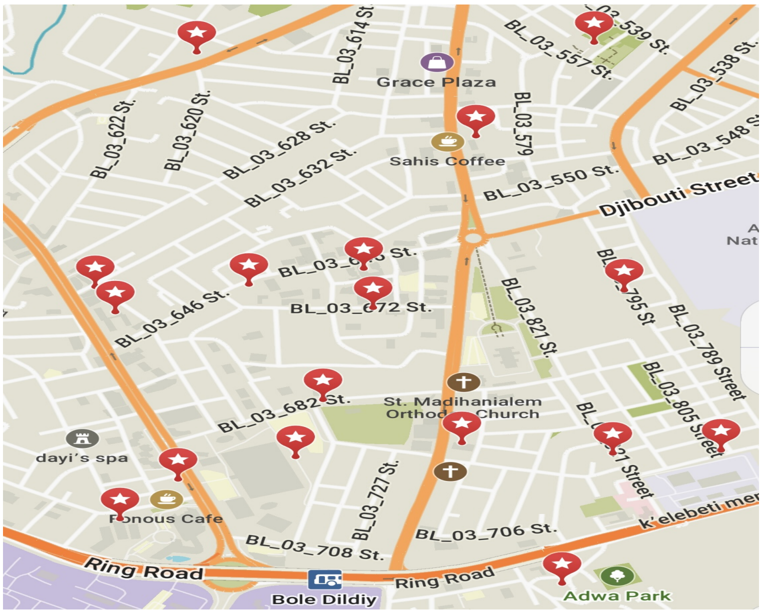

Figure 4.1.1: Selected deployment area.

Deployment scenario and benefits of Open RAN are discussed in chapter 2, section 2.3. Also specifically there are various deployment scenarios (Indoor Picocell, Outdoor Picocell, Outdoor Microcell, Integrated Access and Backhaul, and Outdoor Macrocell) and and use cases (eMBB and URLLC) being considered for Open RAN in the open RAN deployment process [63], [20]. It also considers carrier frequency, inter-site distance, and other base station related key attributes in the base station deployment scenarios. Key performance indicators such as peak data rate, peak spectral efficiency, bandwidth, latency, and mobility are considered to specify the requirements for both indoor and outdoor base station deployment scenarios.

- Indoor Picocell: This scenario is for small cells that are deployed indoors, such as in offices, hospitals, and shopping malls.
- Outdoor Picocell: This scenario is for small cells that are deployed outdoors, such as in parking lots and street intersections.
- Outdoor Microcell: This scenario is for medium-sized cells that are deployed outdoors, such as in residential areas and industrial parks.
- Integrated Access and Backhaul: This scenario combines the access and backhaul functions in a single cell. This can be useful in rural areas where there is limited infrastructure.

- Outdoor Macrocell: This scenario is for large cells that are deployed outdoors, such as in city centers and highways.

The following are some of the use cases for Open RAN that can be considered:

- eMBB: This stands for enhanced mobile broadband. It is a use case for providing high-speed data services to mobile devices.
- URLLC: This stands for ultra-reliable low-latency communication. It is a use case for providing low-latency and high-reliability services, such as industrial automation and mission-critical applications.

This thesis focuses on the deployment scenarios of Outdoor Macrocell for the eMBB use case Based on White-box Hardware Design open RAN use case. Figure 4.1.2 illustrates the implemented Open RAN architecture. Additionally, the base station architecture utilizes Split option 7-2x Architecture.

The vRAN reference model shown in the diagram consists of 64 cells that are located at a single vRAN hub site (vDU) [20]. Each cell site contains a Radio/Massive MIMO Radio. However, instead of using the usual DU, a virtualized DU (vDU) is used along with a virtualized CU. These vDUs are situated at the edge vRAN hub site, while the vCUs are positioned at the regional vRAN hub site.

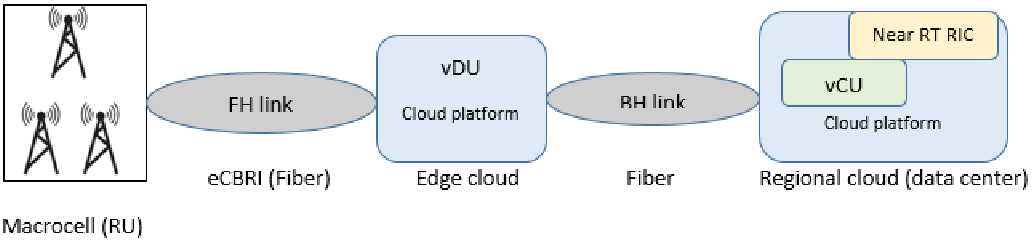

Figure 4.1.2: Implemented open RAN architecture [20]

Additionally, in D-RAN, the lower physical layer cannot be handled by the RRU, leading to the utilization of radio interface units (RIUs) between the RRU and O-DU to implement the CPRI RRU interface with the vDU [23], [64].

4.2 Network dimensioning

Chapter 3, Section 3.4 provides a comprehensive explanation of the network dimensioning procedure used to calculate the network dimensioning requirements for the deployment of D-RAN and Open RAN architectures. This section provides a detailed analysis of the results derived from the dimensioning procedure and condenses and presents all of the key findings. The dimensioning procedure takes into account the number of subscribers, the types of services offered, the desired performance requirements, the available budget, and the different network architectures being considered.

4.2.1 Inputs and Assumptions

1. **Network configuration and HW & SW data**
    - Number of cell sites consisting of radio functionalities is the same in both RAN architectures and the number is expected to increase.
    - Open RAN architectures are gradually virtualized from the year 0's D-RAN architecture. Baseband processing is being transitioned from cell sites to data centers and the number of vRAN will be increased.
    - The cell site and the hub site utilizes the eCPRI interface, which is a standard interface that operates over Ethernet for front haul communication. The functional split option supported is eCPRI standard Option 7-2x, and it is estimated that the total bandwidth needed for front haul is approximately 25Gbps [23], [22].
    - Current Open RAN solutions were also assumed to be able support 64 cells per VNF [20], [11], [12], [10].
    - The initial stage in server dimensioning involves allocating the CPU resources. A 32-core CPU is designated for both vDU, vCU. Following the determination of the number of CP VM and UP VM, VM is allocated with a 2-core CPU [63], [65], [66].
2. **Cell site configuration**

    Cell configuration is discussed in Chapter 3, Section 3.3, and is used in the BBM and server dimensioning process to determine the cell connectivity requirements at each cell site. This data was collected from Ethiotelecom and shows that the cell configuration uses FDD type 20 MHz 2x2 MIMO and 20 MHz 4x4 MIMO in D-RAN. Over the five- year period, more cells are added and replaced by cells with 20 MHz 4x4 MIMO.

    Also busy hour throughput and cell site data volume are important factors to consider when dimensioning servers and acquiring software licenses. Servers need to be able to handle the peak load of traffic during busy hours, and also necessary to be able to store and process the large volumes of data that are generated by cell sites.

    It is anticipated that both the busy hour throughput at cell sites and the daily data volume will continue to rise over the next five years. As both busy hour throughput and cell site data volume continue to rise, it will be necessary to dimension servers and acquire software licenses accordingly. This will involve increasing the number of servers, upgrading the hardware specifications of servers, and purchasing additional software licenses. Table 4.2.1 show BH and data volume pattern for the next five years.

- **Busy hour throughput:** is the amount of data that is processed by a cell site during its peak hour of operation.
- **Cell site data volume:** is the total amount of data that is processed by a cell site over a period of time, such as a day or a month.

Parameter	2023	2024	2025	2026	2027	2028
BH share of traffic per day per site	9%	9%	9%	9%	9%	9% %
UL share of total throughput (DL+UL)	8%	9%	10%	12%	13%	15%%
Average BH throughput (Mbps)	17	18.78	20.85	22.93	25	27
Data volume/site (GB/day)	117.93	127.02	135.62	144.22	152.82	161.42

Table 4.2.1: Cell site Throughput & data volume.

Figures (4.2.1, 4.2.2, and 4.2.3) illustrate the patterns of data traffic and throughput, as well as the projected patterns for cell site throughput and data volume, based on data provided by Ethiotelecom. The data shows that the total duration of the busy hours is 2 hours within a day. The figures show that the data traffic and throughput patterns vary throughout the day, with the highest traffic and throughput occurring during the busy hours.

The projected patterns for cell site throughput and data volume show that both are expected to increase significantly in the coming years. This is due to the growing popularity of smartphones and other mobile devices, as well as the increasing use of data-intensive applications such as video streaming and online gaming.

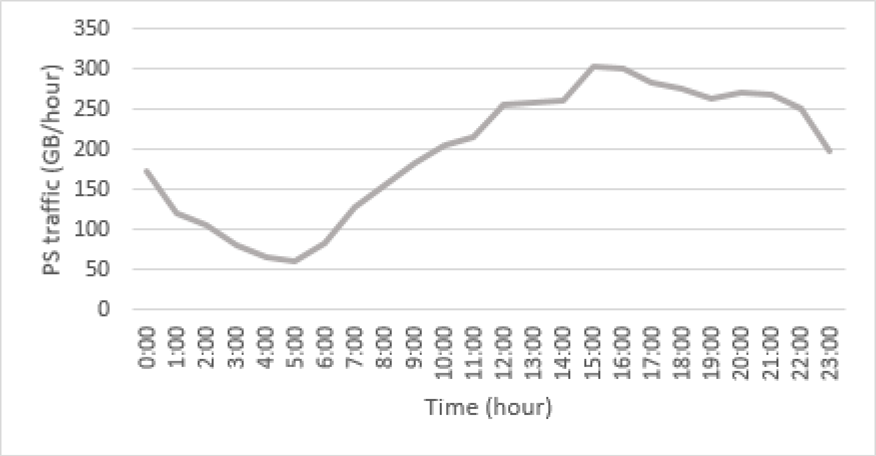

Figure 4.2.1: Data traffic pattern.

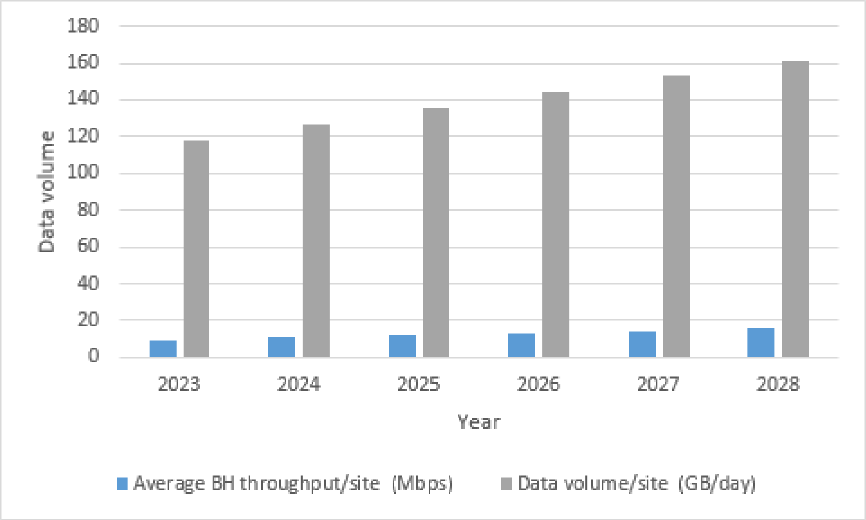

Figure 4.2.2: Forecasted Cell site throughput and data volume.

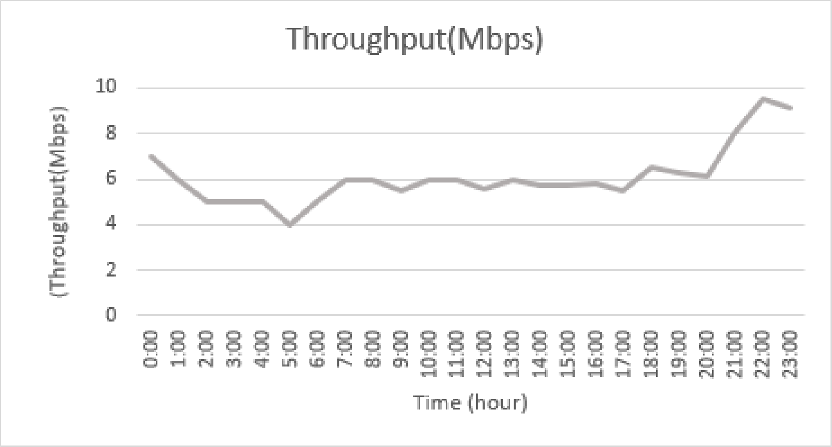

Figure 4.2.3: Throughput pattern.

C-plane traffic is another parameter on network dimensioning for both proprietary BBMs and COTS hardware (servers). When analyzing the increase in C-plane traffic, it is crucial to take into account two primary factors: the maximum limit of CUE allowed per cell site and the C-plane traffic load per CUE. The maximum CUE per cell site refers to the maximum number of devices that can be connected to a single cell site, including mobile phones and IoT sensors. In case of Ethiotelecom, in LTE advanced network maximum RRC connected user is 450 and maximmun concurrent user is 45. This number is expected to increase over time as shown in figure 4.4.9. On the other hand, the C-plane traffic load per CUE measures the frequency of signaling messages transmitted by these devices.

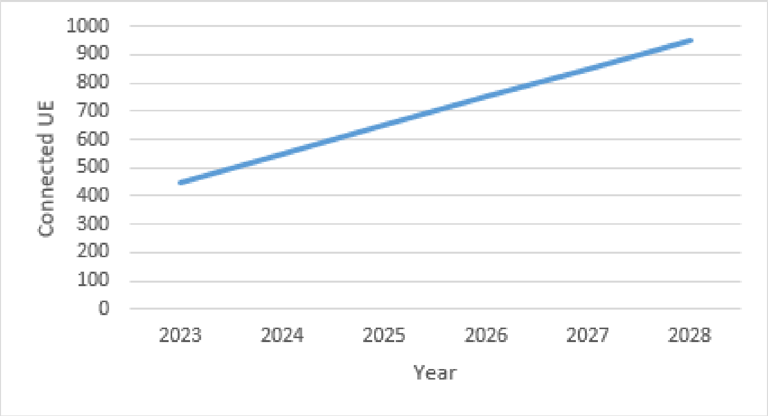

Figure 4.2.4: Forecasted maximum connected UEs per cell site.

4.3 Network Dimensioning Result

Using the data collected from Ethiotelecom in Section 4.2.1 and the procedure to compute the necessary number of BBMs and servers described in Section 3.4, network dimensioning was computed as shown in Table 4.3.1.

The dimensioning of D-RAN is computing the necessary BBM for each cell site. Also dimensioning of the vRAN is the determination of the required number of servers that are necessary to ensure the processing of the base band of LTE sub frames within a specified period for a given number of cell sites. Also vRAN server settings and required software licenses vary depending on busy hour bandwidth and data volume per cell site. A linear forecasting method was used to predict busy hour throughput and data volume per day. Also the number of cell site is increased because of the growth of subscriber. The results obtained in the network dimensioning process are summarized in table below.

Network architecture	Hard ware component	2023	2024	2025	2026	2027	2028
D-RAN	Total number of cell site	63	90	117	144	171	198
Open RAN	vDU hub site	1	2	2	3	3	3
	vCU hub site	1	1	1	1	1	1
	No. of cell per BBU Pools	63	45	59	72	57	64
	No. of Server	40	60	60	60	81	81

Table 4.3.1: Network dimensioning result.

4.4 Cost Analysis

Cost assumptions

The CAPEX and OPEX costs were estimated based on certain assumptions. A thorough analysis of the cost modeling conducted in this thesis can be found in section 3.5. The following assumptions were made.

- Due to the assumption of a functional split in the model, the cost of the Front haul in the Open RAN is considered to be equal to the cost of the backhaul in the D-RAN.
- Expenses associated with renting the cell tower and the floor space required for the baseband equipment was considered. It is important to note that the operator already possesses their own data center and core sites, so the costs related to renting the data center were not included.
- In this thesis, the costs associated with OAM for network operations and troubleshooting, preventive maintenance, performance optimization, capacity analysis and planning, and software release upgrades are calculated based on the information obtained from the operator's annual report and relevant literature pertaining to each of the architectures.
- The calculation of CAPEX cost does not take into account the expenses for RF hardware, as it is presumed to be consistent across both architectural designs.
- The annual energy costs are calculated using section 3.5.2 energy cost calculation and assuming a cost of \$0.022 per kWh [67].

Once the necessary number of BBMs and vRAN servers are determined as described in section 4.3, the next step is to calculate the costs associated with deploying and operating the system including energy cost for the study period. These costs are provided in Table 4.4.3 and Table 4.4.2, based on information from Ethio telecom, vendors, literature, and online sources [23], [11], [25], [20], [68]. A 5% annual inflation rate is taken into account.

No..	Component	Cost [k$]
1	BBM (CAP, COM, CAB)	126
2	BB SW	46
3	BBM License	117
4	BH & FH link cost	20
5	Annual BH & FH cost per site	40
6	Annual Cell site rent	54
7	Annual OAM	126
8	Capacity upgrade	75
9	HW & SW maintenance (4% & 5% of equipment)	128

Table 4.4.1: Cost of D-RAN components.

No.	component	cost($)
1	vRAN cloud server HW cost	200
2	Cloud SW	140
3	SW License	120
4	BH & FH link cost	20
5	RIU	21
6	Annual OAM	88
7	capacity upgrade	34
8	Annual Cell site rent	54
9	Annual BH & FH cost per site	40
10	HW & SW maintenance (2% & 10% of equipment)	98

Table 4.4.2: Cost of Open RAN components.

The cost of D-RAN and open RAN components listed in both table 4.4.3 and table 4.4.2 plays a crucial role in determining the capex and Opex involved in implementing these technologies. Moreover, the TCO is derived from these costs. TCO, in turn, serves as a basis for calculating important economic metrics such as NPV, IRR, and PP.

4.4.1 CAPEX calculation

Hardware dimensioning is a crucial process that involves determining the appropriate size and capacity of hardware components required for the RAN deployment. This calculation is essential for accurately estimating the CAPEX and OPEX associated with the implementation of the RAN architecture. The cost of network components in section 4.4 is used to determine the CAPEX cost for each architecture. The deployment of Open RAN architecture is done in two phases, with 70% being deployed in 2024 and the remaining 30% in 2025. In the context of Ethiotelecom's D-RAN architecture, the existing architecture currently in operation provides services. Figure 4.4.1 provides an illustration of the hardware components in both architectures.

In the D-RAN architecture, based on data from Ethiotelecom [69] annual depreciation rate of deployed RAN is 12.5% and most of cell site was deployed before 5 years. Based on this depreciation rate the initial investment for D-RAN is decreased. Thus, the calculation of the CAPEX cost takes into account the cost associated with adding extra CAP units, while MPU and CAB components remain deployed as long as their capacity meets the requirements for additional CAP units.

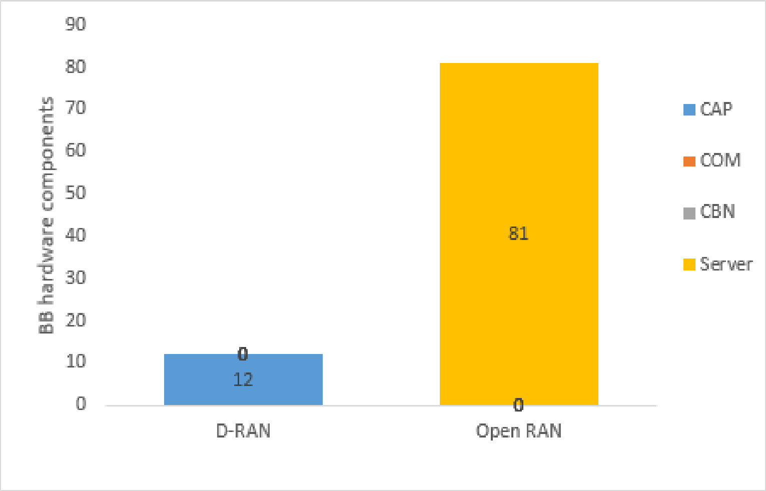

Figure 4.4.1: Required BB processing hardware for each architecture.

Figures 4.4.2 and 4.4.3 compare the CAPEX contribution of all components for D-RAN and Open RAN architectures. The data shows that the total CAPEX of Open RAN is 62% higher than that of D-RAN. This is because the existing D-RAN architecture does not require additional BBM deployment, as the existing BBM CAP units have capacity for additional subscribers. In other words, the D-RAN architecture can be scaled up to meet increasing demand without the need to deploy new BBM units. This results in significant CAPEX savings compared to Open RAN, which requires the deployment of new BBM units.

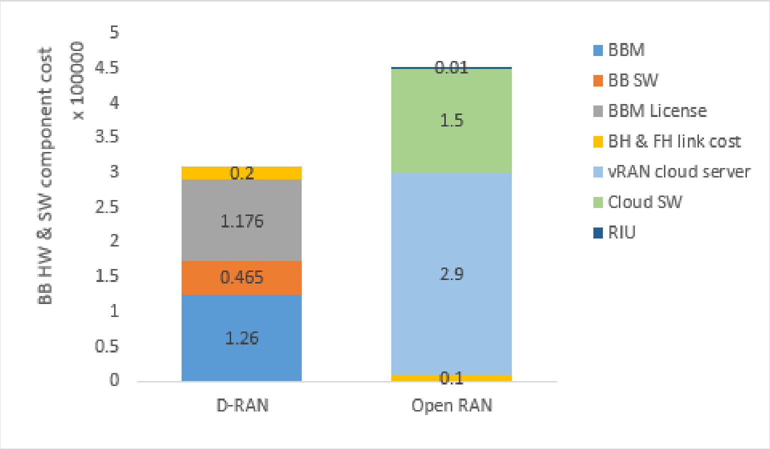

Figure 4.4.2: Cost contribution of hardware and software components.

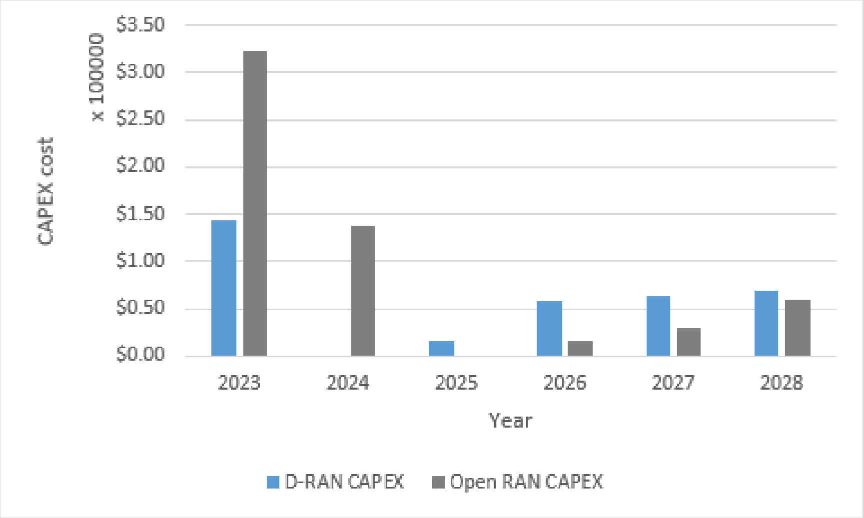

Figure 4.4.3: D-RAN and Open RAN capex cost pattern.

4.4.2 OPEX calculation

In section 4.4, OPEX cost also described in the table, by using such cost, each architecture Opex are determined for the study period, as illustrated in Figure 4.4.4 and 4.4.5. From the result Open Ran OPEX proves to be 34% lower than D-RAN. The reason behind the substantial savings in operational costs with Open RAN can be primarily attributed to the reduction in maintenance, energy, and operation expenses. By virtualizing the baseband units into the cloud, there is a significant decrease in the need for baseband capacity upgrades and subsequent energy costs. This is achieved through a reduction in equipment requirements and a decrease in the number of site visits required.

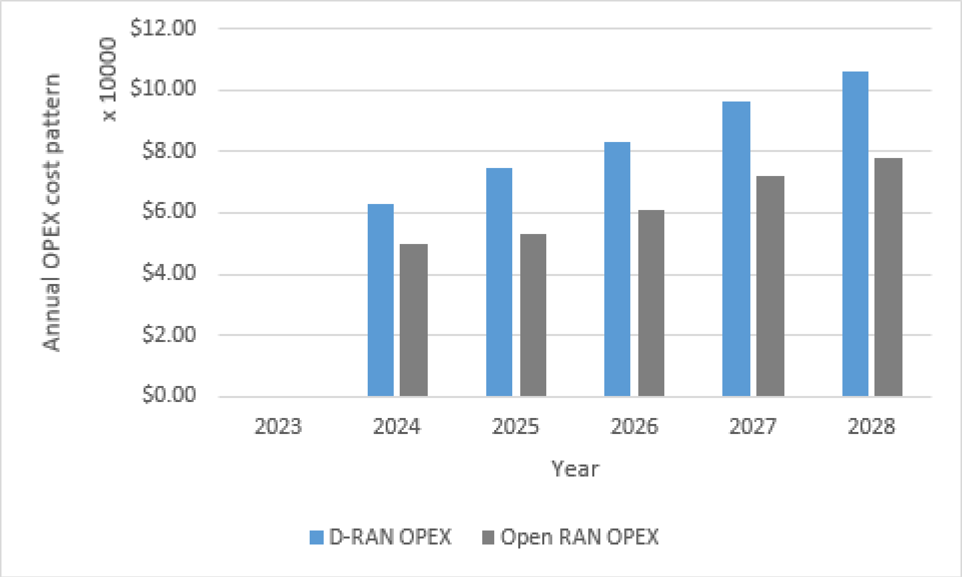

Figure 4.4.4: D-RAN and Open RAN Opex cost pattern.

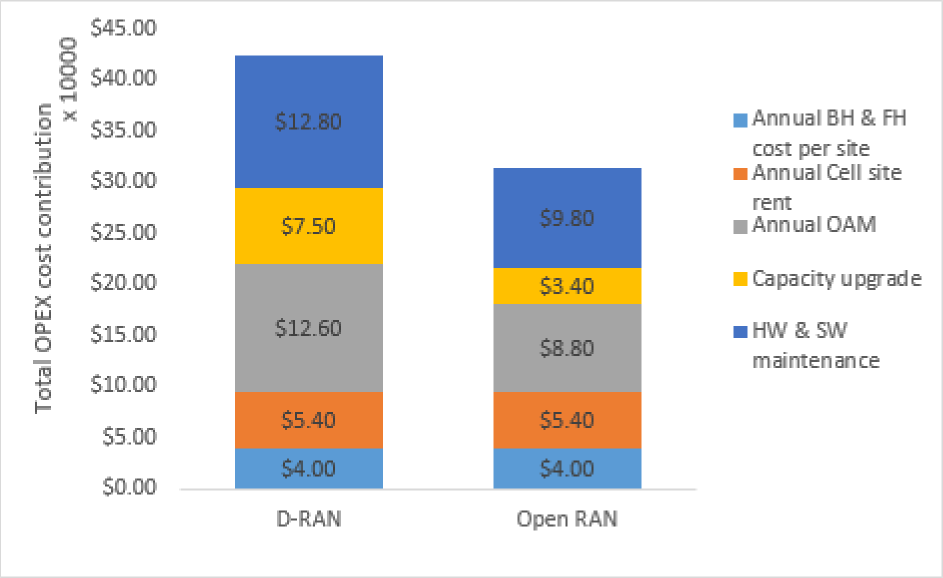

Figure 4.4.5: Opex cost contribution.

4.4.3 Total Cost of Ownership (TCO)

Once CAPEX and OPEX calculations are obtained, the total TCO of the RAN can be evaluated by considering both the initial investment and ongoing expenses for a specific period of analysis. The following figure 4.4.6 illustrates the TCO of D-RAN and Open RAN architectures. In comparison to the D-RAN system, the TCO of the open RAN is significantly higher, exhibiting a increase of 13% over the study period. This indicates that the existing RAN infrastructure are cost effective.

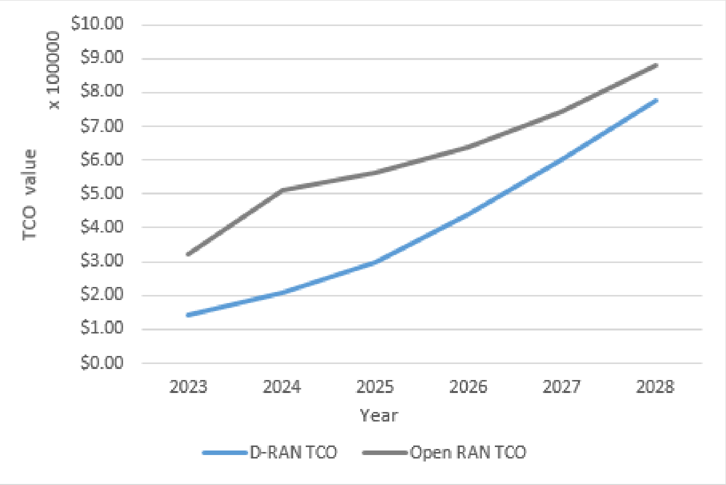

Figure 4.4.6: TCO of D-RAN and Open RAN.

4.4.4 Techno economic evaluation

The techno-economic analysis plays a crucial role in determining the economic viability of each architectural solution. In order to assess the feasibility, various factors such as CAPEX and OPEX costs, revenue, and market analysis are taken into consideration, all of which are discussed in detail in section 3.5. Subsequently, using method that are discussed in section 3.5.5 the techno-economic evaluation generates results for D-RAN and Open RAN architecture, employing significant evaluation parameters such as CF, NPV, IRR, and PP.

To compute economic metrics different inputs are used. Those input include average revenue per user (ARPU) and number of subscriber. The number of subscribers and ARPU are collected from Ethiotelecom [70], [62]. The projections for ARPU and subscriber figures were made by applying the linear regression method for the duration of the study period. It was assumed that the market share would remain at 100% throughout the study period and discount rate of 10%. Figures 4.4.7 and 4.4.8 illustrate there is a continuous growth in both subscriptions and ARPU.

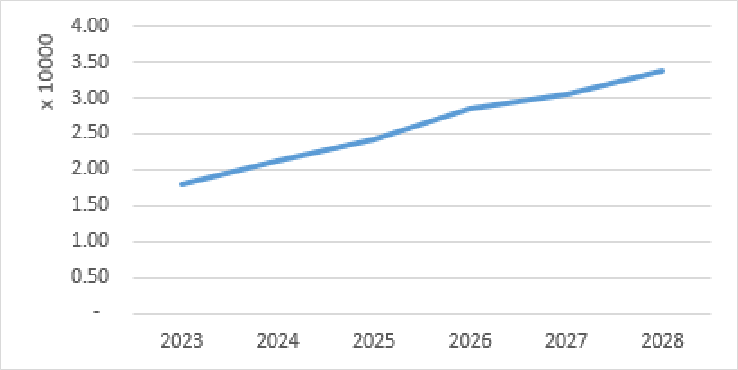

Figure 4.4.7: Forecasted subscriber.

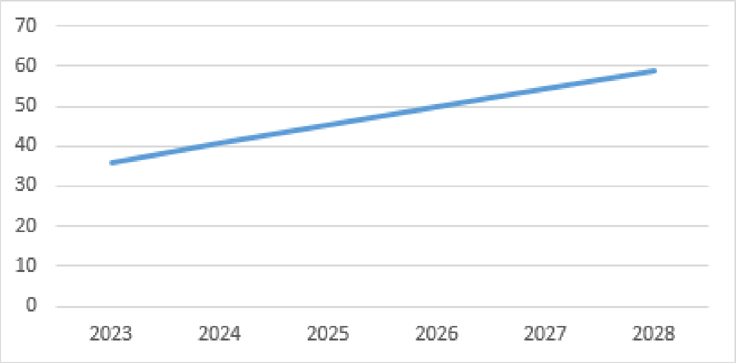

Figure 4.4.8: Forecasted ARPU per year.

The revenue has been calculated by using the input ARPU and the number of subscribers, as outlined in section 3.5, 3.5.4. Afterward, the cash flow was computed by utilizing the revenue and applying a discount rate. The diagram provided below illustrates an upward trend in the cash flow analysis. The cash flow is increasing in both architecture but open RAN has higher cash flow.

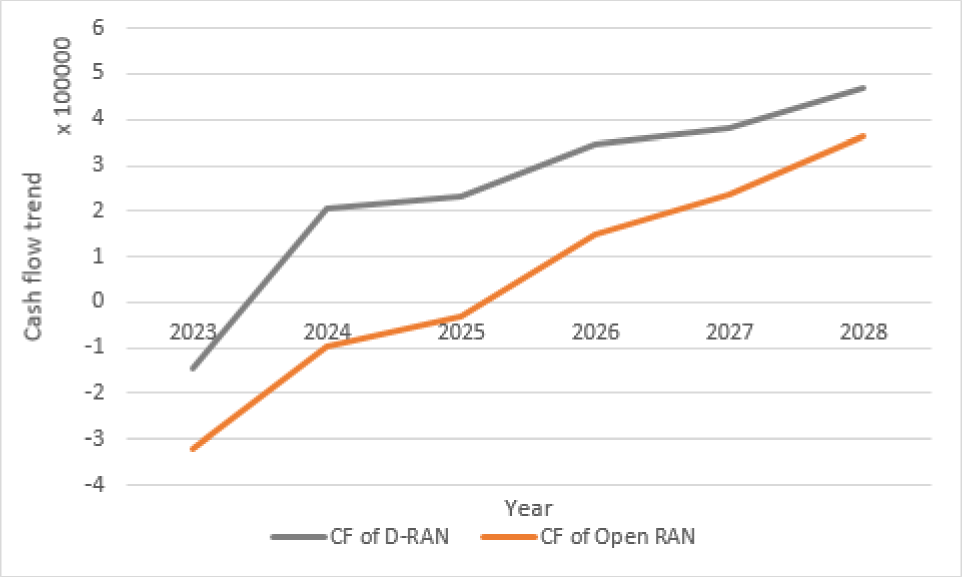

Figure 4.4.9: Cash flow comparison.

The economic metrics, including NPV, IRR, and PP, are computed by utilizing the guidelines outlined in section 3.5.5, taking into account the TCO as specified in section 3.5.4. A summary of the results for all of these metrics is presented in the table 4.4.3 provided below.

Architecture	NPV($)	IRR(%)	Payback period(years)
D-RAN	954,547	63%	2.4
Open RAN	57,385	14%	3.5

Table 4.4.3: Economic Metrics result summary

The data presented in the table reveals that both D-RAN and Open RAN architectures have positive NPV and a higher IRR than the defined discount rate of 10%. The D-RAN technology has a much higher IRR than the specified discount rate, due to its lower initial investment cost. The result indicated that both architectures are expected to generate a positive return on investment. Additionally, the PP for both architectures is indicated. When comparing the two architectures in terms of PP, D-RAN has a lower PP, meaning that it is expected to pay for itself sooner than Open RAN.

This is a significant finding, as it suggests that D-RAN is not only a more cost-effective architecture in terms of TCO, but also a more financially viable option overall. This is due to a number of factors, including the lower CAPEX and OPEX costs associated with D-RAN.

Chapter 5

Conclusion and Future Works

5.1 Conclusion

Open RAN revolutionizes telecom operators' operational flexibility via diverse vendor RAN hardware and software integration. This shift unlocks a plethora of benefits, flexibility, intelligence, performance enhancement, and cost efficiency by embracing openness. Unlike closed RAN, it nurtures vendor collaboration and interoperability, facilitating tailored network component selection. Open RAN also streamlines network management and cuts deployment costs. Ultimately, it empowers operators to craft agile networks meeting evolving telecom demands.

The result of this thesis illustrate that the total CAPEX of D-RAN is 61% lower than Open RAN. The existing infrastructure of D-RAN reduce the initial investment. A comprehensive evaluation of OPEX across both architectures shows that Open RAN's OPEX is 34% lower than D-RAN. This significant reduction in operational costs within the Open RAN framework can primarily be attributed to the decrease in maintenance, energy, and operational expenses. The virtualization of baseband units within COTS servers significantly reduces the need for baseband capacity upgrades and the associated energy costs. This optimization is achieved by reducing the need for equipment and minimizing the frequency of on-site visits.

Over the study period, Open RAN has a 13% higher TCO than D-RAN. The cash flow analysis reveals that the PP for D-RAN and Open RAN is 2.4 and 3.5 years, respectively. Both architectures have a positive NPV, IRR that exceed the defined discount rate of 10%, demonstrating the feasibility of both architectures within the study period. Hence, D RAN is a more profitable RAN architecture than open-RAN over the study period and it is expected to pay for itself sooner than Open RAN.

Future Works

Some recommendations for future research are proposed

1. By broadening the scope of this investigation, a more thorough comprehension of the various RAN options can be attained. Also In future studies, it would be beneficial to include various open RAN deployment scenarios in the analysis for a more comprehensive comparison.
2. Another potential thesis title could be ”Exploring the Technoeconomic Analysis of Network Design and Planning with a Focus on Use Cases such as RAN Sharing in Open RAN.” Within the realm of open RAN, various use cases present themselves, making the exploration of network design and planning even more intricate and diverse.
3. The focus of this study was solely on the economic evaluation of the open RAN approach utilizing LTE network data. But, there exists immense potential for the exploration and application of this approach within the framework of upcoming next-generation mobile networks such as 5G. To fully understand and harness its benefits, a thorough and all-encompassing analysis of various parameters is necessary to guarantee its seamless implementation and success.

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Appendices

Techno-economic analysis of open RAN deployment scenario: in the case of Ethiotelecom

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***Abstract*—The telecommunications industry is facing challenges due to the increasing demand for data services and the complexity of integrating hardware and software from multiple vendors. Open Radio Access Network (Open RAN) is a solution that can address these challenges by providing an open, flexible, intelligent, efficient, and cost-effective ecosystem. This thesis assesses the viability of deploying Open RAN network architecture in Addis Ababa, Ethiopia. A techno-economic analysis (TEA) was conducted with a study period of 5 years using TERA model. The analysis investigated deployment scenarios of Open RAN Distributed Unit (DU) pooling to edge cloud and Central Unit (CU) pooling to regional cloud. The optimal locations for CU and DU components were selected based on a variety of factors, including available bandwidth, fiber accessibility, and latency considerations. The analysis involved network dimensioning, cost modeling, and assessment using economic metrics for both D-RAN and open RAN architecture. The results of the analysis indicate that D-RAN has a shorter payback period of 2.4 years compared to Open RAN's 3.5 years. Also D-RAN CAPEX cost of initial investment are taken by considering depreciation rate of RAN component. Both architectural approaches exhibited positive Net Present Value (NPV) and Internal Rate of Return (IRR) that exceeded the assumed discount rate of 10%. The findings of this study indicate the profitability of D-RAN architecture.**

***Index Terms*—RAN, Open RAN, Virtualized RAN, TEA, CAPEX, OPEX, NPV, IRR, PP**

I. INTRODUCTION

A. Motivation

The growth of mobile data traffic is being driven by a number of factors, including the increasing popularity of smartphones, the proliferation of connected devices, and the emergence of new applications such as augmented reality and virtual reality. This growth is putting a strain on mobile network operators (MNOs), who are looking for ways to reduce the cost of their networks while maintaining or improving service quality [1] [2]. One integral element of a mobile network is the radio access network (RAN), responsible for more than half of an MNO's expenditure [2] [3]. This component's performance directly impacts the quality of service that subscribers experience. MNOs have been looking for ways to reduce the cost of the RAN without compromising its performance.

Globally, growth of mobile data traffic is projected that the average monthly data usage per smartphone will surpass 20 GB in 2023 and is anticipated to reach 47 GB by the close of 2028. Also, in the Sub-Saharan Africa region, the average monthly mobile data usage per smartphone was 4.7 GB by the end of 2022 [1]. The surge in wireless capacity demand has led to the exploration of innovative solutions to increase network capacity without requiring significant financial investment. One such solution is the densification of the RAN, which involves the installation of more base stations. However, this expansion can be costly. To minimize capital and operating expenditure, network providers have proposed various network architectures, such as centralized RAN (C-RAN), virtualized RAN, and the Open RAN framework. These architectures offer different trade-offs between cost, flexibility, and performance.

As Mobile Network Operators (MNOs) transition to the 5G era, Open RAN emerges as a solution that offers an open, adaptable, and interoperable network. Open RAN uses virtualization and disaggregation to enable RAN workloads to operate on commercially available servers as VNFs or CNFs [4]. This approach can lead to cost efficiency, expedited deployment, and adaptability to diverse use cases.

Open RAN uses a split architecture between central and distributed units. This split can be adjusted to meet the specific requirements of the use case, such as latency tolerance, transport dependencies, and deployment scenario [52]. The significance of front haul performance also increases with higher functional splits. By detaching baseband functions from hardware, MNOs can meet latency demands while adhering to various VM requirements.

Telecommunications operators need to conduct a comprehensive analysis to identify and evaluate the feasibility of new technologies. Different technologies vary in terms of their technological attributes, maturity levels, and associated costs. Therefore, this thesis thoroughly explores the feasibility of Open RAN deployment alternatives and investigates the techno-economic viability of the selected deployment scenarios using TERA model. The insights gained from this techno-economic analysis of deployment strategies can help to optimize resource utilization, enhance network efficiency, and understand the cost dynamics of different RAN architectures.

B. Related works

The literature on open RAN is wide and constantly evolving, with research papers covering a wide range of topics, including the architecture, use cases, and deployment scenarios of open RAN and related technologies. This section provides an overview of the key findings from this literature.

The total cost of ownership (TCO) of virtualized radio access networks (vRANs) in comparison to traditional RANs are discussed in Article [6], [7]. Those article presents a TCO model that takes into account the costs of different components of the RAN, such as radio, baseband, transport, site rental, and operations and maintenance (OAM). The results of the study show that vRANs offer cost savings of around 30% in terms of CAPEX and 25% in terms of OPEX compared to traditional RANs. The main cost savings of vRANs come from reduced hardware costs, reduced power consumption, increased scalability, and improved flexibility. The second article presents a more general cost model for comparing different RAN architectures. The model can be used to compare different RAN architectures and to determine the most economical deployment option for a particular network. Overall, the two articles provide valuable insights into the TCO of vRANs. The results of these studies suggest that vRANs can offer significant cost savings compared to traditional RANs.

Article [8], [9], [10] presented that open RAN technology can save mobile network operators up to 30% on the costs of deploying 5G networks. Also the negative effects of using a proprietary radio access network (RAN) on the quality of service (QoS) and quality of experience (QoE) in wireless networks. Open RAN is a software-defined RAN architecture that utilizes virtualization to improve the efficiency of the network. It offers the most savings due to the use of open hardware and software, as well as the ability to pool resources across multiple vendors. The O-RAN Alliance RAN architecture is a carrier-led initiative that aims to create virtual radio access networks for multi-vendor deployments. It discusses the six different deployment scenarios for O-RAN networks and the use of AI-assisted orchestrators to manage radio and computing control policies. The article also highlights the innovations made possible by O-RAN technology, such as complete virtualization and programmability.

In general, all the studies quantified that as TEA is an essential tool for operators specially to evaluate a new and evolved emerging technology in a different network environment. Each author follows a different approach in a different perspective to evaluate techno-economic in each of their studies. In addition, most of the studies only considered the geographical scenarios and technology comparison mainly focused on input data assumption.

II. OPEN RADIO ACCESS NETWORK (OPEN RAN)

A. D. Overview of mobile networks

The enduring fascination with instant long-distance communication became a reality with the emergence of the electric telegraph in the mid-nineteenth century. Initially, electromagnetic radiation was harnessed for ”wireless telegraphy,” primarily connecting distant points where conventional telegraph lines proved unreliable or impractical. As radio technology progressed, it facilitated simultaneous message broadcasts to multiple locations, initially utilizing telegraphic code (dots and dashes) and eventually advancing to full audio transmission [11].

Cellular networks have undergone a series of evolutions since their inception in the 1980s. The first generation (1G) analog voice service offered speeds of up to 2.4 kbps. The second generation (2G) introduced digital technology and supported text messaging, resulting in increased demand and success. Within the GSM network architecture, key elements included the Mobile Station (MS), Base-Station Subsystem (BSS), Network and Switching Subsystem (NSS) or Core Network (CN), and External Network [12]. In 1998, 3G networks were introduced, enabling information transmission at speeds of at least 200 kbits per second. Subsequent releases such as 3.5G and 3.75G emerged, driven by packet-switched advancements in 3G technologies, eventually leading to the birth of 4G networksv [12]. A UMTS network encompassed three interconnected domains: Core Network (CN), UMTS Terrestrial Radio Access Network (UTRAN), and User Equipment (UE). 4G networks operated as all-IP, packet-switched networks, achieving data rates of at least 100 Mbit/s between any two points worldwide. 5G aimed to offer a significantly higher capacity than its predecessor, surpassing 1 Gb/s [13]. This enhanced capacity promised more efficient communication, increased reliability, and support for a higher density of mobile users [14].

B. Evolution of Radio access network

Mobile cellular networks have three main components: User Equipment (UE), RAN, and Core Networks.

- UE encompasses a broad range of devices like mobile phones, smartphones, tablets, as well as diverse devices such as cars, drones, industrial machines, robots, home appliances, and medical devices.
- RANs establish radio connectivity between UE and the core network. This network segment comprises a base station and antennas that provide coverage based on factors like capacity, design, and propagation characteristics.
- The core network coordinates the various sections of the access network and also connects to the internet.
- Transport network connects the RAN and the Core Network.

Mobile network operators have various methods to enhance their coverage, capacity, and services, driven by the rapid advancements in wireless network broadband. Over time, the RAN has adapted to accommodate more users, faster data rates, and improved Quality of Service (QoS).

One pivotal transformation in the RAN involves its shift towards virtualization, where base station functions are distributed across different physical devices. This not only simplifies RAN management and scalability but can also enhance overall performance. Through the integration of new technologies and virtualization, mobile network operators can enhance network performance, scalability, and satisfy even the most demanding users.

Within RANs, there are two primary components: the radio unit (RU) and the baseband unit (BBU).

- RU: is responsible for handling the transmission and reception of wireless signals within the mobile network. It manages the physical layer of the wireless connection, ensuring that data is transmitted accurately and received efficiently.
- BBU: plays a critical role in managing the radio resources within the RAN. It is responsible for tasks such as radio resource allocation, power control, modulation and demodulation, error correction, and various operational functions.

1) Traditional RAN: In a traditional RAN setup, a single base station integrates both radio and baseband functions. These base stations typically comprise one or more equipment racks, housing both baseband and radio equipment, usually situated at the base of a cell tower. As depicted in Figure 1, coaxial cables (referred to as feeders) connect these antennas to the equipment racks. However, this approach presents several challenges, including the need for substantial shelter space, robust structural support, high acquisition costs, and significant energy consumption. Furthermore, within this architecture, base station racks experience an approximate 3 dB loss when transmitting signal power to antennas. To overcome these challenges, a distributed Base Station (BS) architecture comes into play. This distributed BS architecture was prevalent during the 1G and 2G eras of mobile network deployments [15].

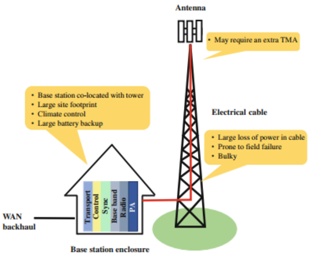

Fig. 1. Traditional RAN [15].

2) Distributed RAN (D-RAN): In Distributed RAN, the traditional RAN base station is separated into a radio unit (RU) or Remote Radio Unit (RRU) or Remote Radio Head (RRH) and a signal processing unit (BBU) as shown in Figure 2. BBUs handles higher-layer processing tasks, dynamically allocating resources to RRUs based on the network's requirements. RRUs, on the other hand, handle RF (radio frequency) functions and incorporate components like power amplifiers (PAs), duplexers, low noise amplifiers (LNAs), as well as analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). The communication interface connecting the BBU and RRU is typically referred to as the Common Public Radio Interface (CPRI) [16].

One significant advantage of D-RAN is its simplicity of implementation, notably due to the absence of a high-speed interface requirement between the RU and BBU. This autonomy allows each RAN to function independently. However, the increasing proliferation of UEs has led to a higher density of cellular networks, necessitating the construction of additional BS). D-RAN can be used with a variety of radio access technologies, such as 2G, 3G, 4G, and 5G.

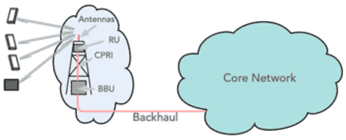

Fig. 2. Distributed radio access network base station [13].

3) Centralized RAN: C-RAN is a revolutionary network architecture that comprises two fundamental components: the BBU pool and RRHs. In this architecture, numerous RRHs, often numbering in the hundreds or even thousands, are interconnected with a central pool of BBUs through a front haul network, as visually depicted in Figure 3.

A major advantage of C-RAN architecture is its ability to establish significantly lower costs, greener communication, and capability of supporting advanced wireless technologies such as coordination multi-point due to the centralized processing of the radio signal.

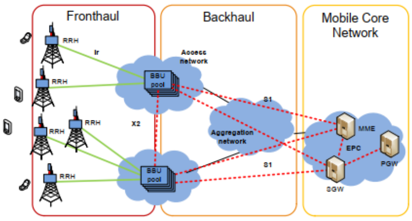

Fig. 3. Centralized RAN [17].

4) Virtualized RAN (vRAN): RAN virtualization heavily relies on concepts such as software-defined networking (SDN) and network function virtualization (NFV). With vRAN, the proprietary radio hardware remains as it is, but the BBU gets replaced by a COTS server rather than being proprietary BBU hardware. In the cloud server, multiple virtual BBUs (vBBUs) are deployed. vBBU can be deployed on either a Virtual Machine (VM) or container. The software that runs on the BBU is virtualized to run on any COTS server [18], [19].

Virtualization is an abstraction of physical resources that enables multiple VMs to run on the same physical server. VM applications are isolated from each other. Hypervisors or virtual machine monitors (VMMs) provide an abstraction of physical resources. The hypervisor manages the physical resources and schedules between the VMs. The VMs are configured with virtual resources such as virtual CPU (vCPU) and does not own physical resources [20].

The implementation of network function virtualization and cloudification in vRAN, along with its deployment across different scales such as site, far edge, edge, and core clouds, allows for a more flexible and adaptable approach to capacity management. This flexibility and adaptability provide various advantages, such as preventing the need for over-provisioning RAN capacity based on peak traffic demand. Additionally, it offers a practical and cost-effective solution for scaling capacity without the need for unnecessary investments in vDU servers.

C. *Open RAN network*

Open RAN was first proposed in May 2002 and has gained traction in recent years due to the challenges faced by traditional RAN deployments, such as the high cost of proprietary hardware and software, the lack of interoperability between different vendors, and the difficulty of upgrading and scaling networks. It is a concept that aims to define and build 2G, 3G, 4G, and 5G RAN solutions based on general-purpose, vendor-neutral hardware and software-defined technology with open interfaces between all the components. Also It is a movement to drive the mo- bile industry towards an ecosystem of innovative, multi-vendor, interoperable, and autonomous RAN, with reduced cost, improved performance, and greater agility [21], [19], [18].

1) Architecture of open RAN: Open RAN architecture is composed of two main groups: the radio group and the management group. The radio group is comprised of various components such as Near-Real Time RIC (Near-RT RIC), Next Generation RAN (NG-RAN) which includes O-RU, O-DU, O-CU, and ORAN eNodeB (O-eNB), figure 4. These components are responsible for facilitating radio communications within the system [22].

On the other hand, the management group consists of the Service Management and Orchestration (SMO) framework and the Non-Real Time RIC (Non-RT RIC). This group is responsible for manag- ing the system's performance. Additionally, the Open RAN Cloud (O-Cloud) is a cloud computing platform that serves as the host for various Open RAN functions and software.

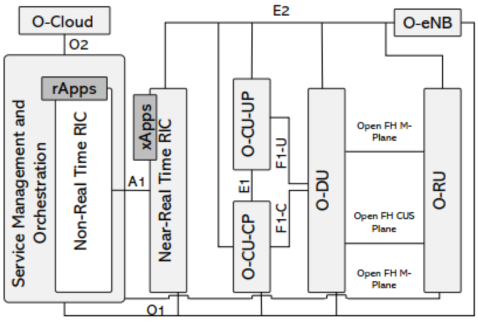

Fig. 4. Open RAN architecture [23].

The Open RAN concept involves the use of COTS servers for the software components of the DU and CU, while RU can be sourced from any vendor. The DU works closely with the RU and is controlled by the CU. The CU is connected to the DU and controls its operation. It can also support multiple DUs and control their operation over the midhaul interface. Additionally, the CU can be co-located with the DU software on the same server at the site.

2) Open RAN functional spli: Open RAN is enabled by the use of standardized open network interfaces, which are outlined in various organizations such as 3GPP, O-RAN Alliance, IEEE, and other industry fora and SDOs. 3GPP has established various options known as functional splits, which outline the relationships between these logical nodes and detail the specific tasks that each node is responsible for. In addition to the traditional "monolithic" NG-RAN architecture, 3GPP have defined the following two split architectures [24]:

- Split option 2 which is high-level CU/DU split,
- NG-RAN architecture with separated control and user plane functions.

Small Cell Forum has adapted its functional application platform interface (FAPI) specification for option 6 to accommodate the advancements in 5G technology. Similarly, the O-RAN Alliances have defined the low-level split, known as option 7. The CPRI specification has been improved and is now referred to as eCPRI, enabling support for not just option 8 but also higher splits.

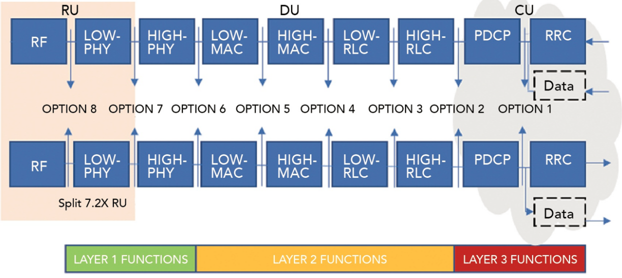

Fig. 5. Functional Splits [25].

As can be observed from the figure 5; Different RAN functional splits work for different use cases. Split 8 will be the best option for 2G and 3G whereas Split 7.2 is the best for 4G and 5G so in case of requirements for more delay-sensitive service, based on appropriate front haul availability, the MAC-PHY split will be the preferred solution. Open RAN architectural component function are described below based on split 7.2 [23].

- RU: is Deployed on site near to the antenna, the RRU converts radio signals sent to and from the antenna into digital data for transmission. It controls the digital front end (DFE), the lower layer 1 (L1, physical layer) baseband processing, as well as front haul transport.
- DU: handles real-time layer 1 (L1, physical layer) and lower layer 2 (L2, Data Link Layer) functions including MAC (Media Access Control) and RLC (Radio Link Control).

- CU: controls DU operation, connects to the cellular network, and communicates with other base stations. It is responsible for performing non-real time, higher L2 and L3 (network layer) protocol stack workloads, such as the functions of RRC (Radio Resource Control) and PDCP (Packet Data Convergence Protocol). One CU can manage one or more DUs over the midhaul interface.

3) Open RAN Deployment scenario: One major option for operators to improve their RANs is to disaggregate the architecture, modularize, and virtualize the deployments. Disaggregating software from hardware is one method of implementing Open RAN, allowing RAN software to run on any popular hardware platform such those based on Intel x86 and ARM architectures [21]. Different deployment scenario are described in figure 6 and discussed as folows [26], [9].

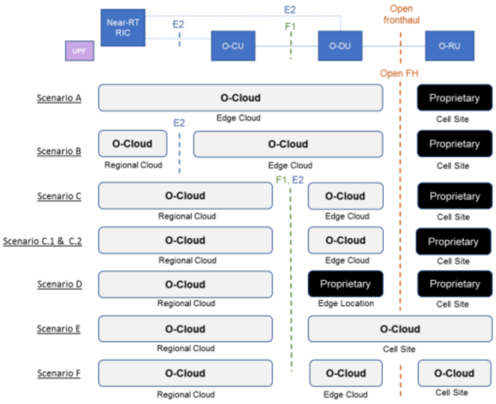

Fig. 6. Open RAN deployment scenario [21].

Scenario A: A single edge cloud is used here to centralized all near-RT RIC, virtual O-CU, and O-DU functions, enabling the deployment of a high-capacity front haul network in dense urban areas. An edge cloud with substantial hardware acceleration capabilities is expected for this type of deployment.

Scenario B: With this scenario, virtual O-CUs and O-DUs are separated from near-RT RICs, which can be placed in a regional cloud and are interfaced with through E2. For near-RT RIC, this gives a global view of optimization.

Scenario C: In a regional cloud, virtual O-CU network services can be co-located with the near-RT RIC to reduce latency and meet the latency criteria of the 3GPP-defined F1 interface. This allows for deployment in areas with limited front haul capacity and O-RUs.

Scenario D: This example is the same as of Scenario C, except it uses a PNF that is capable of supporting O-RAN, rather than a virtualized O-Cloud.

Scenario E: It is replica of Scenario C, in which both O-RU and O-DU functions are virtualized into a common O-Cloud.

Scenario F: This example is the same as of Scenario E. The O-DU and O-RU functions are virtualized into separate O-Clouds in this scenario.

4) Benefits of Open RAN: Open RAN creates a unified architecture through the disaggregation of hardware and software, bringing several benefits such as low latency and network slicing. In addition to facilitating network automation, Open RAN provides the following benefits [27]:

- Open standard interfaces increase interoperability between different equipment and help create a diverse supplier ecosystem by engaging a broader participation of vendors in 5G development.
- Using multi-vendor COTS hardware prevents proprietary vendor lock-in risk and provides solution agility and new capabilities leading to further innovation, giving operators more deployment options and partnership resources to quickly address 5G issues and deliver the best possible customer experience.
- Increased virtualization of network functions extends cloud capabilities to the edge of the network, minimizing physical deployment limitations and costs to accelerate 5G penetration.
- One of the key benefits of network automation is the significant reduction in OPEX. This is achieved through the implementation of plug-n-play configuration and hands-free optimization, which greatly diminishes the need for professional services to handle deployment or maintenance tasks [50].

5) Challenge of open RAN: When planning the deployment and management of Open RAN networks, operators are primarily concerned with ensuring interoperability, manageability, optimization, and end-to-end performance, especially in a multi-vendor environment. Today, networks must support multiple technology generations, such as 3G, 4G, and 5G, while also scaling up to meet the ever-increasing demand for data. Some challenges regarding the implementation of open RAN include [28]:

- It is challenging to deploy policies for the RIC, near-RT and non-RT control loop meeting the economical and ecological aspects.
- Coordination, updation and training is difficult with the modern learning techniques.(i.e., ML and AI).
- It is challenging to handle data (specifically cross layer data) to support the intended operation while protecting other internal operations.

Orchestration & Performance challenges: this challenges include on service management and intelligence management challenges. The Open RAN faces significant challenges in terms of deploying and managing various hardware and software components due to its multi-vendor ecosystem [23]. Also intelligence plays a crucial role in Open RAN as it assists in tackling the escalating intricacy of mobile networks, which stems from the rising user demand and data consumption. This is achieved by incorporating intelligence at both the network and component levels, enabling efficient resource management and optimization [29], [18].

Security challenges: Open RAN harnesses the power of network softwarization and Artificial Intelligence to optimize the functioning of RAN devices and operations by creating an open ecosystem. While Open RAN brings about numerous advantages, it also introduces novel security and privacy concerns. Given the significant departure from traditional RAN configurations, mismanagement of Open RAN could potentially result in grave security and privacy ramifications [30].

6) Related technologies: Open RAN is a new radio access network architecture that uses a variety of technologies and approaches to create a more open and intelligent network. These technologies include disaggregation, SDN, NFV, functional split, cloudification, automation, intelligence, network slicing, open source, and mobile edge computing (MEC) [28]. The specific technologies and approaches that are used will depend on the specific requirements of the network.

Cloudification: is the process of moving network functions to the cloud. This makes it possible to scale the network more easily and efficiently, as well as the ability to take advantage of the latest cloud-based technologies. Also Containerization is a virtualization technology that allows multiple applications to run on the same operating system instance. This makes it more efficient to utilize hardware resources and simplifies the deployment and management of applications [31]. This offers a number of advantages over traditional RAN architectures, including, Scalability and flexibility, Cost savings, Innovation.

MEC: is a technology that brings computing resources closer to the end users. This can be used to improve the performance of applications and services, as well as to reduce latency. It is a key enabler of the 5G network, providing ultra-low latency and high bandwidth capabilities at the edge of the network. This makes it ideal for hosting and delivering applications and services that require real-time data processing and response.

Moving network functions to the edge is a crucial way to improve the performance of mobile networks. This is especially important in virtualized networks, where the location of network functions is more flexible. MEC allows software applications to take advantage of local resources and conditions, which can reduce latency, improve performance, and reduce bandwidth usage [32].

III. TECHNO-ECONOMIC MODELING AND EVALUATION METHOD

The TERA (Techno-Economic Results from ACTS) model is a comprehensive techno-economic analysis tool that was developed by the European Union's Advanced Communications Technologies and Services (ACTS) program to assess the economic feasibility of different telecommunications technologies and architectures. As shown in figure 7 the model integrates various factors, such as technical aspects, market conditions, economic considerations, and costs associated with network elements, to provide a holistic assessment of the economic viability of a new technology or service [33], [34].

A. Open RAN TEA Model

The TERA model is used in this thesis to conduct a techno-economic analysis of the deployment of Open RAN. The inputs to the model include the marketing, technical, and economic parts. The model is based on network dimensioning, mathematical modeling and cost calculations. The outputs of the model include the revenues, costs, cash flows, and other economic indicators for the network. The implemented TERA model are presented in the figure 8.

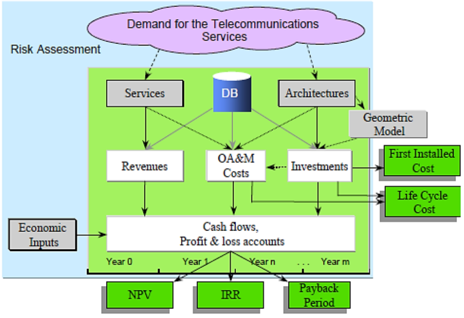

Fig. 7. TERA framework [35].

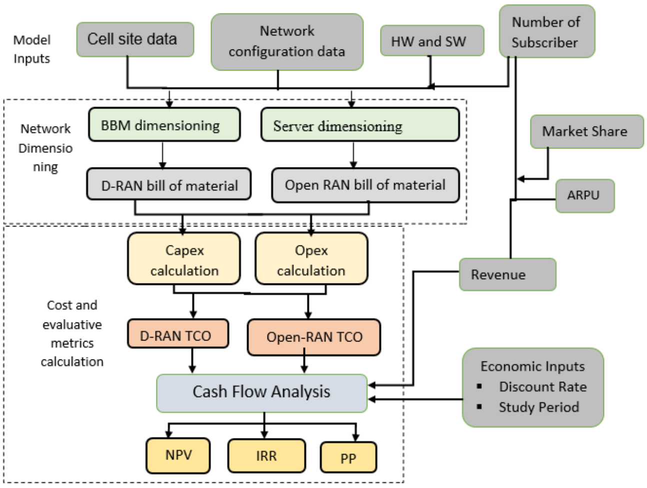

Fig. 8. Implemented TEA model.

B. Input data

The open RAN TEA model can be used to evaluate the cost and performance of open RAN. The model requires a variety of data sets, including cell site data, network configuration data, hardware and software data, and financial data. By using this data, the model can provide operators with valuable insights into the potential benefits of deploying open RAN. Each input data set can be described and explained in the following way:

1) Cell site data: Cell site data is essential for network planning, optimization, and troubleshooting. By analyzing cell site data, operators can gain insights into the performance of their networks and identify areas where improvement is needed. This data includes information on the configuration of the cell site, data throughput, and C-plane traffic.

2) Network configuration data: Network configuration data includes information on the topology of the network, the types of equipment that are used, and the configuration of those devices. This data is needed to model the network and to understand how RAN architecture would impact the performance and cost of the network. It is used to quantify the overall quantity of networking hardware and networking software licenses needed.

3) HW and SW data: includes information on the HW and SW used in a network, as well as their specifications, performance, capabilities, and limits. This data includes information on the type, model, and specifications of the hardware used in the network, such as base stations, routers, and switches. The software data includes information on the type, version, and specifications of the software used in the network, such as operating systems, network management software, and applications. This data can be obtained from different sources, including operators, books, literature, and other relevant sources.

4) Financial data: Financial data includes information on the cost of previously owned hardware and software licenses, which is crucial for determining CAPEX. It also encompasses various expenses associated with network operations, such as energy prices, rental fees for cell sites and data centers, and costs of hardware upgrades and installations. These expenses are essential for calculating the OPEX of the network. This data can be obtained from a different sources, including operators, books, literature, and other relevant sources.

C. Network Dimensioning

Network dimensioning is the process of determining the number and type of network equipment that is needed to support a given level of traffic and service quality. It is a critical process for both D-RAN and Open RAN networks, as it ensures that the network is able to meet the needs of its users without over-provisioning or under provisioning resources.

The network dimensioning approach in this thesis is adapted from the papers [8], [36] and customized to the local context. The general principles of network dimensioning from those papers are taken and applied them to the specific conditions. Network dimensioning requirements can vary depending on a number of factors, such as the type of network, the traffic load, and the regulatory environment.

The result of network dimensioning is a comprehensive bill of materials (BoM) of all the necessary baseband processing HW and SW licenses for both D-RAN and Open RAN architectures.

Network dimensioning includes:

- Baseband module dimensioning
- Server dimensioning

1) Baseband module dimensioning: In D-RAN, the dimensioning process focuses on the number and capacity of BBUs required to support the desired network capacity. The number of BBUs is determined by the number of cell sites in the network, while the capacity of each BBU is determined by the traffic load expected at each cell site. Within D-RAN architectures, the hardware for the BBM is situated at individual cell sites, making the dimensioning process specific to each site. Figure 9 illustrate BBM dimensioning. It is comprised of three distinct units: the capacity plug-in unit (CAP), the main processing unit(MPU), and the cabinet unit (CBN)[58]. BBM unit are described below:

- Capacity plug-in unit (CAP): responsible for processing the radio signals from the antennas. The number of CAPs required depends on the traffic load at the cell site.
  - The capacity of a single CAP unit to accommodate cells is determined by the bandwidth and MIMO configuration of the cell.
- Main Processing Unit (MPU): The MPU is responsible for controlling the CAPs and other BBM components. There is typically one MPU per cell site.
  - It handle the C-plane traffic and establish connections between multiple BBMs. COM is responsible for managing the transport and centralized control functions for various radio access technologies, as well as routing antenna data.
- Cabinet unit (CBN): The CBN houses the CAPs, MPU, and other BBM components. The number of CBNs required depends on the size of the cell site.
  - Additionally, it provides a backplane for internal communication and ensures that the units are properly cooled through air conditioning.

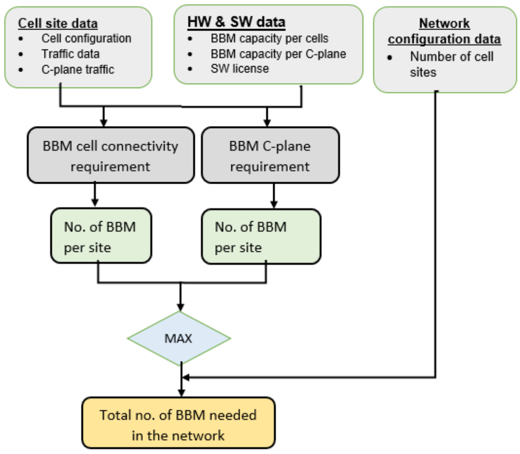

Fig. 9. Baseband module dimensioning Flow chart [8], [36].

2) Server Dimensioning: Open RAN architecture dimensioning focuses on the number and capacity of servers required to support the desired network capacity. The number of servers is determined by the number of VNFs that need to be hosted, while the capacity of each server is determined by the resources required by each VNF. Server dimensioning is used to determine how many servers are needed by the VNFs to handle the virtualized baseband processing. The virtualized baseband processing functions are carried out by multiple VMs within the vRAN's VNFs. These VMs are responsible for handling both NRT and near RT baseband functions in the virtualized environment [37], [38].

To ensure efficient processing of these baseband functions, several VMs are deployed. These include the Cell VM, User VM (UE VM), OAM VM, and Central eNB VM (CeNB VM). Each of these VMs serves a specific purpose and contributes to the overall functionality of the virtualized baseband processing system. Server dimensioning involves determining the necessary number of VMs in a network. This calculation is performed using the Cell VM and UE VM dimensioning. Additionally, it is assumed that the number of necessary OAM VMs and Central eNB VMs is equivalent to the number of VNFs, thus eliminating the need for separate dimensioning procedures.

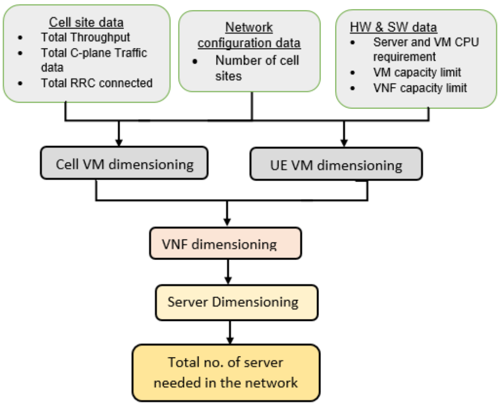

Fig. 10. Server dimensioning flow chart [8], [36].

- **Cell VM dimensioning:** Cell VM is responsible for running the cell related functions in the VNF. Cell VM dimensioning is the process of determining the number of Cell VMs required to support the expected traffic load at each cell site. It is based on three parameters, total number of cells, number of simultaneous RRC connected users and C-plane traffic in the network. The HW & SW data defines the Cell VM's capacity limits for each of these parameters. These capacity limits are then used to determine the Cell VM dimensioning requirements.
- **UE VM dimensioning:** UE VM is responsible for processing the user related functions in the VNF. It hosts the UE functions for a single user. UE VM dimensioning is the process of determining the number of UE VMs required to support the expected traffic load at a cell site. It is done based on the total uplink and downlink throughput traffic, simultaneous RRC connected user, and C-plane traffic in the network.
- **VNF dimensioning:** VNFs are composed of multiple VMs. The quantity of VNFs needed in a network is influenced by various factors, such as the total number of cells, C-plane traffic, and the overall count of Cell VMs and UE VMs present in the network. The hardware and software specifications of the VNF determine its capacity for each of these parameters, ultimately establishing the necessary VNF dimensioning requirements.

Server dimensioning: Once the number of VMs and VNFs required is known, the next step is to compute the Cell VM per VNF and UE VM per VNF [8], [36].

$$VNF_{CP} = \frac{N_{CPVM}}{VNF_T} \tag{1}$$

Where VNF_{CP} is CP VM per VNF, N_{CPVM} is the total number of CP VMs in the network and VNF_T is the total number of VNFs required in the network.

$$VNF_{UE} = \frac{N_{UEVM}}{VNF_T} \tag{2}$$

Where VNF_{UE} is UP VM per VNF N_{UEvM} is the total number of CP VMs in the network and VNF_T is the total number of VNFs required in the network.

After computing CP VM per VNF and UP VM per VNF, server per VNF can be calculated as follows

$$S_{VNF} = \frac{VNF_{CP} * C_{CP} + VNF_{UE} * C_{UE} + C_{ceNB} + C_{OAM}}{C_{server}} \tag{3}$$

Where S_{VNF} is server per VNF the VNF_{CP} and VNF_{UE} are the total numbers of VMs per VNF, C_{CP} , C_{UE} , C_{ceNB}, and C_{OAM} are the required number of CPU cores per VMs and C_{server} is the number of CPUs per server. Then after server per VNF calculated, number of servers required in the network is computed as follow:

$$N_S = S_{VNF} * VNF_T \tag{4}$$

Where N_S is the total number of servers required in the network, S_{VNF} is the number of cloud servers per VNF, and VNF_T is the total number of VNFs in the network.

Once the optimal number of cloud servers needed for the network has been determined, the bill of material can also encompass additional essential hardware components like switches, controllers, and server racks.

D. Cost and Revenue Modeling

The expense associated with establishing and maintaining a network is a crucial factor in determining the practicality and viability of deploying cellular network. This expenses includes CAPEX and OPEX costs. Cost modeling component are described below,

1) Capital expenditures (CAPEX): encompasses the investments made towards the acquisition of BBM hardware, server hardware, and software licenses. The process of calculating CAPEX involves utilizing the bill of material, which comprises all the necessary hardware and software components for study period, as well as the financial data that provides pricing information for these required items [7], [8].

$$\begin{aligned} CAPEX = \sum_{i}^{T} (C_{BBMi} + C_{BBSWi} + C_{BBLCi} + \\ C_{CCHWi} + C_{CSWi} + C_{CPi} + \\ C_{BFHLi} + C_{RIUi}) \end{aligned} \tag{5}$$

Where, C_{BBM} is BBM cost, C_{BBSW} is BB software cost, C_{BBLC} is BB license cost, C_{CCHW} is COTS HW cost ,

C_{CSW} is cloud SW License cost, C_{CP} is cloud platform cost, C_{BFHL} is BH & FH link cost, C_{RIU} is radio interface unit (RIU) cost, T is study period.

2) Operational Expenditure (OPEX): OPEX encompasses various costs such as energy expenses, rental fees, expenses related to upgrading baseband capacity, Operation and Maintenance (OAM) costs, as well as fees for hardware and software maintenance. This cost calculation is performed for both network architectures, taking into account a yearly basis starting from the first year [11][12].

$$\begin{aligned} OPEX = \sum_{i}^{T}(C_{energy} + C_{siterent} + \\ C_{CUP} + C_{OAM} + C_{maint}) \end{aligned} \quad (6)$$

Where, C_{energy} is Energy Cost, $C_{siterent}$ is site Rent cost, C_{CUP} is Capacity upgrade cost, C_{OAM} is OAM Cost, C_{maint} is HW & SW maintenance cost and T study period.

Energy cost

The annual energy cost of the network is determined by adding up the total amount of energy used by both the BBM units and cloud servers. Energy cost can be calculated as [8] [36],

$$P_T = \sum_{i} P_i * n_i + \sum_{i} P_j * n_j \quad (7)$$

Where i represents the total number of BBU units in the network, j represents the total number of power consuming elements in cloud servers (compute nodes, switches) and P is the power consumption of the BBM unit i or cloud server hardware element j.

The annual energy consumption (E_T) in kWh can be calculated as:

$$E_T = \frac{P_T}{1000} * \frac{Hrs}{Day} * \frac{Days}{Year} \quad (8)$$

Where P_T is yearly power consumed by the baseband processing hardware.
Then yearly energy cost (C_{Energy}) can be calculated as:

$$C_{Energy} = E_T * C_{kwh} \quad (9)$$

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

3) Total Cost of Ownership (TCO): The TCO model integrates the outcomes of both CAPEX and OPEX calculations for each architectural option, allowing for the computation of economic metrics. TCO can be calculated as,

$$TCO = \sum_{i}^{T} Capex_i * Opex_i \quad (10)$$

Where $Capex_i$ is the total CAPEX in the year i, $Opex_i$ is the total OPEX in the year i, and T is the study period.

4) Revenue Modeling: Revenue is determined by taking into account the number of subscribers, average revenue per user, and the market share. This calculation serves as a basis for determining the total revenue generated. Revenue can be calculated as [48],

$$R = N_S * ARPU * M_S \quad (11)$$

Where R is the revenue generated, N_S is the predicted number of subscribers, $ARPU$ is the average revenue per user, and M_S is the Open RAN market share.

5) Techno-economic Evaluation Metrics: There are different methods for assessing the profitability of a project, including the NPV, IRR, and PP. Those methods are applied in this thesis including cash flow analysis and discounted cash flow analysis. These methods allow for a thorough examination of financial aspects by taking into account the timing and value of cash inflows and outflows.

Cash Flow (CF) and Discounted Cash Flow (DCF)

Cash flow analysis is a process that thoroughly investigates the inflow and outflow of cash within a company. By utilizing the data obtained from the cost and revenue model, the cash flow is mathematically represented in equation 12. This analysis serves as a tool to gain a comprehensive understanding of the financial activities within the company [35].

$$C_F = \sum_{i}^{T}(R_T - C_T)i \quad (12)$$

Where: C_F is the cash flow, R_T Total revenue, C_T is TCO, T is the study period.

The discounted cash flow (DCF) approach is a technique employed to determine the value of an investment by analyzing its expected future cash flows. This valuation method is expressed mathematically through Equation 13 in a DCF model.

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_i}{(1+r)^i} \quad (13)$$

Where DCF is the discounted cash flow , CF is cash flow for the given year, i is the study period, and r is the discount rate.

Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PP)

The NPV is widely acknowledged as the most advantageous metric, as per the NPV, it is advised that a company would allocate funds towards projects that exhibit a positive NPV. This economic indicator calculated based on obtained cash flow or discounted cash flow [39], [40].

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+r)^i} \quad (14)$$

Where: NPV is the net present value, CF_i is cash flow occurring in the year i, r is the discount rate, and T is the study period.

The IRR is an economic metric that is closely related to the NPV. IRR is calculated by determining the discount rate that results in an NPV of zero. In relation to the IRR rule, a company only consider investment opportunities that offer an IRR greater than their discount cash flow [39], [36]. IRR can be calculated as,

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+IRR)^i} = 0 \tag{15}$$

Where: NPV is the net present value, IRR is internal rate of return, CF_i is net cash flow in the year i, and T is the study period.

The PP refers to the number of years it will take for the company to recoup its initial cash investment according to the projected cash flow outlined in the proposal. If the calculated PP falls below a predetermined maximum duration, then the condition for accepting the PP is satisfied. PP can be calculated as

$$PP = LP + [\frac{ABS(CCF)}{CF}] \tag{16}$$

Where: LP is the last period of negative cumulative cash flow, CCF is value of cumulative cash flow at the end of last period, CF is the total cash flow after last period.

IV. RESULT AND ANALYSIS

This chapter discusses the techno-economic analysis of the Open RAN deployment scenario results and analysis. The analysis was designed to assess and compare the costs associated with the D-RAN and Open RAN architectures. The data was collected from Ethiotelecom and includes existing 4G traffic data. The study was conducted over a span of five years, starting from the initial year of 2024. Ethiotelecom currently has a RAN utilizing the D-RAN architecture. In order to determine the most cost-effective RAN architecture, both options are being evaluated based on TCO and economic metrics over a study period.

To select deployment area, the process entails the acquisition of the existing RAN deployment architecture details from Ethiotelecom. the Bole area emerges as the most capable selection, attributed to the existence of a fiber optic infrastructure that holds the potential to serve both front haul and mid haul functionalities. The study area contains 21 macro cell site with 3 sector for each site. Also population density and increment is taken into 2.3% Annual Population growth [41]. Figure 11 depicts a specific region that has been chosen within an area measuring 4 square kilometers.

Deployment scenario and benefits of Open RAN are discussed in section II-C. Also specifically there are various deployment scenarios (Indoor Picocell, Outdoor Picocell, Outdoor Microcell, Integrated Access and Backhaul, and Outdoor Macrocell) and and use cases (eMBB and URLLC) being considered for Open RAN in the open RAN deployment process [42], [37]. Key performance indicators such as peak data rate, bandwidth, latency, and mobility are considered to specify the requirements for both indoor and outdoor base station deployment scenarios. Deployment scenario for this thesis are shown in figure 12.

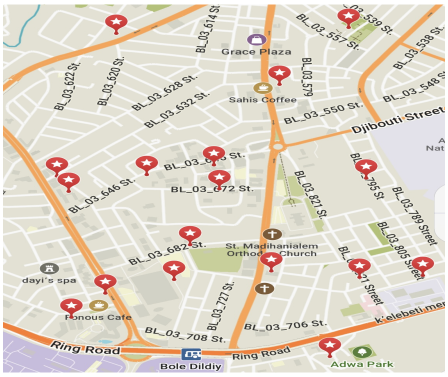

Fig. 11. Selected deployment area.

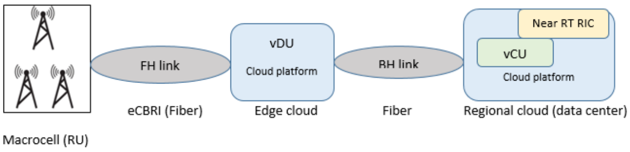

Fig. 12. Implemented open RAN architecture [37].

Additionally, in D-RAN, the lower physical layer cannot be handled by the RRU, leading to the utilization of radio interface units (RIUs) between the RRU and O-DU to implement the CPRI RRU interface with the vDU [43], [44].

A. Network dimensioning

Section III-C provides a comprehensive explanation of the network dimensioning procedure and this section provides a detailed analysis of the results derived from the dimensioning procedure and condenses and presents all of the key findings. The dimensioning procedure takes into account the number of subscribers, the types of services offered, the desired performance requirements, the available budget, and the different network architectures being considered.

1) Inputs and Assumptions:

- Number of cell sites consisting of radio functionalities is the same in both RAN architectures and the number is expected to increase.
- Open RAN architectures are gradually virtualized from the year 0's D-RAN architecture. Baseband processing is being transitioned from cell sites to data centers and the number of vRAN will be increased.
- The cell site and the hub site utilizes the eCPRI interface, which is a standard interface that operates over Ethernet for front haul communication. The functional split option supported is eCPRI standard Option 7-2x, and it is estimated that the total bandwidth needed for front haul is approximately 25Gbps [43], [45].
- Current Open RAN solutions were also assumed to be able support 64 cells per VNF [37], [8].
- The initial stage in server dimensioning involves allocating the CPU resources. A 32-core CPU is designated

for both vDU, vCU. Following the determination of the number of CP VM and UP VM, VM is allocated with a 2-core CPU [42], [46], [47].

Cell site configuration

This data was collected from Ethiotelecom and shows that the cell configuration uses FDD type 20 MHz 2x2 MIMO and 20 MHz 4x4 MIMO in D-RAN. Over the five- year period, more cells are added and replaced by cells with 20 MHz 4x4 MIMO. Also Servers need to be able to handle the peak load of traffic during busy hours, and also necessary to be able to store and process the large volumes of data that are generated by cell sites.

Parameter	2023	2024	2025	2026	2027	2028
BH share of traffic per day per site	9%	9%	9%	9%	9%	9% %
UL share of total throug-hput (DL+UL)	8%	9%	10%	12%	13%	15%%
Average BH throughput (Mbps)	17	18.78	20.85	22.93	25	27
Data volume/ site (GB/day)	117.93	127.02	135.62	144.22	152.82	161.42

TABLE I
CELL SITE THROUGHPUT & DATA VOLUME.

C-plane traffic is another parameter on network dimensioning for both proprietary BBMs and COTS hardware (servers). In C-plane traffic, primary factors: the maximum limit of CUE allowed per cell site and the C-plane traffic load per CUE. The maximum CUE per cell site refers to the maximum number of devices that can be connected to a single cell site. In case of Ethiotelecom, in LTE advanced network maximum RRC connected user is 450 and maximum concurrent user is 45. On the other hand, the C-plane traffic load per CUE measures the frequency of signaling messages transmitted by these devices.

2) Network Dimensioning Result: Using the data collected from Ethiotelecom in Section IV-A1 and the procedure to compute the necessary number of BBMs and servers described in Section III-C, network dimensioning was computed as shown in Table II.

Network architecture	Hard ware component	2023	2024	2025	2026	2027	2028
D-RAN	Total number of cell site	63	90	117	144	171	198
Open RAN	vDU hub site	1	2	2	3	3	3
	vCU hub site	1	1	1	1	1	1
	No. of cell per BBU Pools	63	45	59	72	57	64
	No. of Server	40	60	60	60	81	81

TABLE II
NETWORK DIMENSIONING RESULT.

B. Cost Analysis

The CAPEX and OPEX costs were estimated based on certain assumptions. A thorough analysis of the cost modeling conducted in this thesis can be found in section III-D. The following assumptions were made.

- Due to the assumption of a functional split in the model, the cost of the Front haul in the Open RAN is considered to be equal to the cost of the backhaul in the D-RAN.
- Expenses associated with renting the cell tower and the floor space, operator already possesses their own data center and core sites, so the costs related to renting the data center were not included.
- The costs associated with OAM for network operations and troubleshooting, preventive maintenance, performance optimization, capacity analysis and planning, and software release upgrades are calculated based on the information obtained from the operator's annual report and relevant literature pertaining to each of the architectures.
- The calculation of CAPEX cost does not take into account the expenses for RF hardware, as it is presumed to be consistent across both architectural designs.
- Annual energy costs are calculated using section III-D2 energy cost calculation and assuming a cost of \$0.022 per kWh [49].

Once the necessary number of BBMs and vRAN servers are determined as described in section IV-A2, the next step is to calculate the costs associated with deploying and operating the system including energy cost. These costs are provided in Table III and Table IV, based on information from Ethio telecom, vendors, literature, and online sources [43], [8], [36], [37], [50]. A 5% annual inflation rate is taken into account.

No..	Component	Cost [k$]
1	BBM (CAP, COM, CAB)	126
2	BB SW	46
3	BBM License	117
4	BH & FH link cost	20
5	Annual BH & FH cost per site	40
6	Annual Cell site rent	54
7	Annual OAM	126
8	Capacity upgrade	75
9	HW & SW maintenance (4% & 5% of equipment)	128

TABLE III
COST OF D-RAN COMPONENTS.

No.	component	cost($)
1	vRAN cloud server HW cost	200
2	Cloud SW	140
3	SW License	120
4	BH & FH link cost	20
5	RIU	21
6	Annual OAM	88
7	capacity upgrade	34
8	Annual Cell site rent	54
9	Annual BH & FH cost per site	40
10	HW & SW maintenance (2% & 10% of equipment)	98

TABLE IV
COST OF OPEN RAN COMPONENTS.

1) CAPEX calculation: The cost of network components in section IV-B is used to determine the CAPEX cost for each architecture. The deployment of Open RAN architecture is done in two phases, with 70% being de- ployed in 2024 and the remaining 30% in 2025. In the context of Ethiotelecom's D-RAN architecture, the existing architecture currently in operation provides services. Figure 4.4.1 provides an illustration of the hardware components in both architectures. he data shows that the total CAPEX of Open RAN is 62% higher than that of D-RAN. This is because the existing D-RAN architecture does not require additional BBM deployment, as the existing BBM CAP units have capacity for additional subscribers.

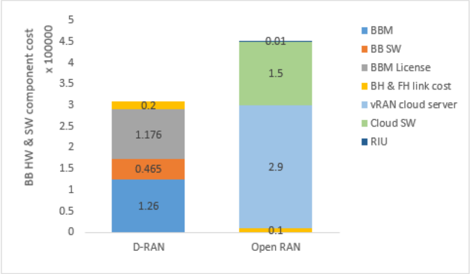

Fig. 13. Cost contribution of hardware and software components.

2) OPEX calculation: OPEX cost computed using inputs in section IV-A1 and IV-A2 for the study period. Open Ran OPEX proves to be 34% lower than D-RAN. The reason behind the substantial savings in operational costs with Open RAN can be primarily attributed to the reduction in maintenance, energy, and operation expenses.

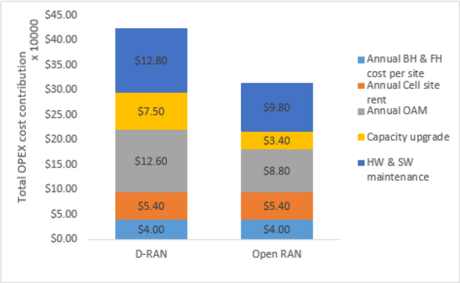

Fig. 14. Opex cost contribution.

3) Total Cost of Ownership (TCO): Once CAPEX and OPEX calculations are obtained, the total TCO of the RAN can be evaluated by considering both the initial investment and ongoing expenses for a specific period of analysis. The following figure 4.4.6 illustrates the TCO of D-RAN and Open RAN architectures. In comparison to the D-RAN system, the TCO of the open RAN is significantly higher, exhibiting a increase of 13over the study period. This indicates that the existing RAN infrastructure are cost effective.

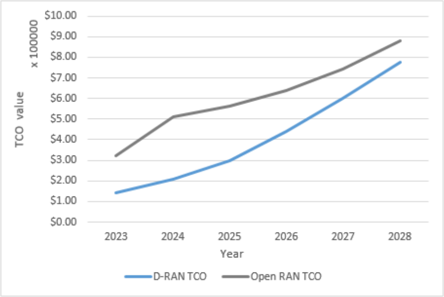

Fig. 15. TCO of D-RAN and Open RAN.

4) Techno economic evaluation: Using method that are discussed in section III-D5 the techno-economic evaluation generates results for D-RAN and Open RAN architecture, employing significant evaluation parameters such as CF, NPV, IRR, and PP. To compute economic metrics different inputs are used. Those input include average revenue per user (ARPU) and number of subscriber. The number of subscribers and ARPU are collected from Ethiotelecom [51], [41]. The projections for ARPU and subscriber figures were made by applying the linear regression method for the duration of the study period. It was assumed that the market share would remain at 100% throughout the study period and discount rate of 10%. Figures 16 and 17 illustrate there is a continuous growth in both subscriptions and ARPU. The revenue has been calculated by using the input ARPU and the number of subscribers, as outlined in section III-D4. Afterward, the cash flow was computed by utilizing the revenue and applying a discount rate. The diagram provided below illustrates an upward trend in the cash flow analysis. The cash flow is increasing in both architecture but open RAN has higher cash flow. The economic metrics, including NPV, IRR, and PP, are computed by utilizing the guidelines outlined in section III-D5, taking into account the TCO as specified in section III-D3. A summary of the results for all of these metrics is presented in the table V provided below.

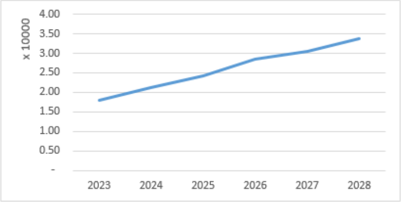

Fig. 16. Forecasted subscriber.

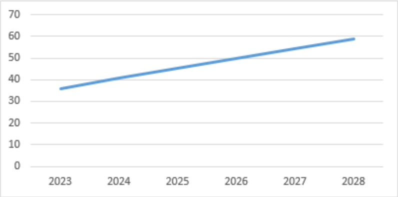

Fig. 17. Forecasted ARPU per year.

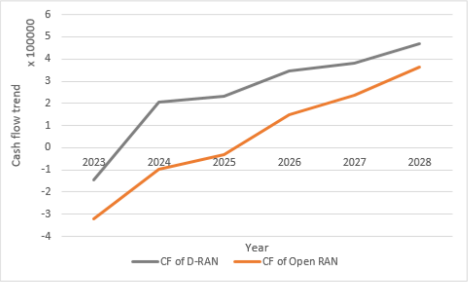

Fig. 18. Cash flow comparison.

Architecture	NPV($)	IRR(%)	Payback period(years)
D-RAN	954,547	63%	2.4
Open RAN	57,385	14%	3.5

TABLE V
ECONOMIC METRICS RESULT SUMMARY

V. CONCLUSION

The result of this thesis illustrate that the total CAPEX of D-RAN is 61% lower than Open RAN. The existing infrastructure of D-RAN reduce the initial investment. A comprehensive evaluation of OPEX across both architectures shows that Open RAN's OPEX is 34% lower than D-RAN. Also economic metrics result reveals that both D-RAN and Open RAN architectures have positive NPV and a higher IRR than the defined discount rate of 10%. The D-RAN technology has a much higher IRR than the specified discount rate, due to its lower initial investment cost. The result indicated that both architectures are expected to generate a positive return on investment. Additionally, the PP for both architectures is indicated. When comparing the two architectures in terms of PP, D-RAN has a lower PP, meaning that it is expected to pay for itself sooner than Open RAN.

This is a significant finding, as it suggests that D-RAN is not only a more cost-effective architecture in terms of TCO, but also a more financially viable option overall. This is due to a number of factors, including the lower CAPEX and OPEX costs associated with D-RAN.

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