Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Telecommunication Engineering Graduate Program

Techno-Economic Analysis of Cloud RAN Deployment Scenarios: in the Context of Ethio Telecom

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Advisor

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Addis Ababa, Ethiopia

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Thesis Title

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Dean, School of Electrical and Computer Engineering

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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Behailu Getachew Moges
January 24, 2022

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

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January 24, 2022

Abstract

The explosive mobile traffic growth, as well as rapid deployment of innovative wireless technologies and services, have all put significant strain on network capacity in the radio access network (RAN). Mobile network operators (MNOs) are considering Cloud-based RAN deployment to address this capacity challenge while improving cost, energy usage, deployment flexibility and network management. Efficient deployment of Cloud RAN requires selecting suitable deployment scenarios and a thorough understanding of both its technical and economic aspects in the context of the RAN service area. Such techno-economic study has not been undertaken in the context of Addis Ababa, Ethiopia and it is required to scientifically understand viable deployment of RAN architecture in Addis Ababa.

In this thesis work, potential Cloud RAN deployment scenarios are formulated using scenario planning method. For selected scenarios in the context of Addis Ababa, a thorough techno-economic analysis is performed applying a modified TERA framework that includes marketing forecast, network dimensioning, cost modeling, revenue modeling and economic analysis. The analysis is performed using net present value (NPV), internal rate of return (IRR) and payback period (PP) economic metrics that are obtained from its implementation in MS-Excel and MATLAB. For the analysis, we assume a 6 years study period and a 10% discount rate.

Achieved results show traffic growth forecasts have a great impact on Cloud RAN economic benefits that in turn affect the rate of return on investment. In scenario 1 with low traffic expectation, centralized RAN architecture shows a better cost position than Cloud RAN and distributed RAN (D-RAN) with a payback period of 2.94, 3.04 and 3.14 years respectively. However, for small scale deployment under a high traffic growth scenario, Cloud RAN architecture becomes the most cost-efficient architecture with all economic indicators as shown by the result. In this scenario, the payback period for Cloud RAN, Centralized RAN, and D-RAN is 3.5, 3.95 and 4.16 years respectively for Addis Ababa. Regarding NPV and IRR, all architectures have positive NPV for the study periods and greater IRR value than the defined discounted rate. The results indicate that Cloud RAN achieved significant cost benefits under a high traffic growth scenario.

Keywords: *LTE, 5G, RAN, Cloud RAN, Virtualization, TERA Model, Cost Modeling, Techno-economic Analysis*

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Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AC	Air Conditioner
ACTS	Advanced Communications Technology and Services
ADC	Analog-to-Digital Converter
API	Application Programming Interface
APRU	Average Revenue Per User
AR	Augmented Reality
ARQ	Automatic Repeat Request
BB	Baseband
BBM	Baseband Module Unit
BBU	Baseband Unit
BH	Busy Hour
BS	Base Station
CAGR	Cumulative Annual Growth Rate
CAPEX	Capital Expenditures
CDMA	Code Division Multiple Access

CF	Cash Flow
CN	Core Network
CoMP	Coordinated Multi-Point processing technology
COTS	Commercial-off-the-shelf
COVID-19	Corona Virus Disease of 2019
C-plane	Control Plane
CPRI	Common Public Radio Interface
C-RAN	Cloud-based Radio Access Network
CUE	Connected User Equipment
DAC	Digital-to-Analog Converter
DCF	Discounted Cash Flow
D-RAN	Distributed Radio Access Network
EB	Exabyte
ECOSYS	Techno-Economics integrated Communication Systems and Services
eCPRI	enhanced Common Public Radio Interface
EDGE	Enhanced Data rates for GSM Evolution
eICIC	enhanced Inter-Cell Interference Coordination
eNB	Evolved NodeB
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EPS	Evolved Packet System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access

HSUPA	High Speed Uplink Packet Access
HW	Hardware
ICIC	Inter-Cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IQ	In-phase and Quadrature
IRR	Internal Rate of Return
ISP	Internet Service Providers
ITU	International Telecommunication Union
JT	Joint Transmission
LNA	Low Noise Amplification
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
M2M	Machine-to-Machine
MAC	Medium Access Channel
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MPLS	Multi-Protocol Label Switching
MTTR	Mean Time To Repair
NFV	Network Function Virtualization
NGMN	Next Generation Mobile Network
NPV	Net Present Value
NRT	Non-Real-Time
OAM	Operation and Management
OBSAI	Open Base Station Architecture Initiative

OPEX	Operational Expenses
OPTIMUM	Optimized Architectures for Multimedia Networks and Services
OTT	Over-The-Top
PA	Power Amplifier
PB	Petabyte
PDCP	Packet Data Convergence Protocol
PESTLE	Political Environment Social Technological Legal and Economical
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
RRC	Radio Resource Control
RRU	Remote Radio Unit
RT	Real-Time
SDN	Software Defined Networking
SMS	Short Message Service
SW	Software
TCO	Total Cost of Ownership

TEA	Techno-Economic Analysis
TERA	Techno-Economic Results from ACTS
TITAN	Tool for Introduction scenarios and Techno-economic studies for the Access Network
TONIC	Techno-economics of IP optimized networks and services
TWDM	Time and Wavelength Division Multiplexing
UE	User Equipment
UHD	Ultra-High Definition
UMTS	Universal Mobile Telecommunications Systems
vBBU	virtualized Baseband Unit
VM	Virtual Machine
VNF	Virtualized Network Function
VR	Virtual Reality
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing

Introduction

1.1 Background and Motivation

Mobile data traffic has been growing exponentially due to the proliferation of mobile devices and services. Several sources reveal that mobile data traffic continues to grow explosively owing to the released new kinds of mobile services such as ultra-high definition (UHD) video, self-driving cars, wearable devices, virtual reality (VR), augmented reality (AR) and ubiquitous access to high-speed cloud content anytime that are confirmed as key future wireless network applications [1]. A report from Ericsson mobility also shows that the global mobile data traffic will reach 300 Exabyte (EB) (an EB is one billion gigabytes) per month in 2026 from where it was 58 EB per month at the end of 2020 which is a growth by a factor of 5 according to the report [2]. The forecast also reveals that at the end of 2026, 5G will lead the traffic growth with 53% of the total mobile data traffic carried by 5G as shown in Figure 1.1.

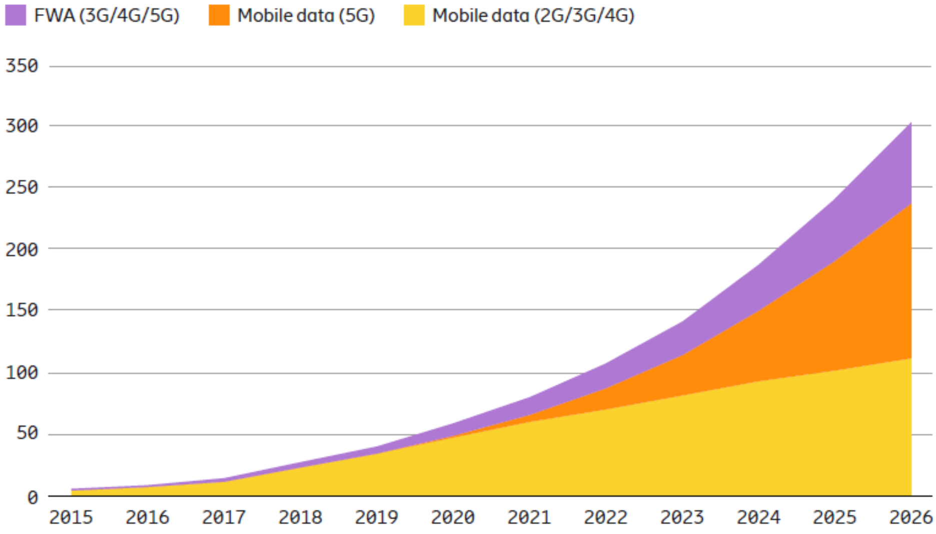


Figure 1.1: A forecast of Global mobile data traffic up to 2026 (EB per month) [2]

Mobile data traffic growth can be very volatile between years and vary significantly between countries based on the local market dynamics. According to [2], [3], the number of mobile subscriptions in Africa is the second-highest on the global scale, and the third-generation (3G) and fourth-generation (4G) networks surpass the second-generation (2G) mobile network. In Sub-Saharan Africa, mobile data traffic is estimated to grow by 12 times the current figures. Over the forecasted period, mobile broadband subscriptions are predicted to increase dramatically approaching 76% of the total mobile subscriptions. LTE subscriptions are set to triple and its share will reach 28% by the end of the forecast period. Over the six years period, the projection shows that a small amount of 5G subscriptions are expected to reach 7% in 2026 as shown in Figure 1.2.

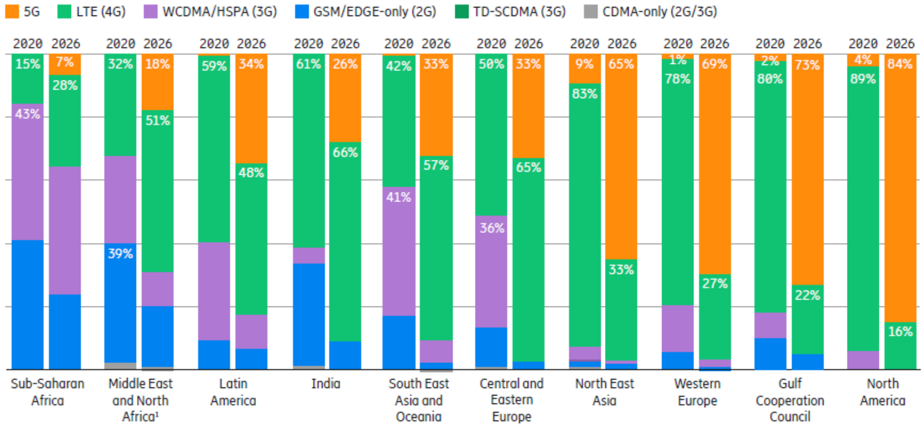


Figure 1.2: Mobile subscriptions by region and technology [2]

The use of mobile data services has also grown significantly in Ethiopia over the past years, in conjunction with a plethora of network expansion projects undertaken. According to ethio telecom [4], the number of mobile subscriptions in the country for voice and data services has grown significantly in the past few years to over 56 million. As outlined in [5], mobile data consumption is expected to grow at an accelerated rate, and capacity challenges will continue to exist in Ethiopia for the foreseeable future. The total mobile data demand in Addis Ababa reached 20.27 Petabyte (PB)/month in 2021, which is 38.7 times the traffic usage in 2016 as shown in Figure 1.3. This number presents real challenges to the operator to address the much needed capacity. Thus, in order to address possible capacity issues, it is essential to explore new technologies, which will provide capacity enhancements for mobile communications in the future.

Considering that mobile data traffic continue to grow over time with no sign of slowing down, this forecast presents some very real challenges for mobile network operators (MNO). The first challenge is finding a way to enhance the bandwidth capacity to handle the growing number of mobile data traffic that is both economical and scalable permitting future growth and secondly, performing it in a way that can reduce both the capital expenditure (CAPEX) and operational expenditure (OPEX).

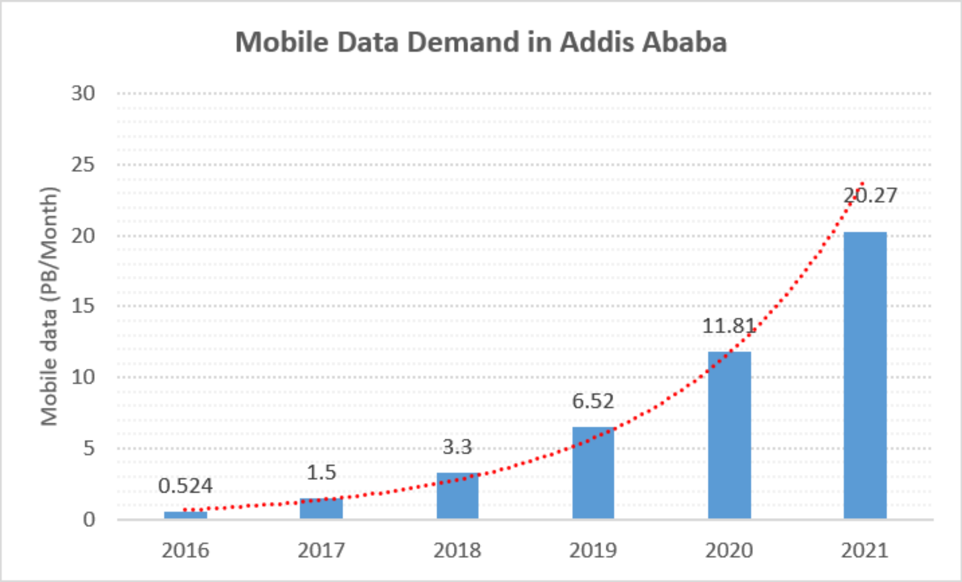


Figure 1.3: Mobile Data Demand Trend in Addis Ababa from 2016 - 2021 [5]

The most important part of mobile network infrastructure is the radio access network (RAN) which provides wide-area wireless connectivity between the end-user and the core network (CN). It delivers features such as availability of the network to end-users, provides high data rate, and quality of service (QoS). MNOs spend 60-80% of the CAPEX on RAN equipment [6], [7] to meet the increasing demand for mobile subscriptions and data traffic, and 60% of the total cost of ownership (TCO) on the RAN operation expenses [7]. China mobile research institute estimate that 72% of power consumption comes from cell sites [7]. Since RAN is an expensive part of the network, MNOs are looking for a solution that reduces the total cost of their network.

Today's RAN architecture cannot cope with the exponential demand for data; it has served its purpose. Its inefficiency arises mainly from the fact that it does not efficiently utilize resources, such as spectrum, processing power, and energy efficiency since with dedicated resources, specific cells can be congested, but others can be underutilized. In order to deal with these challenges and meet the explosive data demand, disruptive solutions are required. In the future, these challenges should be addressed by a new generation of networks such as cloud-based networks that integrate cloud computing into RAN [8], [9].

The IT sector has been using cloud computing, virtualization, and SDN successfully for its advantages such as reduced costs, flexibility, and scalability in data centers and wide area networks (WAN) [10]. The use of cloud computing and virtualization technologies in the Radio Access Network could help MNOs meet the high capacity demand at lower costs. Cloud Radio Access Network (C-RAN) is a new paradigm that utilizes cloud computing concepts in the RAN by moving, centralizing, and virtualizing the baseband (BB) processing into the cloud which can be implemented on commercial-off-the-shelf (COTS) hardware. C-RAN is one of the next-generation cellular network solutions that are cost-effective and enhance network capacity, reduce power consumption, site rental, simplify network management and decrease investments in base station equipment. This will result in an increase in profitability and competitiveness for the MNOs by reducing their total operational costs.

Even though Cloud-based RAN brings tremendous advantages to the mobile network and MNOs, it is extremely significant to conduct the techno-economic analysis before deployment. Pre-deployment analysis is significantly important for any new technology that is about to be released to the market, as it provides insight into its significance. Technologies differ in technical features they brought, performance, maturity level, and costs. Therefore, a thorough investigation is essential for telecom operators to pinpoint business alternatives and opportunities. As seen from ethio telecom's view, new technologies are deployed typically vendor-driven rather than supported by localized techno-economic assessments. Therefore, C-RAN deployment scenarios should be analyzed on a techno-economic basis since it will help the network operator decide what the optimum strategy with regards to C-RAN deployment is, optimize their network performance, and maximize their network utilization levels. In this thesis, the feasibility of C-RAN deployment options will be analyzed using the scenario planning method, and the viability of the selected scenarios will be explored techno-economically. Techno-economic analysis (TEA) plays a key role in strategic planning as well as in decision-making [11].

1.2 Statement of the Problem

As mobile data traffic grows exponentially, Mobile Network Operators face an increasingly large bandwidth requirement. As competitors race to adopt converged network technologies and meet end-user demands, ethio telecom must discover effective solutions to improve the QoS, increase spectrum efficiency and sustain reasonable revenues while lowering CAPEX and OPEX.

Various network architectures and technologies are proposed to cope with the increase in network capacity in the domain of RAN such as i) deploying advanced techniques such as Multiple Input Multiple Output (MIMO) [12] or massive MIMO [13]], Millimeter Wave (mmWave) transmission, and Beamforming [14] ii) adding more cells, making a Heterogeneous network (HetNet) and Small cell Networks [15]. However, these techniques face major challenges including implementation complexity, inter-cell interference, increase in power consumption, and incur higher costs. Hence, a cost-effective scheme for the next generation of the cellular network is required in terms of reducing energy consumption, face the increasing of data rate issues and simplify system management.

C-RAN is one potential solution to improve the highly demanded network capacity, flexibility in network expansion, a major reduction in cost and energy consumption [16]. However, deploying new technologies without a detailed investigation and decision of techno-economic analysis will bring many problems. For instance, according to [17], sample assessed technologies deployed in ethio telecom (CDMA, Fixed Access Network & LTE) shows that the target and utilization level of each selected sample project is not in line with the operational duration of the projects due to lack of detail localized techno-economic assessments before project deployment. These problems contribute to the noticed system performance issues such as capacity reduction, interference, and resource underutilization that affects QoS, resources wastage, high CAPEX and OPEX cost, reduction of revenue, and throwing out before return on investment. C-RAN is a promising solution to the mobile network paradigm that is also surrounded by uncertainties such as technological features, costs, and availability of capable devices. Besides, deploying it cannot guarantee its feasibility and provisioning of QoS. From the technology perspective, it is unclear which features and use cases of C-RAN can fit with the local context. Therefore, articulating the viability of C-RAN deployment scenarios and examining their feasibilities by applying techno-economic analysis is very important. In this study, we are going to address the following questions:

1. What are the use cases of C-RAN?
2. What are the most important alternative C-RAN deployment scenarios in the context of ethio telecom?
3. What are the trends and uncertainties of the alternative C-RAN deployment scenarios?
4. What are the techno-economic benefits and challenges for the C-RAN deployment scenarios?
5. Which C-RAN deployment scenarios are most likely feasible techno-economically in the context of ethio telecom?
6. When is the return on investment (ROI) achieved?

1.3 Objectives

The research work aims to achieve the following general and specific objectives.

1.3.1 General Objectives

The main objective of the thesis is to investigate the techno-economic feasibility of C-RAN deployment scenarios by combining technological background with an economic evaluation methodology in the context of ethio telecom.

1.3.2 Specific Objectives

The specific objectives of the research work are:

- To explore the state of the art research and related works on the techno-economic analysis of C-RAN deployment.
- To identify the different use cases of C-RAN.
- To analyze and formulate feasible C-RAN deployment scenarios in the context of ethio telecom.
- To identify the trends and uncertainties of C-RAN deployment scenarios.
- To investigate the techno-economic benefits and challenges of C-RAN deployment scenarios.
- To investigate the existing techno-economic analysis (TEA) frameworks, select a suitable framework for this research work, and modify the selected framework to meet local context.
- To model and estimate CAPEX and OPEX costs.
- To conduct a market analysis and prediction to determine subscribers, ARPU, and market share.
- To perform network dimensioning and assess the required number of network devices.
- To perform cash flow and discounted cash flow analysis based on the inputs from cost model, revenue model, and economic inputs.
- To evaluate the techno-economic feasibility of the C-RAN deployment scenarios by applying key economic indicators.
- To evaluate the ROI.

1.4 Methodology

In this thesis, the general methodology followed during the study of the techno-economic analysis of C-RAN deployment is shown in Figure 1.4. An extensive literature review was conducted by referring to standards, publications, renowned company reports, and related works. The data source for this research work is based on primary and secondary sources of data. The primary data source has been collected from ethio telecom live network. The data includes cell site data, network configuration data, and hardware and software data. The secondary data depend on C-RAN related books, 3GPP documentation, Next Generation Mobile Network (NGMN) documentations, IEEE articles and journals, International Telecommunications Union (ITU) publications, and TEA focused dissertations. Besides, documents and project reports from ethio telecom were utilized. Then relevant data for Addis Ababa such as existing site information, spatial traffic distributions, and digital map were collected. After data collection is completed, the target deployment area is selected. Next, a scenario-planning method applied based on [11], [18], [19], [20], [21] to formulate localized deployment options for Addis Ababa.

For this thesis, reviewed various TEA frameworks and selected the TERA framework for its relevance in the wireless telecommunications sector, and modified it to fit the local context. Revenue is calculated and forecasted for each scenario, which is derived from the forecasted user, and ARPU. Next network dimensioning is performed for each architecture based on [22], [23], [24]. The mathematical model is prepared for the revenue and cost calculation. The cost model is derived from [23] and based on the result from the dimensioning where the required number of BBMs, cloud hardware, and software licenses are obtained the CAPEX and OPEX costs are calculated. The cash flow (CF) analysis and discounted cash flow (DCF) analysis were conducted using cost and revenue modeling results and economic inputs which are implemented in MS Excel and Matlab. As an input to the system model assumed a study period of six years and a discounted rate of 10%. Economic evaluation metrics such as net present value (NPV), internal rate of return (IRR) and Payback period (PP) for each architecture are the output of the model for each architecture.

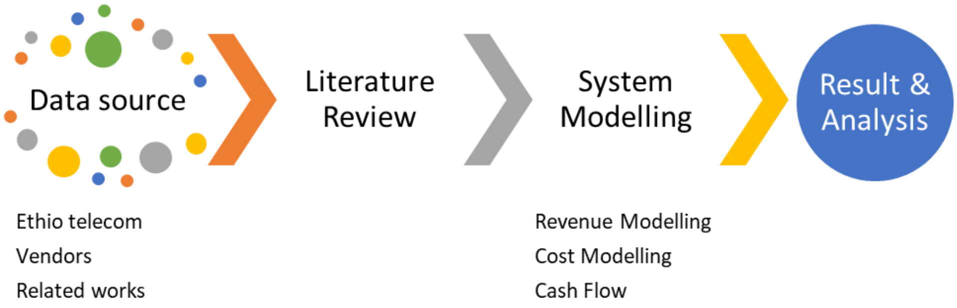


Figure 1.4: General Methodology

1.5 Literature Review

Many research works have been conducted on the techno-economic analysis of emerging technologies. Among these researches, related works that focus on the techno-economic analysis of C-RAN are mentioned below.

The centralization of BB functions into a central location in C-RAN architecture attracted significant attention in academia and industry because of its flexibility, coordination across cells, scalability, performance improvement, and cost. Even though C-RAN provides prominent advantages and opportunities, its deployment brings challenges to MNOs. The recent progress of C-RAN centralization and its challenges are presented in [16], [25], [26], [27]. Fully centralizing all the network functions in the baseband unit to a central location requires a throughput of around 160 Gbps (as it is envisioned in 5G) [28]. To achieve this throughput the allowed latency requirements are tight, between 10 to 250 µs [29], [30]. Transmitting in-phase and quadrature signal (IQ) samples between RRU and BBU via the Fronthaul link requires a high bandwidth hence data compression and aggregation techniques should be implemented at BBU and RRU to limit the Fronthaul bandwidth. By splitting the baseband functions for instance integrating the layer 1 functions (Physical layer) with the RRU, can reduce the required Fronthaul transport link by 40% [29]. In order to attain a better advantage from the C-RAN, fully centralizing the baseband function is recommended however due to limited Fronthaul link capacity issue, this might not be possible. Therefore, MNOs should consider these tradeoffs and their use cases while selecting the functional split that reduces the burden on the Fronthaul link as well as meets their requirements.

Multiplexing gain can be achieved when resources are aggregated into a single pool and shared. In C-RAN, centralizing the BBUs into a pool enhance cooperation techniques which in turn increases the multiplexing gain [10]. Various studies investigated the multiplexing gain achieved from aggregating the BBUs into a central pool. The author in [31] evaluated the multiplexing gain achieved for different functional splits in terms of cost and energy efficiency.

Their result indicates that for fully centralized C-RAN, significant multiplexing gain can be achieved from baseband resources (thus energy and cost-savings). Though, the required Fronthaul capacity is the highest. Moving part of baseband processing functions from BBU pool to cell sites, the multiplexing gain achieved on the BBU pool decreases. However, multiplexing gain can be achieved on the Fronthaul link when traffic becomes variable bit rate. In [32] investigated the multiplexing gain achieved and showed that by aggregating multiple cells into a single BBU pool a significant gain can be obtained. In [33] the authors compared the multiplexing gain based on the teletraffic approach. Their result indicates that 1.2–1.6 gain can be obtained based on the percentage of 30% / 70% office to residential cell sites ratio. This number can grow to 4 by taking into consideration specific traffic patterns and assuming the number of cell sites serving different areas.

To evaluate the cost position of the Cloud RAN architecture, a detailed investigation of the cost model is required. The study conducted in [23] examines the cost benefits of different RAN architectures D-RAN, C-RAN, Cloud D-RAN, and Cloud C-RAN. The author evaluated each architecture in terms of TCO within a 5-year study period to identify the most cost-efficient RAN architecture. Cell site information, network configuration data, hardware/software data and financial information were used for the cost modeling process. CAPEX items comprise investment in BBMs, cloud server HW and SW licenses, OPEX costs include energy, rental, capacity upgrade costs, OAM costs and hardware and software maintenance costs. The architectures are evaluated based on two control plane traffic growth expectations. The result reveals that for low traffic expectation the centralized RAN architecture shows better performance in terms of TCO than the Cloud RAN architectures. However, for high traffic growth, the benefit of Cloud RAN begins to be seen. After the fourth year when the traffic growth starts to explode, the Cloud RAN architectures costs start to decline. Centralizing and virtualizing the BBU on the COTS hardware reveals better scaling of Cloud servers than the vendor-oriented BBMs. In conclusion, the author states that Cloud RAN costs are highly dependent on the control plane traffic growth. Cloud RAN is the best solution to the explosively growing data demand and high capacity need with lower TCO. QoS parameters are not considered and also revenue modeling is not included in the model.

A study conducted in [34] investigated the techno-economic analysis on the integration of SDN/NFV based Cloud RAN architecture in 5G mobile networks for the case of Sweden. The paper provided a cost model to estimate network costs (CAPEX and OPEX) for the proposed 5G architecture in comparison with the corresponding costs of traditional network architecture. For the cost analysis, two scenarios are implemented. For the first case scenario, it is assumed that the legacy RAN network architecture is deployed and for the second case scenario, the proposed SDN/NFV based Cloud RAN architecture is used. In both cases, the virtualization technology building the virtual Evolved Packet Core (vEPC) is used to reap the benefits of virtual network function. The qualitative analysis performed reveal that the proposed SDN/NFV based Cloud RAN architecture provides significant cost saving. The considered CAPEX and OPEX costs could be reduced by 68% and 63% respectively compared to the legacy network and the TCO could be reduced by 69% compared to the legacy network. However, the model does not consider the network traffic and does not provide a detailed emphasis on the implemented hardware, and the baseband pooling gain is not considered in the model which has a high impact on the benefits of Cloud RAN deployment.

In order to formulate a techno-economic analysis of Cloud RAN, all the network costs should be taken into account. In most studies as in [23], [29], [35], [36] the evaluation metrics implemented is only Total Cost of Ownership. The study in [37] provides a comprehensive techno-economic framework for 5G RAN and transport networks and used TCO and other economic feasibility metrics for comparison. The author argues that TCO alone is not enough in order to show the profitability of different architectures and other economic evaluation metrics such as NPV and cash flow analysis should be taken into consideration. The authors' business feasibility assessment indicates that low TCO does not always lead to high profits because, for long-term projects, the point of time the project is invested in affects significantly the overall profit of the projects. The study in [36] analyzed the migration of LTE/LTE-A networks to Cloud RAN and proposed an ILP algorithm for the transition with minimal investment using the existing infrastructure. The authors tried to show the economic benefit of employing the existing legacy network infrastructures during migration to Cloud RAN. The authors found that significant savings could be acquired by using the existing network infrastructure during migration to Cloud RAN. The study in [29] investigated the cost-effective migration of distributed RAN architecture to Cloud RAN using time and wavelength division multiplexing (TWDM) based Fronthaul with functional splitting features. The authors formulated an ILP based optimization method to reduce the TCO of Cloud RAN with fully centralized and partially centralized network functions. Their result shows that partially centralizing the network functions bring about better TCO than the fully centralized Cloud RAN with a lower return period for the investment.

Most of the studies conducted so far mostly emphasized on deploying wireless networks for next-generation mobile networks based on Cloud RAN architecture from the scratch relying on the traffic demand of a specific network. Even though the studies bring better insight into the deployment of Cloud RAN, how MNOs possessing existing network infrastructure (e.g., LTE/LTE-A networks, transport network, site location, etc.) can easily migrate to Cloud RAN architecture without losing those infrastructures resources with minimum TCO is not widely addressed as required. MNOs can reuse the existing network infrastructure for the deployment of Cloud RAN so that they can save a significant amount of costs.

From the mentioned literature, it is inevitable to evaluate new technology viability from a technical and economic perspective. Most of the literature reviewed, used TCO to analyze the cost position of Cloud RAN and assessed the cost-saving obtained. However, to evaluate the economic feasibility of complex technical systems, in addition to TCO, the revenue generated and economic decision making criteria such as net present value (NPV), payback period (PP), and internal rate of return (IRR) should be quantified and it is the main task of this study. Moreover, this thesis presents a detailed techno-economic evaluation of the Cloud RAN to illustrate the differences in the costs of the different architectures based on the developed scenarios. Taking into account real baseband module hardware specifications and future RAN solutions, the TEA model's network dimensioning grants a more realistic estimate of the cost of the Cloud RAN.

1.6 Scope and Limitation

The scope of this study is to investigate the techno-economic feasibility of C-RAN deployment scenarios by examining its benefits and challenges. The study will provide insight into the significance of C-RAN deployment scenarios and their evaluation in technical and economic values using the techno-economic analysis method. The study is limited to C-RAN deployment scenarios for the LTE radio access network for data service and does not include the Core Networks. The analysis includes a wide area network as well as local area solutions, such as small cells. The study was performed for 6 years study period considering a 10 % discount rate for Addis Ababa, Ethiopia. The thesis considers the NRT-RT functional split of the baseband processing unit. Where the NRT functions are processed on the COTS cloud hardware where as the RT functions are processed in the proprietary hardware. The full centralization and virtualization of baseband functions into the cloud are not investigated.

1.7 Thesis Contributions

Techno-economic feasibility investigation of C-RAN deployment under different scenarios in the context of Addis Ababa is the main contribution of this study. The C-RAN TEA modeling developed in this thesis can be used to understand its economic benefits by giving an estimated cost comparison across the different RAN architectures. The detailed techno-economic investigation of the formulated deployment scenarios can also be used as an input for the operator to optimize its network, improve resource utilization level, and make understanding on the costs of the different RAN architectures, which are useful for understanding the viability of each scenario technically and economically. In addition, the output of this techno-economic analysis can be used as an input for operators to plan possible deployment alternatives of C-RAN. To the best of my knowledge, most of the studies conducted so far on cost modeling of C-RAN used TCO in order to analyze the cost position of C-RAN and assess the cost-savings obtained. In this thesis, in addition to TCO, economic decision making metrics such as NPV, IRR and PP are used to assess the economic benefits of C-RAN. Thus, its contributions are vast in this field.

Generally, the results obtained in this thesis work can be used as input for operators and research community.

1.8 Thesis Layout

The remainder of the paper is structured as follows: Chapter 2 provides an overview of mobile networks and the evolution of base station architecture in the cellular network. In addition, provides background to C-RAN, explaining its fundamentals, the main components in the architecture, advantages, and the technical challenges it faces. It also explains different types of C-RAN architectures. Moreover, the developing technology relevant to C-RAN is also outlined.

Chapter 3 explains the background of the techno-economic modeling, evaluation methods, and different mathematical models implemented in the thesis. Chapter 4 discusses trends that have an impact on the deployment of C-RAN and selects uncertainties that can affect C-RAN deployment and formulate possible deployment options for C-RAN. Chapter 5 explains the implemented Cloud RAN TEA framework with its inputs for techno-economic evaluations and performs network dimensioning. Chapter 6 discusses the result obtained from techno-economic modeling in the example case. Finally, Chapter 7 concludes the thesis and explores future research direction.

Cloud Radio Access Network Overview

This chapter mainly focuses on the fundamental and background overview of Cloud Radio Access Network (C-RAN). The mobile network infrastructure developments and the evolution of traditional Base Station (BS) architecture are discussed. The different types of C-RAN architecture based on the function of the baseband processing split between the Remote Radio Unit (RRU) and Baseband Unit (BBU) pool are described in detail. The components of C-RAN including RRU, BBU Pool, and optical fiber Fronthaul transport network are explained in detail. Moreover, the advantages, benefits, and challenges of C-RAN architecture are also explained. In addition, related technologies that are relevant to C-RAN are outlined in this chapter.

2.1 Mobile Network Evolution

The wireless communication system has undergone several evolution stages since the introduction of the first-generation network in the 1980s. Since then, cellular networks and technology have advanced dramatically with consecutive generations (2G to 4G) making significant milestones in the development of mobile connectivity [38].

A first-generation (1G) mobile network, developed in 1979, introduced in Japan, and then rolled out to other countries such as the US (1980), and the UK (1985). Based on an analog system, called AMPS (Advanced Mobile Phone System) uses the frequency division multiplexing access (FDMA) technique and provides a bandwidth of 30KHz and data rate of 2.4kbps. Despite this, 1G networks lacked reliability, signal interference issues, and lacked adequate security against hackers [38], [39].

In the late 1980s, the second generation (2G) also known as Global System for Mobile Communication (GSM) implemented a digital signal that reached up to 64kbps in speed, and was designed primarily for voice transmissions. GSM enhance the security, capacity (30 to 200 kHz), and allowed subscribers to send Short Message Service (SMS) and Multimedia messages. After continuous improvements to GSM technology, 2.5G was introduced, which incorporated packet switching via GPRS (General packet radio service) and EDGE (Enhanced Data rates for GSM Evolution) and supports data rate up to 144kbps [39], [40].

The third-generation (3G) also known as Universal Mobile Telecommunication System (UMTS) in Europe and CDMA2000 in the USA was invented in the year 2000. UMTS increased the peak data rates from 144 Kbps to 2 Mbps, enhanced radio spectrum usage, and also enabled users to make video calls, surf the web, share files, play online games and even watch TV online. A further revision of 3G led to two variants known as 3.5G (High-Speed Downlink Packet Access (HSDPA), High-Speed Uplink Packet Access (HSUPA)), and 3.75G (High-Speed Packet Access (HSPA)) to enhance data rate [38], [39], [40].

The 4G also known as Long Term Evolution (LTE) is the latest and most enhanced broadband wireless access technology. With theoretical download speeds ranging from 10Mbps to 1Gbps in 4G, users would have lower latency, better voice quality, instant messaging services, social media, quality streaming, and higher download speeds. 4G is also the first packet-switched mobile network designed to support all IP packets. In comparison with previous generations, the radio access network in 4G was simplified and flattened. As opposed to the Radio Network Controller (RNC) in previous generations, the 4G RAN only consists of evolved NodeBs (eNBs) and there is no centralized intelligent controller. Having the intelligence distributed between base stations reduces vulnerability caused by a failure in the centralized controller, network complexity, and time for connection setup and handovers. Several factors have motivated the development of 4G technology, the main drivers are the need for higher data rates, better QoS, reducing costs, and simplifying the network [38], [39], [40], [41].

2.2 Evolution of RAN Architectures

Mobile networks have evolved from telephony-based systems to an all-digital communication systems. Every architectural breakthrough has been enabled by new requirements of mobile services that weren't possible with legacy systems due to shortcomings in their obsolete architecture. In order to understand the RAN architecture for the next generation of mobile systems (such as 5G), it is important to look back to previous and current RAN developments. This section will describe the architectural evolution of RAN briefly.

2.2.1 Traditional RAN

The traditional RAN architecture combines the functions of the baseband and radio units into a single base station. As shown in Figure 2.1, the antenna is typically placed near the radio modules due to the high losses experienced by coaxial cables used to connect them. Mobile network deployments using this architecture were common in the 1G and 2G eras [10].

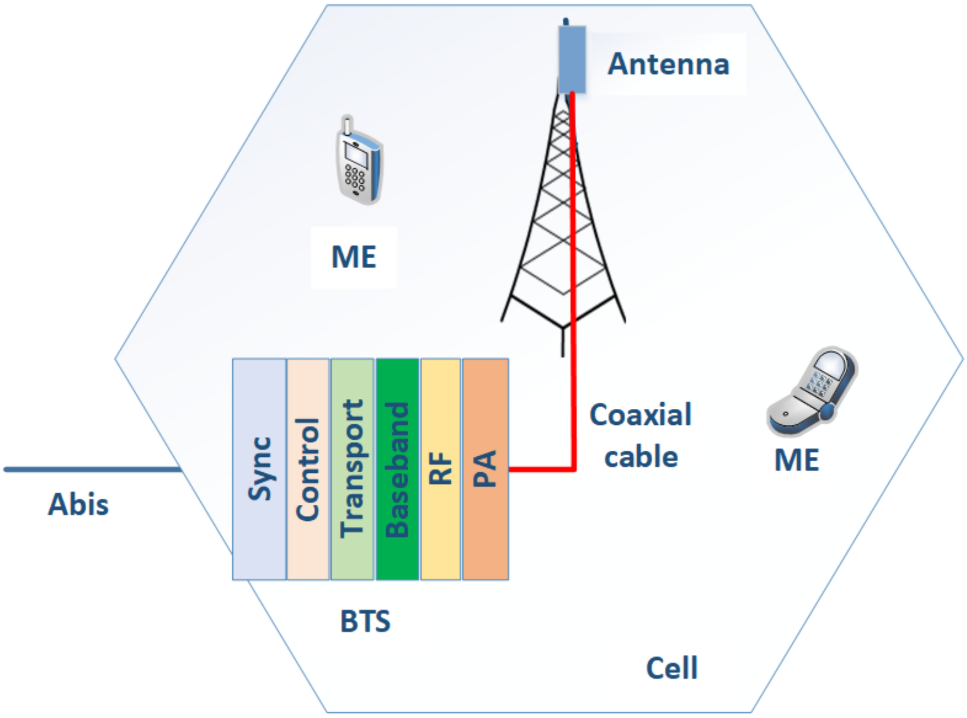


Figure 2.1: Traditional Macro Base station

2.2.2 Distributed RAN (D-RAN)

In D-RAN architecture, the conventional base station is split into two components called the baseband unit (BBU) and remote radio unit (RRU) as shown in Figure 2.2. The BBU is responsible for baseband and higher layer processing and allocates resources dynamically to RRUs depending on network requirements. The RRU is responsible for RF-related function and consists of radio frequency (RF) transmit and receive components such as power amplifier (PA), duplexers, low noise amplifier (LNA), and analog-to-digital converter (ADC) and digital-to-analog converter (DAC). BBU and RRU are collocated at the macro site and their interconnection is using fiber cable and also a microwave connection. The interface between the BBU and RRU is termed a Common public radio interface (CPRI). The adoption of fiber cable provides numerous advantages such as greater bandwidth, lesser noise, decreased power requirements, and more network coverage than copper cabling [10], [42]. The distance between RRU and BBU can be stretched up to 40 km, however, the distance is limited due to the processing and propagation delay that occurred between them [10]. The D-RAN is introduced during 3G network deployment and is widely adopted and exploited by LTE and LTE-A. In this architecture, the BBU equipment can be placed in a more convenient, easily accessible place, enabling cost savings on-site rental and maintenance compared to the traditional RAN architecture.

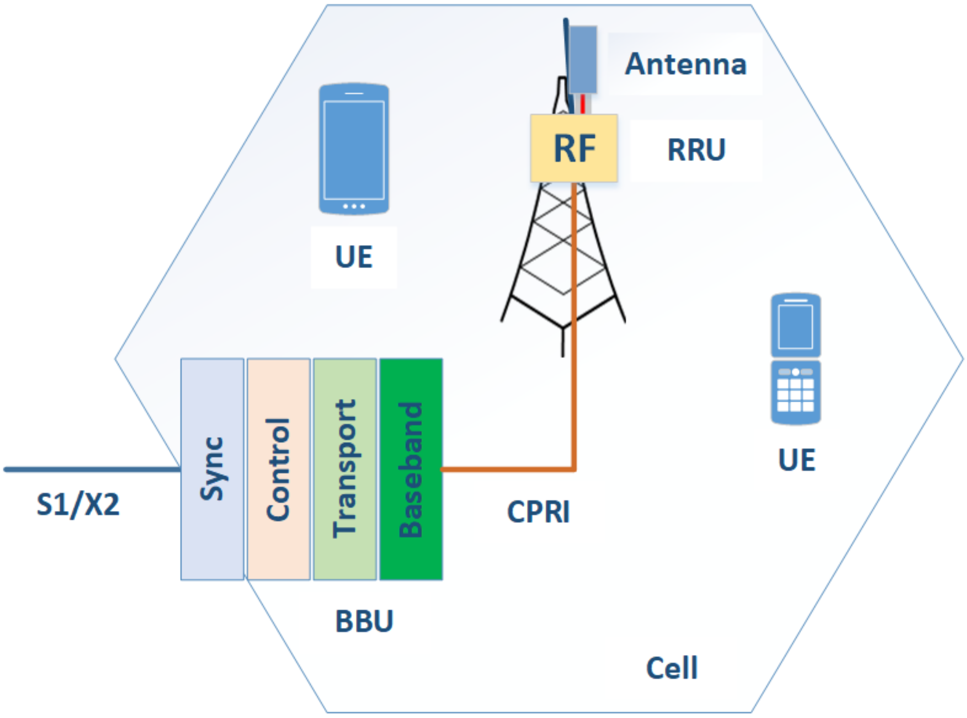


Figure 2.2: D-RAN Architecture

2.2.3 Centralized RAN

The existing D-RAN architecture brings many advantages by utilizing the existing fiber-optic network between the cell site and central office. In Centralized RAN, the BBUs are moved from the cell sites to a central location also known as BBU Hotel or Point of presence (PoP) [43] as shown in Figure 2.3. The RRUs at the cell sites are connected to the BBU Hotel via a CPRI Fronthaul transport network. This architecture makes RRUs easy to install on rooftops or streetlights, thus providing efficient cooling [42]. Centralizing the baseband unit into a central location allows more efficient maintenance, it provides the ability to maintain multiple BBUs in a single location, thereby improving Mean Time to Repair (MTTR) and cutting visits to cell sites significantly [43]. Moreover, the energy used by air-conditioning and other equipment on the premises can be reduced which leads to a reduction in energy consumption [42], [43].

As a result of centralizing the baseband unit, radio sites can be simplified, notably by eliminating or avoiding the need for additional enclosures and rooms [44]. Cell site simplification reduces operational costs such as site rent, energy, maintenance, and repair. In addition, centralization makes management and coordination of the network easier. The centralization of the baseband unit also facilitates the implementation of coordinated multi-point (CoMP) and interference mitigation techniques (ICIC, eICIC) [10], [42], [44].

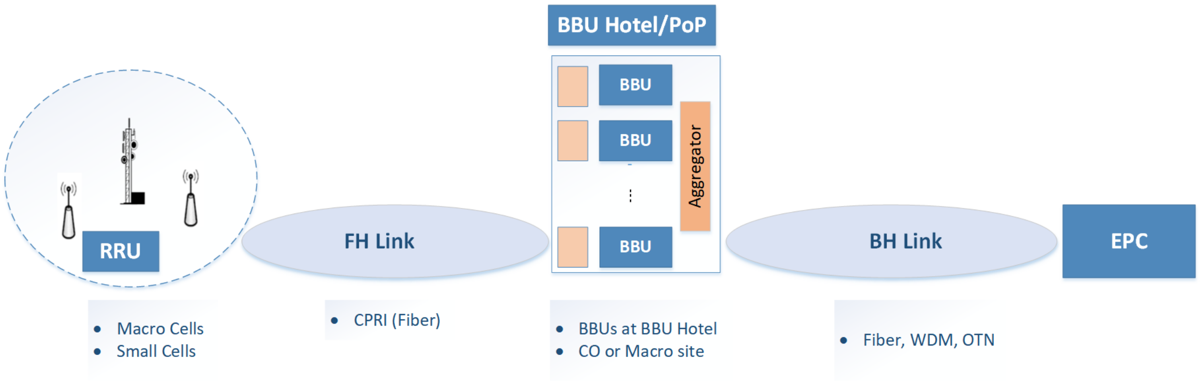


Figure 2.3: Centralized RAN Architecture

2.3 Challenges with Current Radio Access Network

Even though distributed RAN architecture alleviated most of the drawbacks with the traditional, it also faces some limitations and challenges in order to handle the requirement set by the next-generation mobile network such as 5G. Some of the challenges with the current radio access architecture are stated below.

1. Higher Cost

For mobile network operators to keep up with the rapidly growing demands for mobile data traffic, they must significantly expand their network capacity. In the current network architecture, building and maintaining a dense network infrastructure is very expensive [23], [16], [45]. Unambiguously, the CAPEX of wireless networks increases due to the expensive nature of base stations, while the OPEX of cell sites surges due to higher maintenance costs. Despite this, mobile operators continue to incur costs associated with construction, operation, maintenance, and upgrade of their networks. Meanwhile, the Average Revenue Per User (ARPU) remains flat or declines in the long run [10]. This poses real challenges to the MNOs to cope up with the required network capacity. Additionally, the current RAN is not capable of supporting 5G deployment [16], [23]. The next-generation RAN must be able to cope with the rapid growth in data traffic while keeping costs low.

2. High Energy Consumption

One way of increasing the network capacity in order to handle the growing capacity demand is through adding more macro base stations or increasing the MIMO configuration to enhancing spectrum efficiency. However, adding more base stations also increase the energy consumption and carbon dioxide emissions in the network [23], [7]. According to China Mobile, 72% of total power consumption comes from cell sites [7]. Hence, to reduce energy consumption and carbon dioxide emissions, MNOs should plan the deployment of more energy-efficient network architectures.

3. Base station over dimensioning

Wireless networks are designed to permit mobility, which enables users to move freely throughout the network, causing fluctuation in traffic loads on different parts of the network. Therefore, base stations are dimensioned for the peak hour traffic that occurred within a busy hour period in the day. However, the busy hour period occurs for a limited time resulting in the underutilization of the base station resources. The unutilized processing resources cannot be shared with other base stations resulting in over-dimensioning of base stations. A better way to utilize base station resources more efficiently is to share them across different areas, reducing the over-dimensioning of the base station [23].

4. Interference

When more BS are added to the network to improve system capacity, interference among BS is more severe as Base stations are closer to each other even overlap and more of them are using the same frequency. In consequence, neighboring cells can interfere with one another, leading to reduced throughput performance. To mitigate this interference, some radio collaboration techniques have been proposed, including Coordinated Multiple Point (CoMP) and Inter-Cell Interference Coordination (ICIC) [46], [47]. However, due to high latency and low bandwidth, effective CoMP algorithms such as Joint Transmission (JT) cannot utilize X2 interfaces of current LTE architecture for maximum performance gains [26], [47]. Cloud RAN, on the other hand, enables these technologies to be more seamlessly implemented, thereby reducing inter-cell interference, improving network throughput performance, and increasing spectral efficiency [7].

2.4 Cloud-based Radio Access Network (C-RAN)

2.4.1 What is Cloud RAN?

With the progress from 4G to 5G, there will be a significant increase in base station density, causing increased site acquisition costs and network construction costs. Further, dense deployment of base stations creates severe co-channel interference at cell edges, which negatively impacts the user experience. These challenges were addressed with the development of the Cloud-based Radio Access Network (C-RAN). The centralized deployment of the BBUs simplifies site acquisition and reduces the number of equipment required at sites, reducing costs associated with rentals, energy, and equipment rooms. Collaboration between BBUs improves performance at cell edges significantly. C-RAN becomes the best solution in solving the challenges with the traditional RAN as well as its features make it the next generation RAN architecture.

IBM first proposed C-RAN under the name Wireless Network Cloud (WNC) [48]. Further details about C-RAN were added in a China Mobile white paper [7]. Figure 2.4 illustrates the C-RAN primary concept of consolidating all BBUs into a centralized pool of cloud computing-based, shared, and virtualized BBUs. Each RRU is linked to its respective BBU pool through low latency, high bandwidth optical transport link called the Fronthaul link. Radio samples i.e., in-phase and quadrature (IQ) samples, are sent between an RRU and a BBU pool. The BBU Pool supports ten to hundreds of RRUs and is connected to the core network via a backhaul link.

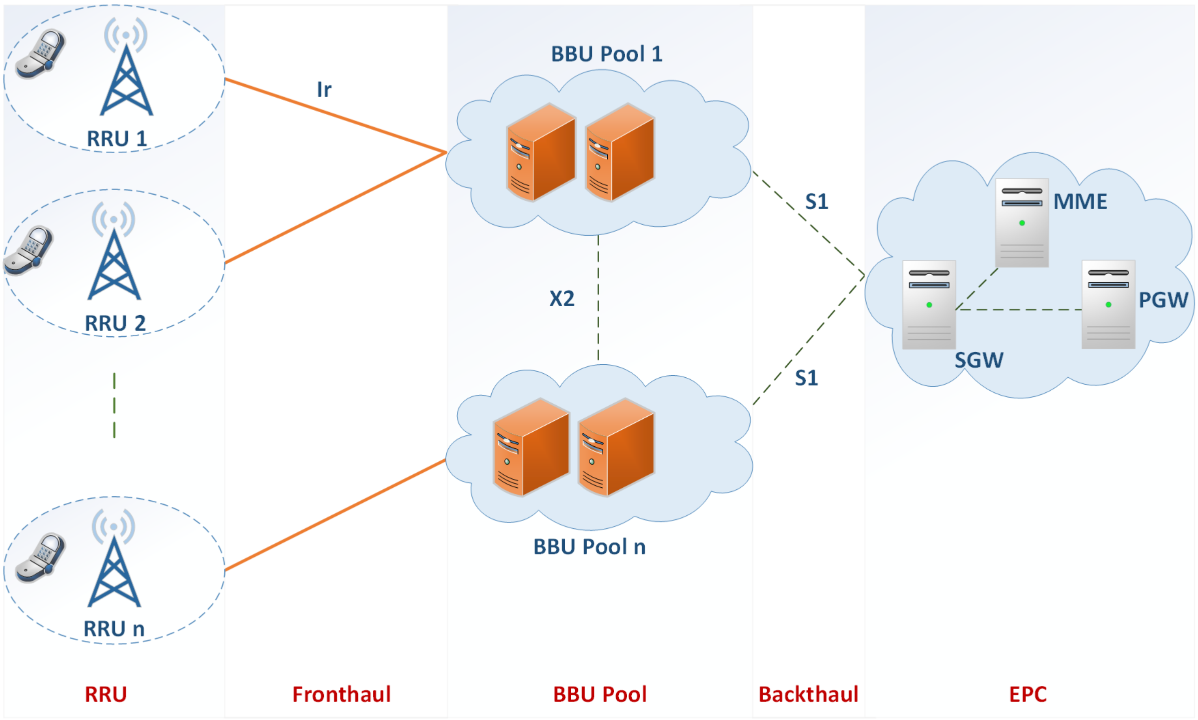


Figure 2.4: The general architecture of Cloud RAN

With C-RAN architecture, due to the multiplexing gain achieved by centralizing the BBUs, the required number of network equipment decreases significantly resulting in the reduction of CAPEX and OPEX, energy consumption is reduced, network operation and maintenance become simpler, network scalability is increased, spectral efficiency is improved, and load balancing is made easier [23], [10], [16].

In the C-RAN, cloud computing is incorporated into the RAN architecture enabling BBU pool virtualization which allows operators to offer RAN as a service (RANaaS) by sharing BBU resources [23], [10]. Since C-RAN is based on an open platform, it opens the possibility for new revenue streams with technologies such as Mobile Edge Computing (MEC).

Initially, C-RAN focuses on two principles: the centralization of baseband processing and the virtualization of it. With centralization, network performance can be optimized, energy consumption can be decreased, and spectrum can be efficiently used. Likewise, virtualizing baseband processing will hopefully result in a reduction of the CAPEX and OPEX of the mobile network operations [16]. Thus, C-RAN can now be used to refer to this architecture, in which the letter C stands for Cloud, Centralized processing, Cooperative radio, or Collaborative or clean networks [16].

2.4.2 Cloud RAN Components

The Cloud RAN architecture consists of the following main components: Baseband Unit (BBU) Pool, Remote Radio Unit (RRU), and a transport network known as Fronthaul. Figure 2.5 shows the C-RAN architecture and the components are described below.

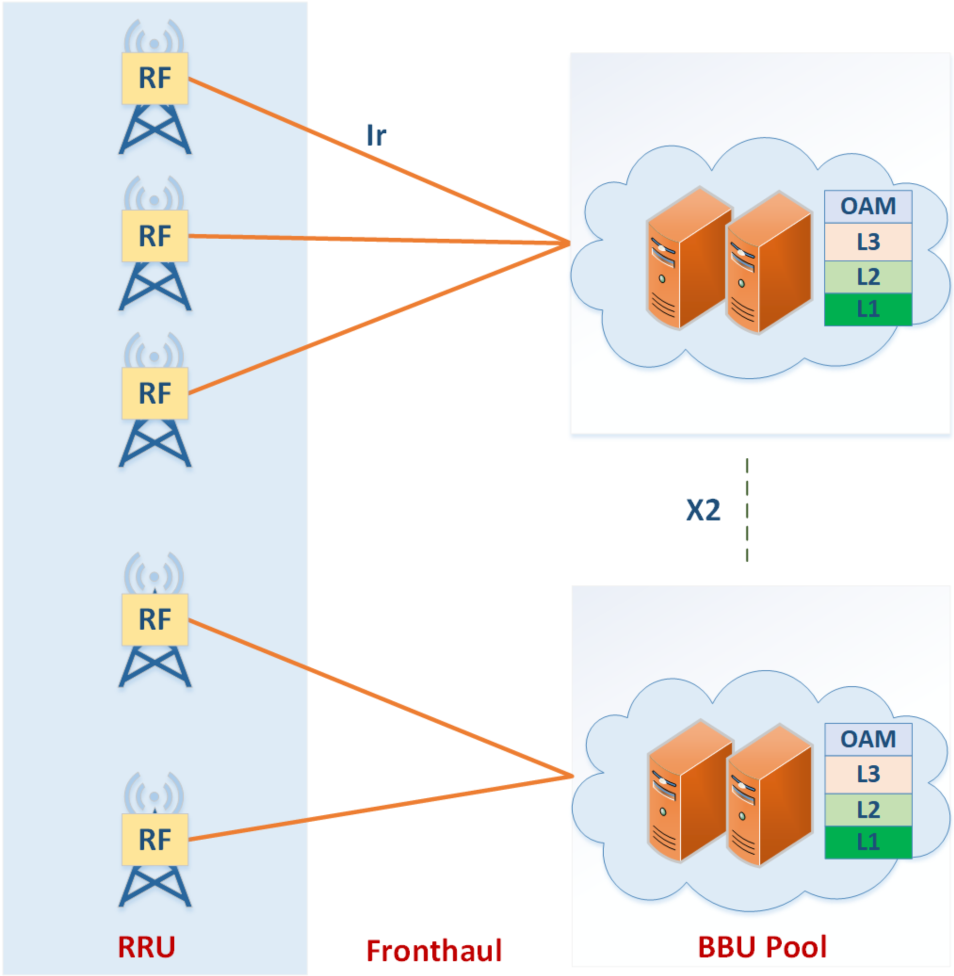


Figure 2.5: C-RAN Architecture

1. BBU Pool

A BBU pool consists of multiple BBUs arranged in a cloud, each serving several RRUs. The virtualized BBUs at the BBU pool is responsible for processing the baseband functions (Layer 1 to Layer 3). A BBU can be located at a cell site, in a BBU Pool, or a data center, depending on the Cloud RAN architecture, centralization level, and functional split implemented [22], [23]. A BBU pool can be entirely filled by different BBUs and their signal processing resources are shared according to data traffic demands and dynamically allocating them to the RRUs depending on the current network demand [22], [49].

2. Remote Radio Unit (RRU)

RRU is located at cell sites and provides signal coverage for the cell sites. RRU comprises RF transmit and receive components and performs the functions such as ADC, DAC, power amplification, LNA, filtering, antenna module, interface adaptation, and provide fiber interface. By relocating the majority of the baseband processing functions from the cell site to the BBU pool, allows less complexity of cell sites as well as efficient use of energy resulting in both CAPEX and OPEX reduction [10], [22], [23].

Therefore, RRU can significantly help cellular network operators to resolve performance, cost, and efficiency challenges when deploying new base stations in 5G networks. Moreover, RRUs distributed in certain areas such as urban areas with high traffic loads offer efficient cost. They are located at the cell sites and used to transmit the RF signals to users and forward the baseband signals from the users to the BBU pool [22].

3. Fronthaul Network

A Fronthaul network is a transport network, which connects the remote RRUs and BBU pool and is responsible for carrying the Fronthaul links to provide low latency and high capacity links [22]. There are different technologies used for C-RAN Fronthaul, including wireless and optical fiber. The most commonly used is a fiber-optic network with CPRI or eCPRI [50] and Open Base Station Architecture Initiative (OBSAI) protocols [51].

2.4.3 Cloud RAN Functional Splits

Initially, it was planned that Cloud RAN would incorporate fully centralized baseband processing. In this scenario, most base station functions would be performed centrally, while only RF functions were handled at distributed sites. Fully centralized BBU provides a maximum gain in multiplexing and easy implementation of coordinated multipoint transmission and reception (CoMP) schemes while reducing operating costs at radio sites. However, fully centralizing the baseband function and transporting the radio samples between the RRU and BBU requires high bandwidth and low latency interconnection network. This may not be cost-efficient and may even offset the benefit gained by centralizing the baseband processing. To overcome this deficiency without sacrificing the benefits of centralized processing, different functional splits are proposed for central and distributed processing units in Cloud RAN [23], [44].

An effective implementation and deployment of a cloud RAN depends on the functional split

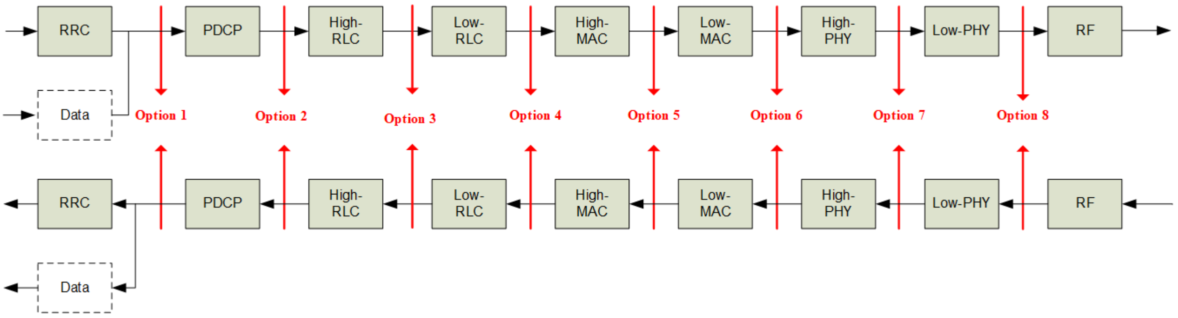


Figure 2.6: Function Split between central and distributed unit [52]

between the central and distributed unit. There are several options studied by 3GPP as shown in Figure 2.6. For Cloud RAN eight functional split options (Option 1 to 8) are realized where option 8 is the fully centralized solution. Currently, options 2 (PDCP) and 3 (Upper RLC) are the most appealing functional splits, which split functionalities into non-real-time (NRT) and real-time (RT) functions as the optimal trade-off between flexibility and performance. According to the NRT-RT split, NRT functions will be performed at the centralized site and RT functions will be performed at the distributed sites [52].

Options to the left of Figure 2.6, higher layer protocols are centralized where the lower layer protocols are distributed which allows coordination for layer 3. This option has a relaxed requirement for latency and bandwidth of the Fronthaul transport that makes them suitable for centralization. Moving progressively to the right, more functions are centralized to the point where only the RF functions are distributed which enables coordination at Layer 1.

Generally, the split on the right of Figure 2.6, where the entire baseband protocol stack is controlled centrally, provides the maximum performance gains from coordination across the cell sites. In order to accomplish this, a high-speed, low-latency connection between the distributed unit and centralized unit is required [52], [53].

Basically, there is a performance tradeoff between the system efficiency and the front-haul link capacity between central and distributed units. The selection of the functional split also highly affects the hardware choices, costs, energy efficiency, and operational simplicity [52], [53]. Since the optimum balance depends on both technical and commercial aspects that are determined by the markets and operator's choice, it is difficult to conclude an optimal model for the functional split. As a rule of thumb, for an operator that owns substantial access to dark fibers, a centralized model will be suitable. A less centralized Cloud RAN may work better if the operator uses prominently microwave to connect to the cell sites.

2.4.4 Cloud RAN Architectures

In terms of the functional splits between the RRU and BBU, there are two types of Cloud RAN architectures: Fully Centralized Cloud RAN and Partially Centralized Cloud RAN.

1. Fully Centralized Cloud RAN

In this architecture, all baseband functions related to Layer 1-3 (i.e., Physical layer, MAC layer, and RRC layer) are moved to the BBU Pool as shown in Figure 2.7. The RRU performs radio-related functions at the cell site. This architecture simplifies and clarifies the maintenance and operation of the system, easy upgrading of the network capacity, support cooperative signal processing of cell sites, and has the ability to accommodate multiple standards within the system [16]. Although fully centralized C-RAN has numerous advantages, it also encounters two significant challenges: the high bandwidth requirements, and IQ samples transmission between BBUs and RRU [7].

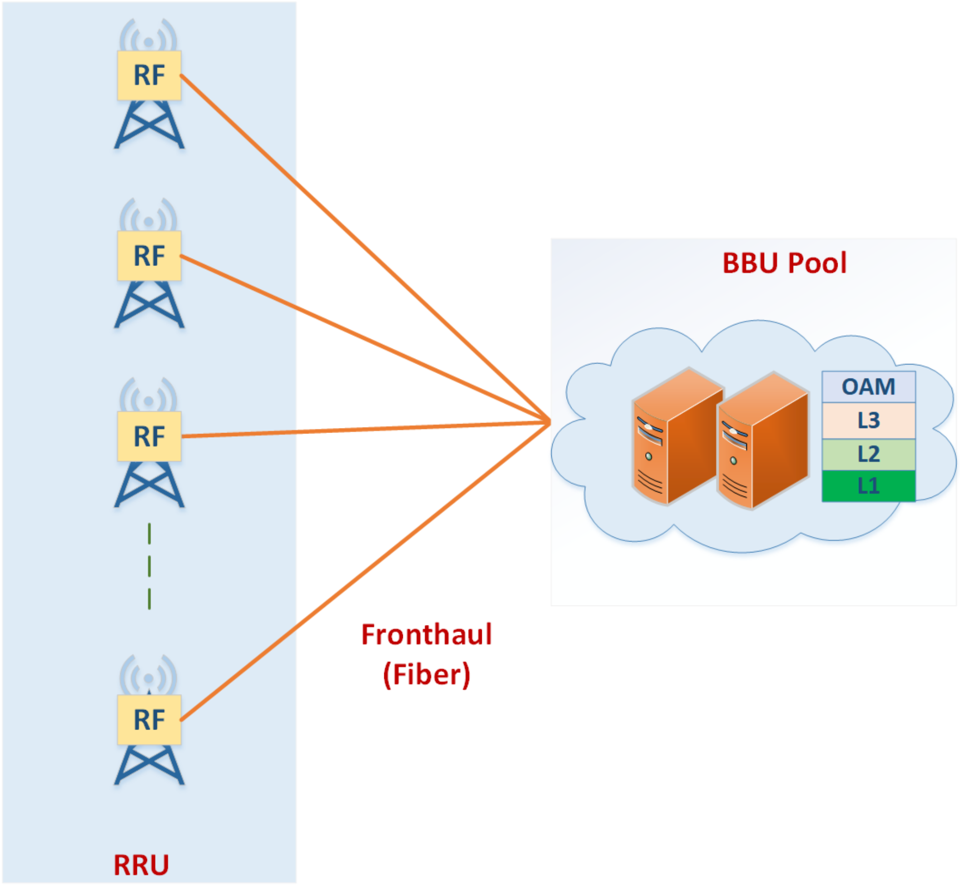


Figure 2.7: Fully Centralized Cloud RAN Architecture

1. Partially Centralized Cloud RAN

In this architecture, the RRU is in charge of radio and baseband processing (Layer 1 and RF related functions) while all high-layer functions are integrated into the BBU (Layer 2 and Layer 3 related functions), as shown in Figure 2.8. Since baseband processing is shifted from the BBU to the RRU, a partially centralized Cloud RAN requires less transmission bandwidth between the RRU and the BBU. There are also some drawbacks associated with this approach, including low flexibility in the upgrade of network capacity and less suitability for cooperative signal processing across cell sites [16].

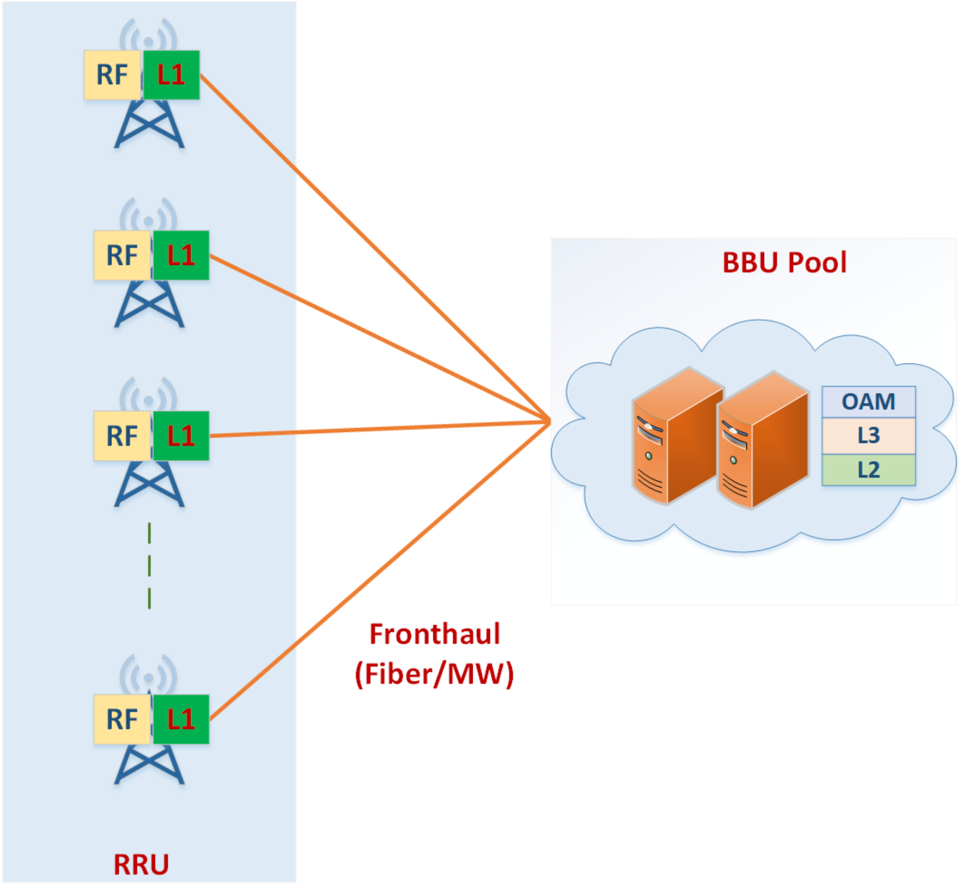


Figure 2.8: Partially Centralized Cloud RAN Architecture

2.4.5 Advantages of Cloud-RAN

Cloud RAN technology has concrete and measurable advantages over the current RAN, which primarily deal with reducing operators' operating costs. The following are some of them briefly reviewed.

1. CAPEX and OPEX saving

With Cloud RAN, there will be substantial savings both in terms of CAPEX and OPEX as upgrades and maintenance costs can be reduced. The Centralization & virtualization of the BBUs as well as relocating site support equipment from the cell sites to BBU pools significantly reduces the required network elements at the cell sites, which in turn reduces the CAPEX. Virtualization allows for the use of generic hardware and thus lowers the cost of equipment. The main source of OPEX savings is energy savings, reduced maintenance costs, and a lesser site visit. Furthermore, because of the lesser footprint required per cell site, the costs of renting and constructing sites decrease [7], [9].

2. Flexibility in Capacity and Spectral Efficiency Improvement

Cloud RAN brings another advantage in network capacity and spectral efficiency improvement. Due to its centralized architecture, it is easily scalable, which simplifies the process of upgrading the capacity of the networks. It can also be easy to connect more RRUs to the Cloud to provide greater coverage over a greater area or split the cell for higher capacity gain. Furthermore, Cloud RAN makes it easier to implement joint processing and scheduling, enabling the mitigation of inter-cell interference and an increase in spectral efficiency [7], [9], [23].

3. Reduce Energy Consumption

In Cloud RAN, BBUs, air conditioning, and site support equipment are centralized, reduced, and better utilized. This enables easy sharing of site support facilities leading to power consumption reduction. C-RAN can benefit from virtualization, which reduces energy consumption significantly. In addition, during low traffic hours, the virtualized BBUs (vBBUs) can be scaled down by turning off the BBU resources to reduce power consumption so that resources can be better utilized [9], [23].

2.4.6 Challenges of Cloud RAN

Although Cloud RAN brings many opportunities discussed above, it also faces challenges that need to be addressed. Below are some of them briefly discussed.

1. Fronthaul Transport Network

With the Cloud RAN architecture, the optical links between RRU and virtualized BBU Pool carry a tremendous amount of IQ samples, which brings a huge overhead on the Fronthaul link. Furthermore, the Fronthaul network must also meet stringent requirements for latency, jitter, and cost efficiency when it comes to transporting the IQ samples [54]. Costs associated with building large optical fiber Fronthaul networks to support Cloud RAN can make it unappealing in comparison to other RAN architectures. However, a potential solution could be used to reduce the capacity required such as IQ data compression. Therefore, the heavy burden on the Fronthaul link can be lowered [23], [54].

2. BBU Cooperation, Interconnection, and Clustering

In order to support CoMP, base stations should collaborate on sharing data, scheduling at the base station, and integrating channel feedback information. With centralized architecture, a large number of BBUs are located at a single location, which has a high risk of a single point of failure if Cloud fails, which increases the need for security and reliability [25]. The connectivity solutions of BBUs should be reliable and must provide a high bit rate, low latency, cost-efficient solution, and offer a flexible topology for interconnecting RRUs [10].

Clustering cells effectively in BBU pools is crucial for both achieving multiplexing gains and preventing the transport network from being overloaded. BBU pools should be composed of cells from a variety of traffic areas such as the office, residential, and business areas such that the number of BBUs and RRUs within the pool is maximized [54].

3. Base station Virtualization Technology

Virtualizing the base station is one of the most challenging aspects of processing radio signals in real-time while meeting strict constraints. Nowadays, the baseband functions are processed more efficiently on custom silicon than on general-purpose processors. The real-time processing requirements of wireless networks make base station virtualization much more difficult than in traditional IT data center settings [23], [54].

2.4.7 Cloud RAN Deployment Use Cases

Cloud RAN is envisioned as an alternative way to deliver cellular standards that include UMTS, LTE, LTE-A, and 5G. As a RAN deployment use case, it can be used in the macro cell, microcell, and picocells, and indoor as well the deployment candidate to be a heterogeneous arrangement [10], [22].

In a white paper jointly produced with Heavy reading and Huawei reveals that several operators now are investigating next-generation C-RAN in order to meet future service demands [53]. They have two main reasons for doing so: business and technology. According to the paper, the main drivers for C-RAN deployment are increasing system efficiency, more flexibility in the network, improvements to scalability, better resource utilization, and reduction in CAPEX and OPEX through centralization and virtualization.

The most important use cases for Cloud RAN deployment are [10], [22], [53]:

1. Large public venues (e.g., stadiums, malls, amusement parks, etc.)
2. Targeted outdoor urban areas (e.g., public squares, shopping streets, etc.)
3. High-density urban areas
4. Large urban areas

In general, C-RAN is suited for a variety of significant deployment scenarios, including greenfield deployments [10], large/medium scale deployments [55], small scale deployments [55], capacity boosting deployments [10], indoor coverage [55], super hot spot coverage [10], [55], railway/subway/highway coverage [10], [55], and different stages of deployment.

Several stages should be taken in order to accomplish the full deployment of C-RAN. Following are the steps toward C-RAN deployment [10], [56]:

1. **Centralized RAN**: First, BBUs are deployed centrally into a BBU Hotel/PoP to support many RRUs. But, there is no pooling or virtualization of resources.
2. **Cloud RAN**:
   - **Step 1**: Second, BBU nodes can connect with each other and exchange information with each other using a low-latency high-speed interconnection network in the BBU Pool. The baseband resources are pooled but not virtulized. Thus, C-RAN would make collaborative radio implementation more likely, reducing interference and improving system performance.
   - **Step 2**: Finally, baseband resources are virtualized, using a general-purpose processor into the cloud and resources are allocated dynamically on-demand.

2.5 Implemented Cloud RAN Architecture

In this thesis, Cloud RAN architecture implemented is based on the NRT-RT functional split, where NRT functions (such as inter-cell handover, cell selection and reselection, user-plane encryption, and multi-connection convergence) are performed on COTS cloud hardware and RT functions (such as radio network scheduling, link adaptation, power control, interference coordination, re-transmission, modulation, and coding) are executed on proprietary hardware [53] as shown in Figure 2.9. Therefore, Cloud RAN BBUs comprise both proprietary baseband hardware and a cloud server based on COTS hardware.

As shown in Figure 2.9, the RRUs are located at the cell sites and contain the macrocells and small cells. Whereas the BBUs are moved to the BBU pools or data centers based on the distance between the RRU and BBU. As distances between RRU and BBU become longer, the BBU pool must accommodate proprietary hardware that cannot be centralized at the data centers. Furthermore, C-RAN Fronthaul must meet strict requirements for latency, capacity, and synchronization that are significantly more stringent than those of a D-RAN backhaul. Hence, to connect RRUs and BBUs in the C-RAN, a fiber optics Fronthaul network is needed. As a result, cell sites with existing fiber access can be selected for C-RAN deployment, or investment is required for the optical fiber network to be built [57]. The Midhaul link between BBU pool and edge cloud uses IP/MPLS. Conversely, the centralization of the proprietary baseband hardware allows for more efficient use of the hardware, as well as simpler updating and management. It also reduces the space requirements at cell sites compared to D-RAN.

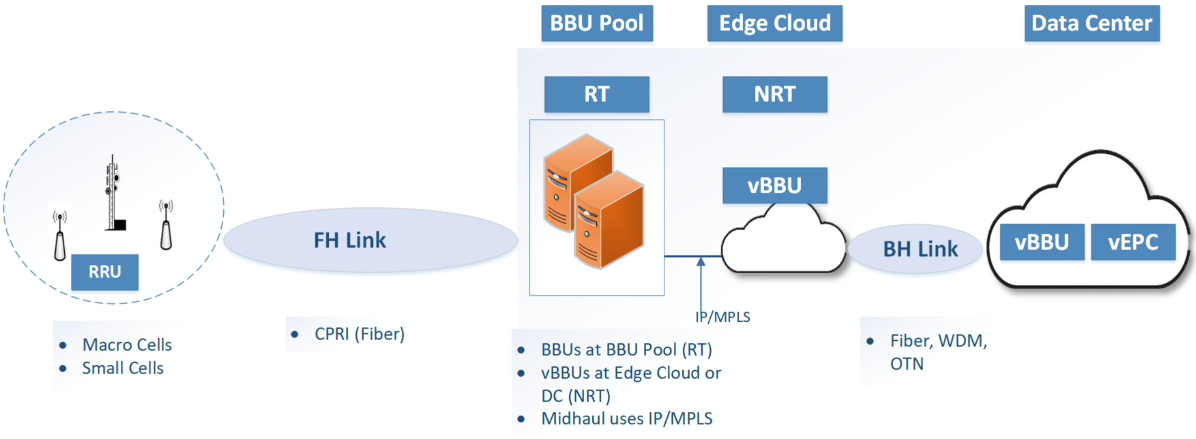
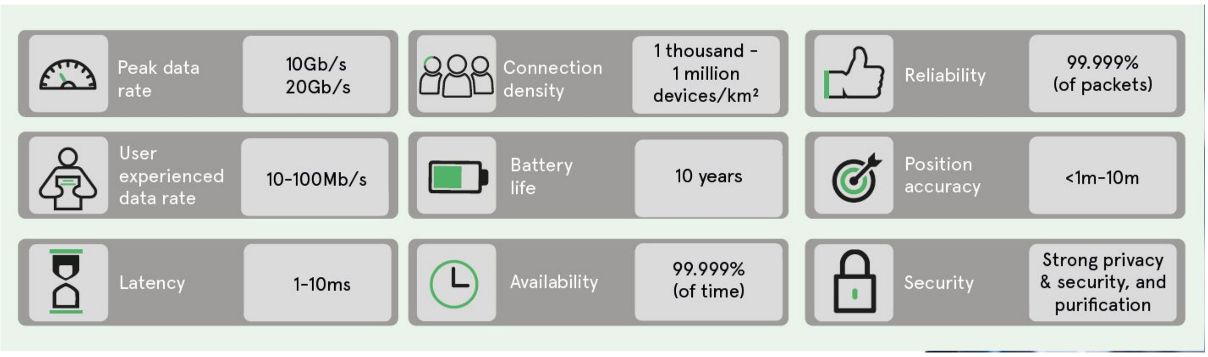


Figure 2.9: Implemented Cloud RAN Architecture

2.6 Related Technologies

2.6.1 5G

Fifth Generation (5G) mobile communication systems are designed to provide a ubiquitous mobile service with improved QoS. It is anticipated that 5G will open up new use cases in the industries including transportation, health care, energy, public safety, entertainment, agriculture, and manufacturing [16]. The technical requirement set for 5G according to ITU are providing peak data rates of up to 10 Gbps which satisfying the demand for ever-growing bandwidth, the latency of 1 ms which ensure near-real-time responses, supports 1000 devices per square kilometer which allow the tremendous growth in IoT devices and sensors [39], [16]. Figure 2.10 summarizes the key performance indicators for 5G.



Peak data rate	10Gb/s 20Gb/s	Connection density	1 thousand - 1 million devices/km²	Reliability	99.999% (of packets)
User experienced data rate	10-100Mb/s	Battery life	10 years	Position accuracy	<1m-10m
Latency	1-10ms	Availability	99.999% (of time)	Security	Strong privacy & security, and purification

Figure 2.10: Selected key performance indicators of 5G according to ITU-R [39]

The ambitious specification shown in Figure 2.10 represents a paradigm shift in all aspects of performance and addresses the needs of emerging applications such as augmented reality

(AR), virtual reality (VR), autonomous vehicles, tactile internet, machine-to-machine (M2M) communication.

In 5G, data traffic is expected to increase exponentially, posing a big challenge to the network architecture, especially in the domain of the RAN [58]. Numerous architectures and technologies have been proposed for 5G mobile networks in order to combat traffic growth, build cost-efficient networks, and provide a better quality of service to massive users. Cloud RAN is one of the concepts for a 5G network architecture, in which Cloud computing and virtualization will be an essential part of the network to alleviate the challenges associated with data traffic growth cost-efficiently.

2.6.2 Network Virtualization

The concept of virtualization can be defined as the ability to create a logical, isolated entity from the physical hardware that enables flexibility and dynamic allocation of resources (such as processing power, memory, and storage). These resources are virtualized by separating them from the underlying physical hardware. Cloud RAN can greatly benefit from network virtualization in addition to the BBU centralization [26].

Virtual Machines (VMs) are the platform on which applications and functions work in virtual environments. The hypervisor, a virtualization layer on top of hardware, is responsible for controlling and creating VMs. It is possible to share resources efficiently between VMs for better resource utilization, scalability, and efficacy [59]. The virtualized BBU pools in a Cloud RAN architecture consist of various VMs, which handle the respective BBU functionality.

2.6.3 Network Function Virtualization in Cloud RAN

Network Function Virtualization (NFV) is a network paradigm that allows the separation of the network functions from the physical hardware. NFV aims at improving network flexibility, manageability, and efficiency by leveraging cloud computing and virtualization to network applications in software [60]. In Cloud RAN, NFV virtualizes the network functions from the proprietary baseband hardware to virtualized BBUs also known as Virtualized Network Functions (VNFs) on the cloud servers [26]. VNFs are composed of different virtual machines, each of which has a specific function and independent of the underlying hardware hence can easily be created, moved, copied, or deleted [61].

2.6.4 Software-Defined Networking in RAN

Software-Defined Networking (SDN) is a network paradigm that emerged as the network intelligence logically centralized, control and data plane decoupled, and the underlying network infrastructure abstracted from the applications and services. SDN eases the complexity of network management and service provisioning, improved security, enabling more efficient and flexible network control, configuration, and operation. These advantages are obtained by decoupling data planes from the control plane using programmable network devices with central software applications [62].

With SDN technology in Cloud RAN, new applications can be deployed quickly, and network load can be dynamically adapted according to changing traffic patterns. Furthermore, by implementing SDN and NFV in a Cloud RAN, it is possible to implement most of the processing on COTS hardware instead of proprietary hardware which reduces equipment costs and energy consumption [9].

2.6.5 Mobile Edge Computing with Cloud RAN

Mobile edge computing (MEC) is a new computing paradigm that offers cloud computing services on the edge of radio access networks, providing a high bandwidth, ultra-low latency, and real-time access to radio network information [16], [63]. The MEC allows applications that are computationally intensive and delay-sensitive to be performed close to the end-user, thus providing a better quality of experience for the end-user, and making the mobile backhaul and core network more efficient [16]. Additionally, MEC's attributes can provide a competitive advantage over Over-the-Top (OTT) players by allowing MNOs to distinguish themselves from them [64]. As a result of using MEC, operators can introduce their own OTT platform to add new services that would provide a better user experience that is superior to those offered by OTT companies [64].

Operators can take advantage of MEC capabilities through Cloud RAN architecture as shown in Figure 2.11. Since Cloud RAN is proposed to be implemented on COTS hardware, the MEC applications can be hosted on these servers rather than on a central core network. Meanwhile, Cloud RAN's BBU Pools are assumed to be located in a distributed manner in the network instead of in a single data center (to avoid a single point of failure), which offers an excellent opportunity for deploying MEC across the network. Besides, the features and capabilities offered by the MEC platform can be leveraged for the creation of broad values and revenue generation by taking the advantage of Cloud RAN infrastructure with COTS servers at the edge of the network [64].

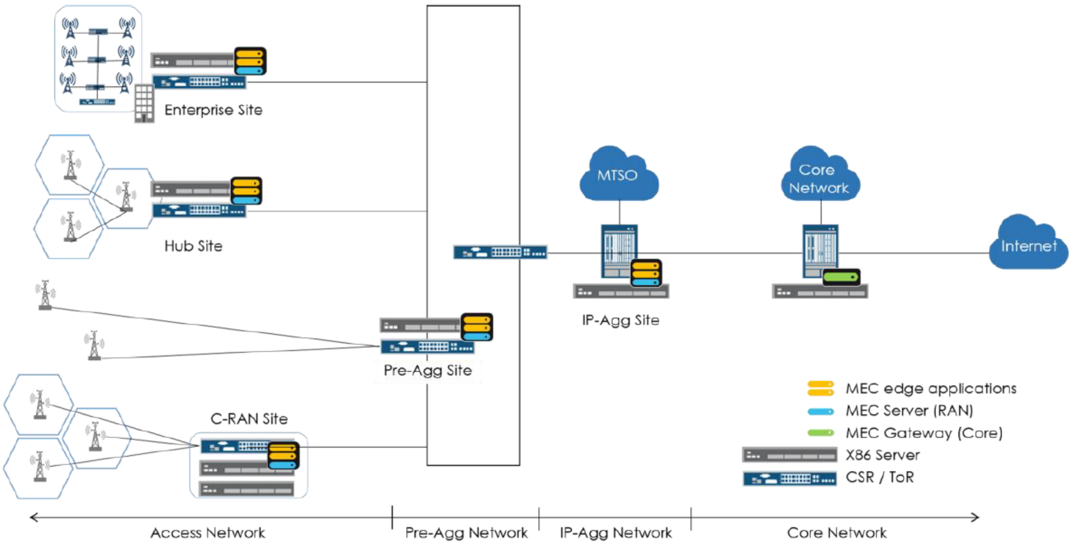


Figure 2.11: MEC Deployment in Cloud RAN [63]

Techno-economic Modeling and Evaluation Method

In this chapter, Techno-economic evaluation models such as the cost model, revenue model, and economic evaluation methods are discussed in detail.

3.1 Introduction to Techno-economic Analysis (TEA)

Techno-economic Analysis is a methodology used for assessing the economic feasibility of a technology, product, or service. The analysis syndicates different processes such as cost-benefit analysis, scenarios development, trend analysis, expert opinion, and quantitative modeling [21], [65]. The term techno-economic was defined within the context of telecommunications during the European research programme RACE (Research into Advanced Communications for Europe), in the 1980s and 1990s [21], [65].

A variety of RACE projects have been modeled and analyzed for the improvement of broadband systems using Techno-economic models. In the RACE 2087 Tool for Introduction scenarios and Techno-economic studies for the Access Network (TITAN) project, methodologies, and tools for evaluating narrowband and broadband services and access networks were developed (1990-1994). The methodology and tools created have been used in a number of research projects over the last two decades for different applications. For instance, Optimized Architectures for Multimedia Networks and Services (OPTIMUM) from 1994-1998, Techno-economic Results from ACTS (TERA) from 1994-1998, Techno-economic of IP Optimized Networks and Services (TONIC) from 1998-2002, and Techno-economic of integrated communication systems and services (ECOSYS) from 2004-2007 were presented for different purposes and application areas based on the projects [21], [65].

3.2 Techno-economic Result from ACTS (TERA) Model

In this thesis, techno-economic analysis is conducted using a tool called TERA (Techno-Economic Results from ACTS). In order to conduct techno-economic evaluations, the TERA tool is very approaching for the model developed and it combines technical, market, economic, and financial factors with relevant low-level parameters. In addition, the output obtained from the tool can easily be interpreted, analyzed, and traced to the input using the formula used [21], [65]. In Figure 3.1, the techno-economic modeling framework used in various TEA projects is depicted.

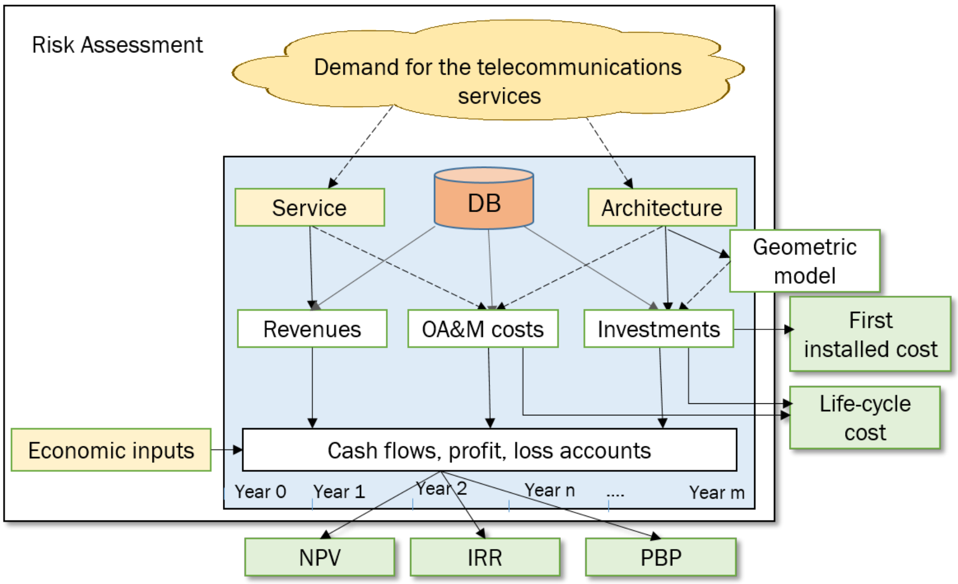


Figure 3.1: TERA Framework [21]

The TERA model shows that there are two key elements of techno-economic model development: services and architectures (technical). The models incorporate high-level economic and market parameters, along with relevant parameters regarding the technologies necessary for delivering services to the customers. The model estimates the revenue, investment costs, and operational costs based on the forecast and assumptions used regarding the service. Some generic economic inputs such as study period, discount rate are also used. To determine the profitability of each scenario, varieties of indicators are used, such as payback period, net present value (NPV), and internal rate of return (IRR) [21].

The modeling techniques developed for techno-economic analysis are suitable for the evaluation of alternative technology architectures [65]. However, the modeling becomes more challenging if the time frame of the analysis is extended in the future as well as there exists increased uncertainty about the technology. These conditions can be addressed by using scenario planning, as it provides a method for tying up this uncertainty and, therefore, creating scenarios that have alternative approaches [21], [17]. Due to these reasons, this research modified the TERA model to incorporate the formulated localized Cloud RAN deployment scenarios into the model.

3.3 Cost Modelling

The cost of the network is one of the main elements for measuring the feasibility of Cloud RAN deployment scenarios. The costs of building and operating a radio access network can be split into capital expenditures (CAPEX) and operational expenditures (OPEX). Based on each year's required network elements, network configuration data, and cost data, the cost calculations are performed. Calculations for CAPEX and OPEX represent the costs associated with implementing and operating the Cloud RAN.

3.3.1 Capital Expenditure (CAPEX)

The components of the CAPEX in this model are investments in BBM hardware, cloud server hardware, and software licenses. Based on the result from the network dimensioning where the required number of hardware (BBM & cloud server) and software licenses are obtained for each year deployment, the investment costs are calculated. CAPEX can be modeled mathematically as shown in Eq. (3.3.1) [23]:

$$CAPEX = \sum_{i,j}^{T} N_j^i * (C_{BBM} + C_{BBSW} + C_{BBLC} + C_{CHW} + C_{CSW} + C_{FL}) * (1 + I_j)^{(i-1)} \quad (3.3.1)$$

Where: j ϵ list of CAPEX items (BBM, BBSW, BBLC, CHW, CSW, FL), N_j^i is the number of item j in the year i, C_{BBM} is the cost of BBM units, C_{BBSW} is the cost of BB software, C_{BBLC} is the cost of BB license, C_{CHW} is the cost of a cloud HW, C_{CSW} is the cost of cloud SW, C_{FL} is the cost of BH & FH link in year i, I is the yearly price inflation and T is the study period.

In the model, we have considered cost data from the vendor databases, well-known industry price catalogs, ethio telecom project document for LTE/LTE-A deployment in Addis Ababa, and other literature associated with Cloud RAN cost modeling.

3.3.2 Operational Expenditure (OPEX)

OPEX is defined as the cost that comes after the deployment of dimensioned networks. It includes operational costs such as OAM (Operations, Administration, and Maintenance) cost, energy cost, site rent cost, HW & SW maintenance cost, capacity upgrades cost and Fiber lease

[23]. For each architecture, the OPEX cost is calculated on a yearly basis, with the total accumulated OPEX computed by adding each year's OPEX cost

1. OAM Cost

Costs associated with Network Operations and Maintenance (OAM) include network troubleshooting, preventive maintenance, performance optimization, capacity analysis and planning, and software upgrades. MNOs have very specific OAM costs that vary based on the nature of their operations and maintenance processes. In the model, D-RAN, C-RAN, and Cloud RAN OAM costs are estimated based on cell site-specific data by taking sample current D-RAN. In this research, the annual OAM is obtained from the operator's annual report and target literature.

2. Energy Cost

In order to calculate the network's annual energy cost, the total energy consumption of all BBM units and cloud servers is added up. The annual total power consumption (P_T) of the baseband processing hardware is computed as shown in Eq. (3.3.2) [23]:

$$P_T = \sum_i (P_i * n_i) \tag{3.3.2}$$

Where i ϵ list of power-consuming network elements (CAP, MPU, CAB, and Cloud server), n_i is the number of power-consuming network element i, P_i is the power consumption of the network element i.

As a result, the annual energy consumption (E_T) in kWh is computed as shown in Eq. (3.3.3):

$$E_T = \frac{P_T}{1000} * \frac{Hrs}{Day} * \frac{Days}{Year} \tag{3.3.3}$$

Where P_T is annual power consumption by the network elements in watt. The annual energy cost (C_E) can be computes as shown in Eq. (3.3.4):

$$C_E = E_T * C_{kWh} \tag{3.3.4}$$

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

3. Site Rent

In the model, the yearly rental cost of cell sites is considered. The rental cost of the data center is not considered since ethio telecom has its own data center and core sites location. For the network, annual site rental costs (C_{SR}) can be calculated as shown in Eq. (3.3.5) [23]:

$$C_{SR} = \sum_{i}^{T} N_j^i * (C_{CS} + C_{PoP} + C_S) \tag{3.3.5}$$

Where j ϵ list of rental items (cell sites/radio tower, D-RAN BBU cabinet, C-RAN PoP, and server rack), N_j^i is the number of item j in the year i, C_{CS} is the rental cost of cell site, C_{PoP} is the rental cost of BBU Pool/PoP, C_S is the rental cost of the server rack per cabinet in the year i, and T is the study period.

4. HW & SW maintenance cost

Each year hardware and software maintenance costs are calculated based on a fixed percentage of the annual total CAPEX that was spent on hardware and software.

5. Capacity upgrade cost

Among the costs of upgrading the baseband capacity are the costs of installing baseband processing hardware at cell sites and central locations (BBU Hotel/BBU Pool). Whenever the network traffic is anticipated to exceed the network capacity, new equipment is needed to be installed each year to handle the traffic growth. As a result of centralized installations, the centralized architectures are presumed to incur fewer installation costs. It is cost-effective and time-efficient to install new hardware at fewer locations since it reduces travel time and costs. The cost of upgrading the baseband capacity (C_{UP}) of the network per year is calculated as shown in Eq. (3.3.6):

$$C_{UP} = \sum_{i}^{T} N_j^i * C_U^i \tag{3.3.6}$$

Where j ϵ list of the baseband processing hardware items required to be installed (BBM, cloud servers), N_j is the number of BB processing hardware items j required to be installed, C_U^j is the cost of the upgrade for item j and T is the study period.

6. Fiber Lease

In the model, the yearly fiber lease per cell site is considered. Hence, the annual fiber lease cost (C_{FL}) can be calculated as shown in Eq. (3.3.7) [29]:

$$C_{FL} = \sum_{i}^{T} N_i * C_F^i \tag{3.3.7}$$

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.

Therefore, the total cumulative OPEX for the network architecture is calculated as shown in

Eq. (3.3.8):

$$OPEX = \sum_{i}^{T}(C_{OAM}^{i} + C_{E}^{i} + C_{SR}^{i} + C_{HW}^{i} + C_{SW}^{i} + C_{UP}^{i} + C_{FL}^{i}) * (1 + P_{i})^{(i-1)} \tag{3.3.8}$$

Where C_{OAM}^{i}, C_{E}^{i}, C_{SR}^{i}, C_{HW}^{i}, C_{SW}^{i}, C_{UP}^{i}, and C_{FL}^{i} are costs of OAM, energy, site rent, HW & SW maintenance, capacity upgrade and fiber lease respectively in the year i, P_i is the yearly price inflation rate in the year i and T is the study period.

3.3.3 Total Cost of Ownership (TCO)

The TCO covers both the CAPEX and OPEX. According to the deployed architecture, i.e., D-RAN, Centralized RAN, and Cloud RAN, the TCO is modeled as shown in Eq. (3.3.9).

$$TCO = \sum_{i}^{T}(CAPEX_{i} + OPEX_{i}) \tag{3.3.9}$$

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.

3.4 Revenue Modeling

Revenues are calculated based on the number of subscribers, average revenue per user, and market share. The revenue is modeled as shown in Eq. (3.4.1):

$$R_T = N_S * ARPU * M_S \tag{3.4.1}$$

Where R_T is the total revenue generated, N_S is the predicted number of subscribers, ARPU is the average revenue per user, and M_S is the Cloud RAN market share.

3.5 Techno-economic Evaluation Metrics

When conducting a techno-economic analysis, one of the most important things to determine is whether a project is profitable or not. Among the most common ways to measure a project's profitability are its net present value, internal rate of return, and payback period. Methods applied in this techno-economic evaluation include cash flow (CF) and discounted cash flow (DCF) analysis illustrated below.

3.5.1 Cash Flow (CF)

Cash flow (CF) refers to how much cash is received and disbursed within the study period. Based on the outputs from the cost and revenue model, the CF modeled mathematically as shown in Eq. (3.5.1) [66]:

$$CF = \sum_{i}^{T} (R_T - C_T)_i \tag{3.5.1}$$

Where: CF is the cash flow, R_T Total revenue C_T Total cost of the network (TCO), T is the study period.

3.5.2 Discounted Cash Flow (DCF)

Discounted cash flow (DCF) is a method of calculating the present value of a company's future cash flows in order to arrive at a current estimate of its fair value using a discount rate. DCF modeled mathematically as shown in Eq. (3.5.2) [21], [66]:

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + ... + \frac{CF_i}{(1+r)^i} \tag{3.5.2}$$

Where: DCF is the discounted cash flow , CF is cash flow for the given year, CF_1 is for year one, CF_2 is for year two, CF_i is for additional years, i is the study period, and r is the discount rate.

3.5.3 Net Present Value, Internal Rate of Return and Payback Period

A project's net present value (NPV) is most effective in determining profitability and is a better investment metric. In order to calculate NPV, we subtract the discounted value of future incomes from the initial investment (CAPEX). An investment should be beneficial to the company if the NPV value is positive. NPV is modeled mathematically as shown in Eq. (3.5.3) [17], [21]:

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+r)^i} \tag{3.5.3}$$

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

The Internal Rate of Return (IRR) and Payback Period (PP) are two commonly used measures when evaluating an investment/project in addition to NPV. In project analysis or capital budgeting, the IRR is a discount rate that makes the net present value (NPV) of future cash flows equal to zero. Intuitively, if a project has a higher IRR (given all other things equal), then it must generate more cash flows. Although the cash flows may vary, we only have one IRR per project since we are calculating a discount rate that is the same each year. The IRR can be computed as shown in Eq. (3.5.4) [17], [21]:

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+IRR)^i} = 0 \tag{3.5.4}$$

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.

A payback period is the period of time in which the initial expenditure of an investment will be recovered through the resulting cash inflows. It is one of the easiest investment appraisal methods widely used. Generally, profitable projects are those that pay for themselves before a defined study period. The Payback period obtained as shown in Eq. (3.5.5) [21], [67]:

$$PP = LP + [\frac{Abs(CCF)}{CF}] \tag{3.5.5}$$

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

Scenario Analysis and Cloud RAN Deployment Options for Addis Ababa

This chapter will detail the process of identifying key forces for Cloud RAN deployment. A brief introduction will be given to scenario planning. After that, key trends and uncertainties will be explained. For the purpose of scenario construction, a correlation table of key uncertainties will be prepared and localized deployment scenarios will be formulated at the end of the chapter.

4.1 Scenario Planning Method

Scenario planning is a tool used for exploring, analyzing, and managing uncertainties and disruptiveness of emerging technologies [11], [19], [21]. In the telecommunications industry, the scenario planning method is effectively implemented. These scenarios were applied to topics such as wireless industry evolution, peer-to-peer services, wireless local area access, and LTE network virtualization [20], [68], [69]. As Cloud RAN represents a new paradigm in network architecture, scenario planning is an appropriate tool to develop alternative futures by combining trends and uncertainties.

To formulate and analyze the deployment of Cloud RAN for the context of Addis Ababa, Ethiopia various data sources are evaluated such as ethio telecom documents, reports and strategies, related works of literature, standards, and expert opinions. From the available literature, Schoemaker's method is selected as the most convenient one for this thesis. The ten-step process presented in [11] was implemented but out of the ten steps, the following processes are selected for the purpose of this thesis:

1. Defining time frame, scope, and Stakeholder identification
2. Trend analysis

3. Uncertainty identification
4. Correlation matrix
5. Scenario matrix development.

The steps are described briefly in the following sub-sections.

4.1.1 Defining Study period, Scope and Stakeholder

Study period: Several studies relating to scenario planning indicate that the timeframe falls within a range of five to ten year intervals. Based on this time interval and technology trends, six years was chosen as the time period for this study.
Scope: The scope of this thesis is to formulate the Techno-economic analysis of Cloud RAN deployment for RAN architecture of LTE network for Addis Ababa, Ethiopia, and does not include the core network.
Stakeholders: The key stakeholders in the deployment of Cloud RAN are Mobile phone users (End users or customers), Mobile Network Operators (e.g., ethio telecom), Ethiopian Communication Agency (ECA), Government, Telecom equipment vendors, Internet Service Providers (ISPs), Environmental Groups, Employees, Policymakers.

4.1.2 Trend Analysis

The contributing factors and trends that have an impact on the deployments of Cloud RAN are investigated based on various works of literature, related works, standards, expert opinions, and vendor reports. To include all the key macro-environmental factors affecting Cloud RAN deployment, the analysis is grouped into political, economic, social, technological, legal, and environmental domains, also known as the PESTLE framework, which is implemented mostly in the Telecom sector specifically in the wireless domain.

The factors and trends that affect the C-RAN deployment are organized based on the PESTLE framework. Through various literature reviews, a survey of previous and existing RAN architectures, ethio telecom strategies and reports, project reports, expert opinions and discussion, and vendor opinions are included to identify the factors that significantly affect the C-RAN deployment in the context of Addis Ababa, Ethiopia. The factors and trends recognized are assumed to be influencing the C-RAN deployment process positively or negatively.

Table 4.1 shows the compiled factors and trends that affect the deployments of Cloud RAN through PESTLE analysis.

Table 4.1: Scenario planning for C-RAN - PESTLE Analysis

No.	PESTLE Analysis	Factors/Trends
1	Political	→ Government interest in regulative control → Spectrum usage and allocation → Competition policy → Site acquisition
2	Economical	→ High costs of network elements, network maintenance, and running cost → Energy consumption becomes a cost driver in wireless network → Pricing policy → Revenue decoupling
3	Social	→ User behavior change towards new technologies → High demand for mobile data service → Availability & reachability of service desire increase → Internet users shift to wireless access from wired access → Growing high data usage APPs → End-user awareness on QoE → Security, trust, and privacy
4	Technological	→ Technological improvement (e.g., computing power, optical transmission rate, storage capacity increase, etc.) → Cloud RAN implementation & deployment depends on the choice of the functional split → Service shift from hardware-based toward Cloud-based → Network architecture evolves towards centralized, Cloud, cognitive, and clean processes. → Challenges with the deployment of HetNet, Indoor traffic → Challenges of the required high bandwidth Fronthaul → Mobile data traffic exponential growth due to the proliferation of new devices, services. → Vendors role → Incompetency of current RAN architecture. → OTT services, Content provides → Cloud features bring new business opportunities
5	Legal	→ Law to enforce venue owners to install macro and small sites → Safety laws
6	Environmental	→ Increasing environmental awareness → Availability of alternative energy source → Green ICT

Table 4.2: Scenario planning for C-RAN - Selected Key Trends via PESTLE Analysis

ID	Trend Name	PESTLE Analysis	Description
T1	Cloud RAN deployment options	Economical Social Technological Environmental	→ Cloud RAN features, deployment options interms of technology, demography, and geography
T2	Cloud RAN architecture	Economical Technological	→ Cloud RAN optimal functional split with better system performance, fronthaul link and cost effficent
T3	Traffic growth expectation	Social Technological	→ Mobile data traffic exponential growth due to proliferation of new devices, services as well as increase in the number of mobile subscribers.
T4	Devices availibility	Economical Social Technological Legal	→ Availability of Cloud RAN compatible devices with the required specification as commercial-off-the-shelf.
T5	Fronthaul Capacity	Economical Technological Legal Environmental	→ Challenges of the required high bandwidth optical transport network (Fronthaul) that is simple, flexible, scalable, reliable, and cost efficient
T6	Power consumption	Economical Technological Environmental	→ The challenge of high power utilization of RAN equipments.
T7	Vendors Role	Political Economical Technological Environmental	→ Vendors role and management
T8	Security & Privacy	Social Technological	→ Need for improvements in security, trust, and privacy
T9	Level of competition	Political Economical Technological	→ Competition level with other operators
T10	Business Opportunities	Economical Technological	→ New revenue source and business opportunities that come up with C-RAN deployment.

Key Trends

Selected key trends are important factors that are likely to be realized and have a substantial impact on the deployment of C-RAN. From Table 4.1 above the following key trends, their name, category, and descriptions are listed as shown in Table 4.2.

4.1.3 Selected Uncertainty

From the selected key trends listed in Table 4.2, the following uncertainties are identified for further investigation as seen in Table 4.3. Next on the selected uncertainties, a correlation matrix is developed in order to identify the key uncertainties for the deployment of C-RAN. A correlation matrix is a technique that helps to pinpoint interrelationships among uncertainties [11].

Table 4.3: Scenario planning for C-RAN - Selected Uncertainties

ID	Description	Possible outcomes
U1	Which deployment options and features of C-RAN are best practical and suitable to Addis Ababa, Ethiopian?	Medium-scale, Small scale
U2	Which functional split is more applicable for Addis Ababa, Ethiopian?	Partially Centralized, Fully Centralized
U3	Will data traffic growth increase significantly in the future?	Low, High
U4	Will C-RAN compatible devices with the required specification can be availible commercial-off-the-shelf (COTS) hardware?	No, Yes
U5	Does the existing Fronthaul capacity will be able to handle the traffic predicted?	No, Yes / Existing or Upgrade or New
U6	Does C-RAN architecture faces a security threats such as single point of attack or failure?	No, Yes
U7	Will Ethio telecom faces a less or fierce competition from competitors? Will the government interven on the market?	Less, More
U8	Will C-RAN deployment significantly improve current power utilization level?	No, Yes
U9	Will C-RAN deployment come up with new possible revenue source and business opportunities for operators?	No, Yes

Based on the list of identified uncertainties in Table 4.3, then we addressed the interrelationship among the uncertainties, such that critical scenarios will be formed. The correlation matrix in Table 4.4 is implemented based on Schoemaker's method [11], [21] as follows, we check whether a "yes" answer for instance to U1 influences the chance of a "yes" answer for U2. If the chance goes up, the correlation between U1 and U2 is labeled as "+" for positive. If the chance goes down, the correlation is labeled as "-" for negative. On the other hand, it can also be labeled as "0" for independent or "?" for indeterminate uncertainties and "1" for correlation with the same parameter. Various scenarios can be constructed from the independent uncertainties from the correlation matrix. For further analysis, a scenario matrix was formed by selecting a combination of the key uncertainties U1 and U3. In the selection of these key uncertain events, each uncertain event described in Table 4.3 relation was considered in detail. The other selected uncertainties most of them are interrelated and support the scenarios developed. The key uncertainties (U1 and U3) can be used as two-dimensional axes for our scenario. One of the axis for our scenario is the deployment option that comprises a medium scale and small scale deployment options. The other axis comprises the traffic demand growth in terms of low and high traffic growth expectations.

Table 4.4: Scenario planning for C-RAN - Correlation matrix

	U1	U2	U3	U4	U5	U6	U7	U8	U9
U1	1	+	0	+	+	0	+	0	+
U2		1	0	+	+	?	0	-	+
U3			1	0	+	0	+	0	+
U4				1	?	?	+	+	0
U5					1	?	+	?	+
U6						1	+	?	0
U7							1	?	+
U8								1	0
U9									1

4.1.4 Scenario Matrix

The final scenarios are constructed based on opinions and interviews with ethio telecom experts to contextualize the identified uncertain events to the local context. The two key uncertainties were used and crossed to form a scenario matrix. Lastly, the scenarios were named descriptively to demonstrate their ideas. The key uncertainties identified are illustrated below in detail.

1. C-RAN features and deployment options

The C-RAN is designed to provide an alternative network architecture for next-generation mobile networks in order to address the requirements of the mobile services. Its deployment is suitable for most typical scenarios, including macro cells, micro cells, and Pico cells as well as indoor coverage. C-RAN deployment options can be either medium scale or small-scale deployment that can be implemented progressively or fully. The choice of medium scale or small scale deployment of C-RAN has to be investigated in depth since it is dependent on the resource availability, CAPEX and OPEX costs, C-RAN features, capacity, human power, time, and vendor choice.

Medium-scale C-RAN deployment can be used to establish a new radio network from scratch that is independent of legacy networks. Where the RRUs and BBU pools placement and transport network solutions are designed according to the specific C-RAN requirements. This deployment preference offers significant performance improvement and economic advantages including BBU pooling, improved coordination among cell sites, network scalability, virtualization, and lower energy consumption. However, it requires high investment costs and abundant access side and aggregative level fiber resources (high Fronthaul capacity) from the operators. Besides, for operators owning legacy network infrastructure, migration to fully Cloud RAN may also bring many challenges and costs. Firstly, migration from and dismantling of existing networks resulted in the invalidity of existing SLA, vendor supports agreements and throwing before the return of investments of infrastructures. Secondly, lack of uniform standards or immature standards as many organizations propose differently [1], [7], [16], [53]. Thirdly, reliability (updating failures, crash of whole BBU, new input streams increase overhead to network management and performance) and security and secrecy challenges for instance primary user emulation attack (PUEA), specimen sensing data falsifying attack (SSDF), and software nature vulnerability [16], [27]. Moreover, professional training and hiring of C-RAN experienced engineer's costs and the initial investment of C-RAN are significant.

Small scale C-RAN deployment option is very promising for operators with existing site room resources such as Air conditioner (AC), power supply units (PSU), and room monitoring equipment, and limited fiber resources. This deployment preference of C-RAN will help operators to minimize the expenditures on equipment, boost network capacity, and meet data traffic big bang in a mobile internet era. Small-scale C-RAN deployment will help operators by progressively extending the benefits of the Cloud RAN features to the rest of the network. In this scenario, small cells can be easily added to the network to increase the network capacity. According to [7], [54], [55], it is recommended to deploy C-RAN in dense urban areas where high user density presence with high data capacity per user to maximize the statistical multiplexing gain since users are moving throughout the day but stays within coverage areas. Besides, its significant benefits encourage many network operators including AT&T, Orange, China Mobile Ltd., SK Telecom, SoftBank Corp, Telefonica, and Rakuten that are deploying C-RAN at various stages [70], [71]. However, it will also result in a performance decline in the coordination of radio resources and interference management across distributed radio access nodes of C-RAN enabled and traditional RAN networks since full Cloud RAN features are not employed across the entire network.

In general, ethio telecom has to plan an efficient strategy when deploying C-RAN that minimizes CAPEX and OPEX costs, efficient resource utilization, Fronthaul link, security, operational staff, and investigate the C-RAN architecture and potential enhancements to it that will help to generate more revenue.

2. Traffic demand growth expectations

Currently, we are living in miraculous times when COVID-19 has influenced everyone around the globe directly or indirectly. Social distancing, custody of millions at home lead to a significant increase in mobile data demand. Health care systems, online educational systems, and businesses of all types fall under huge pressure. Therefore, connectivity becomes key to overcome this challenge and telecom operators have stood up to the task. However, traffic growth may also be very volatile between years and vary significantly between countries based on the dynamics of the businesses. The main drivers for the growth in mobile data traffic attributed to being improved devices capabilities, high data-intensive content and apps, and affordable data plans.

Traffic demand growth in the network serves as an input for the network dimensioning requirement calculation. The number of connected user equipment (UEs) per cell site, the signaling frequency of these devices, and the control plane load per UE are used to compute the total control plane traffic in the network. These parameters will help to predict the traffic growth in the network and are used as an input for network dimensioning. In addition, these parameters determine the number of mobile devices connected to the network. Hence, traffic demand growth has to be forecasted as precisely as possible for efficient resource utilization, enhancement of QoS and quality of experience (QoE), reduction of CAPEX and OPEX costs, and generation of more revenue.

The scenario matrix including some descriptive features of each scenario is presented below in Figure 4.1

The two uncertainties serve as a basis for the selection of the scenarios and the other uncertainties are used for a detailed description. Lastly, four internally consistent and plausible scenarios are constructed based on the most important uncertain elements in the C-RAN implementation and described in the following sub-section.

4.2 Cloud RAN Deployment Options for Addis Ababa

Based on the above arguments and industry recommendations (Vendors, Operators, Standard bodies, etc.) the following deployment options are identified.

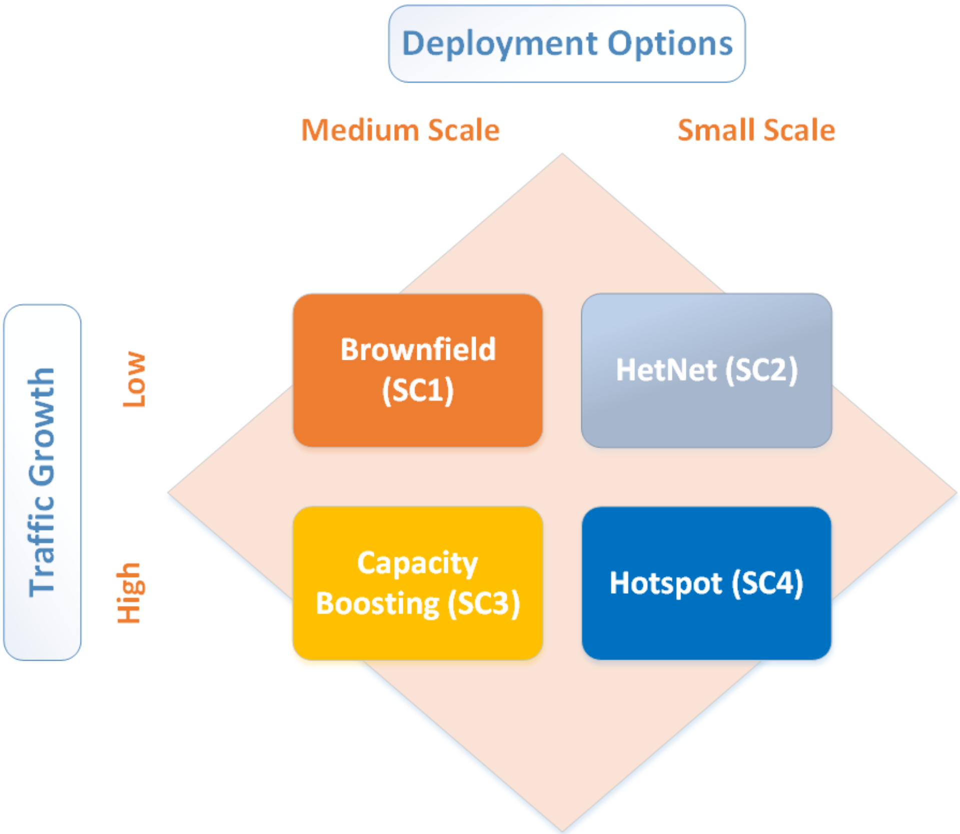


Figure 4.1: Scenario planning for C-RAN - Scenario Matrix

1. Brownfield Scenario (Figure 4.2)

- For new radio network deployment for large or medium scale deployment from scratch.
- MNO with sufficient dark fiber resources.
- RRU, BBU Pool placement & transport solutions need to be according to network planning.
- RRUs can be separate from BBU Pool at a large distance & be centralized to the main office (up to 40 KM).
- Various fiber topologies can be used (Star/Tree or Ring).
- RRUs & outdoor PSU are deployed in all radio sites with zero site room solutions.
- BBU Pools and transmission equipment for Backhaul are deployed in Data Centers.
- Reduce the cost of deployment, minimize TCO, and with high system performance.

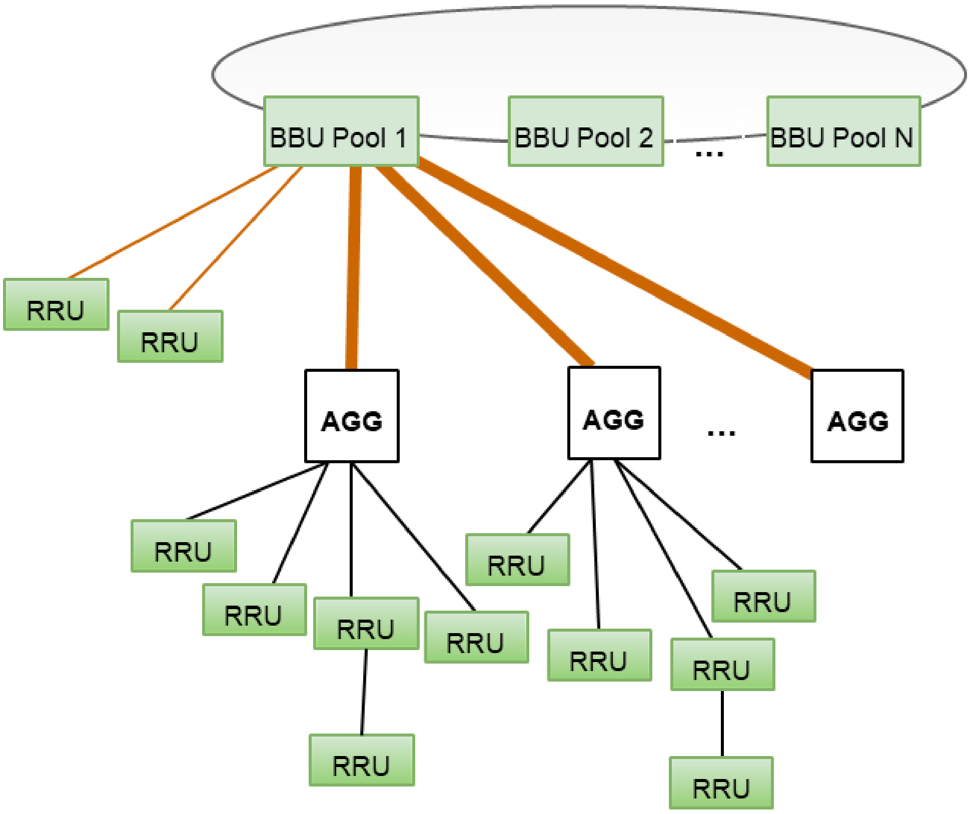


Figure 4.2: Brownfield Deployment Scenario

2. HetNet Scenario (Figure 4.3)

- Existing BBUs of macro BS can be replaced/moved to the BBU pool.
- RRUs can be kept in their existing locations.
- Additional RRUs with outdoor PSU can be deployed to form a small cell.
- RRUs are connected with BBU Pool by fiber.
- This is a small-scale C-RAN introduced for quick network deployment

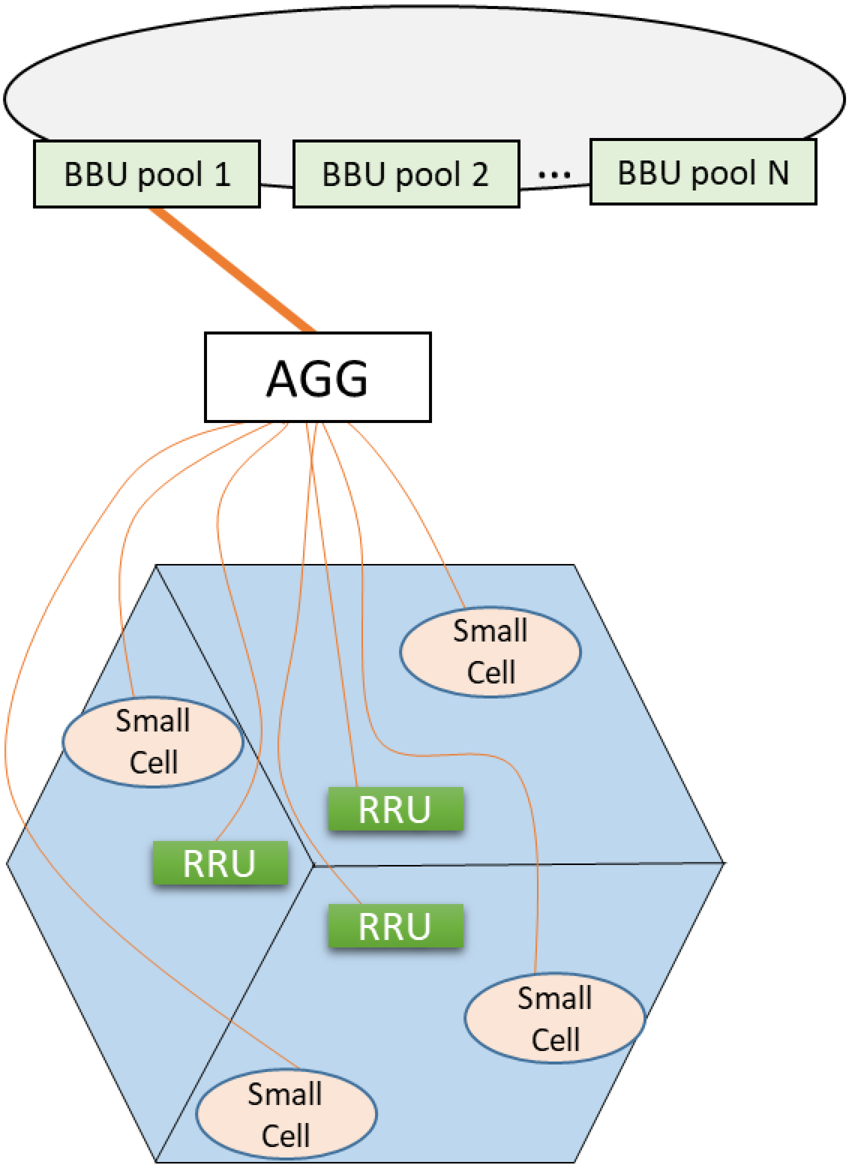


Figure 4.3: HetNet Deployment Scenario

3. Capacity Boosting Scenario (Figure 4.4)

- Existing big macro-cells can be split into several small cells.
- New sites are added & reducing the old macro cell coverage radius.
- Interference management techniques needed (same f).
- C-RAN can enhance cell cooperative techniques like CoMP, eICIC.
- Require high fiber capacity (dark fiber or WDM).
- Additional revenue generation by renting resources.
- It can be used for indoor coverage by deploying RRUs on each floor.

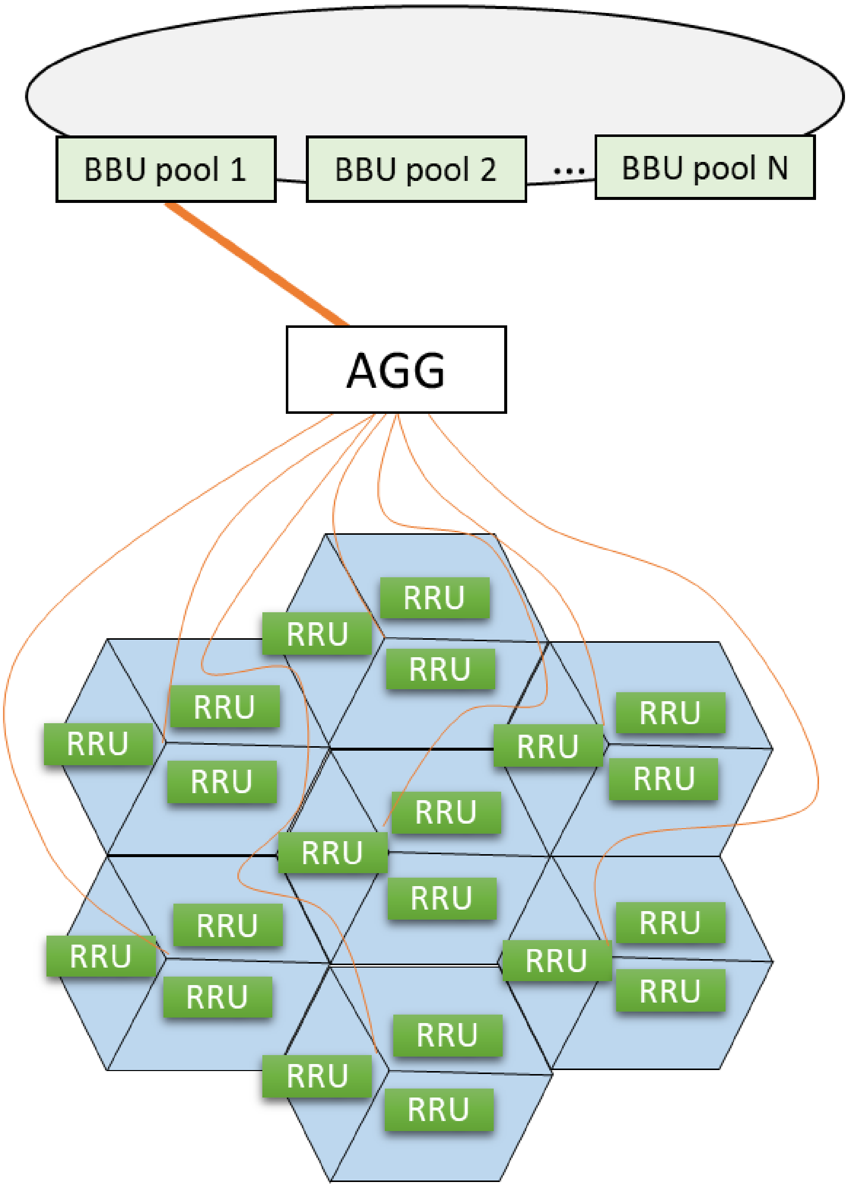


Figure 4.4: Capacity Boosting Deployment Scenario

4. Hotspot Scenario (Figure 4.5)

- There are use cases where several hot areas are close to each other.
- Coverage of mall, stadium are an example of such use case.
- This scenario is characterized by:
- High users density present in one location
- High data capacity per subscriber
- Require several small cells to provide coverage & capacity
- Co-existence with macro-cell
- BBU pool to RRU interconnection can be direct or through daisy chaining

- Centralized BBU is appealing for this scenario
- High interference, requiring advanced interference management between cells (e.g., CoMP, eICIC).
- The deployment of optical fiber is affordable (cost should not be an obstacle).

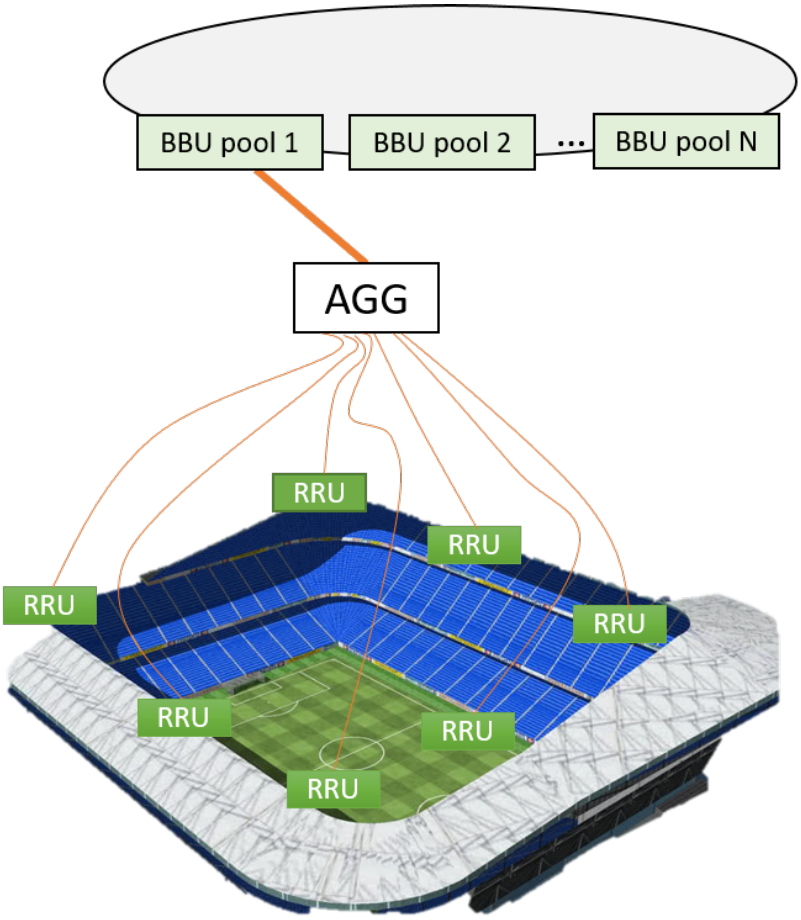


Figure 4.5: Hotspot Deployment Scenario

Cloud RAN TEA Model

In these sections, we will discuss what is done and the methods that are used to accomplish the tasks. Included in this chapter is a detailed implementation of the techno-economic model, a description of the inputs used, network dimensioning, and cost assumptions description.

5.1 Implemented TEA Model

A techno-economic model is a framework used to analyze the economic feasibility of the technologies considering all the system parameters based on the framework from the model is derived. For this thesis work, the TERA framework is modified to comprise the input parameters and follows the flow chart in Figure 5.1 below. The model consists of marketing, technical, and economic parts. The formulated scenarios are implemented based on the developed tool.

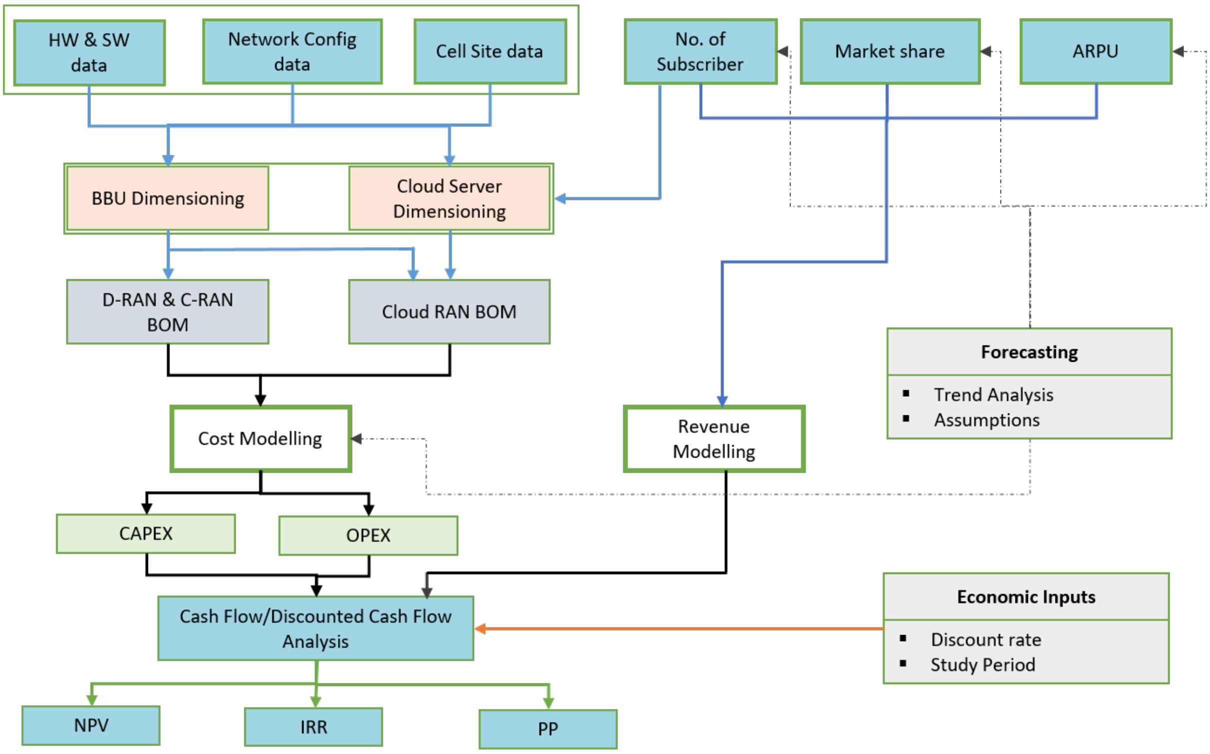


Figure 5.1: Modified and Implemented TEA Model

5.2 Model Description

The TEA model developed is further explained below. The TEA is performed for a certain period and six years is used for this research. The service to be provided and the target subscribers for the service are defined over the study period. Based on the combination of yearly subscribers, market share, and ARPU, revenue is calculated for each year. For network dimensioning, three datasets are collected from ethio telecom. These datasets are cell-site data, network configuration data, and Hardware and Software data. The cost for calculating the CAPEX for the used HW and SW licenses is derived from literature, vendors, and previous ethio telecom LTE and LTE-A project documents. The OPEX cost including OAM, site rent, HW maintenance, SW maintenance, and energy consumption are also computed based on literature and ethio telecom data. For the analysis, a 10% discount rate is used and the standard economic metrics such as TCO, cash flow (CF), discounted cash flow (DCF), NPV, IRR, and PP are calculated based on the developed TEA tool.

5.3 Techno-economic Analysis Model Inputs

5.3.1 Cell Site Data

The TEA model uses cell configuration and traffic data, which are collected from ethio telecom as input to the model. These data include parameters about sites such as cell configuration, data throughput, and control plane traffic. The cell site data are described in detail below.

Cell site data consists of:

1. Cell configuration:

- Cell BW and MIMO configuration at cell sites (e.g., 20 MHz 2x2 MIMO).
- Used to compute total cell in the network.
- Used to compute peak DL and UL throughput per cell site.
- In the process of network dimensioning, this is needed for the design of cell size limitations as well as cell connectivity.

2. Data throughput:

- Average busy hour (BH) throughput per site
- Traffic share per day on the site for BH.

- Traffic throughput share between DL and UL.
- Computes the daily data volume per site and throughput for Cloud RAN.
- Cloud server dimensioning uses this data to calculate throughput requirements.

3. Control plane traffic:

- Maximum connected user per site
- Average connected user per site
- Control plane load per connected user
- The number of connected UEs per site specifies the number of devices per site
- Each connected UE has a control plane load that specifies a signaling frequency for the devices
- In order to determine the number of RRC users in a network, we use the number of connected UEs on each site
- The parameters are required for the network dimensioning criteria

5.3.2 Network Configuration Data

Network configuration data describes the complete network structure for the RAN architectures. The data is collected from ethio telecom and used as input to the TEA model. It describes the network hardware and software licenses requirements by each RAN architecture.

Network configuration data consists of:

1. Network configuration:

- Total number of sites in the network
- Used to compute the overall network HW and SW license required in the network.

2. Centralization:

- Number of BBU pools and data centers.
- Number of cell sites served per BBU pool.

5.3.3 Hardware and Software Data

Data about hardware and software are used to describe specifications, performance, and limits for a network's hardware and software.

HW and SW data contains:

1. BBM:

- Cell connectivity and control plane capacity per BBMs.
- BBM configuration per cabinet.
- BBM energy consumption.
- Helps for dimensioning of BBM.
- To computing network energy consumption.

2. Cloud Server

- Required CPUs per server
- CPUs needed per various VMs
- VM and VNF capacity limit
- Cloud RAN Pooling gains
- To dimension VNFs, cloud servers, and VMs.

3. SW licenses

- BB and cloud software licenses
- Used for computing the required BB and cloud server license cost.

5.4 Network Dimensioning

The network dimensioning is performed for the three RAN architectures D-RAN, centralized RAN (C-RAN), and the Cloud RAN based on data collected from ethio telecom LTE network. In D-RAN and C-RAN architectures, the network is dimensioned by using a proprietary HW per-site basis for the BBM, whereas the Cloud RAN architecture utilizes both proprietary and COTS HW for the BBM and Cloud server dimensioning. The network dimensioning performed in this thesis is adopted from the paper [23] and contextualized into the local context.

The baseband and cloud software licenses are calculated based on the network configuration data and user traffic data. Hence, the output of the network dimensioning is the number of baseband processing hardware and software licenses required for the three architectures on yearly basis.

5.4.1 Baseband Module dimensioning

Cloud RAN aims at consolidating the baseband processing of the radio signals emerging from different RRUs into a central office called BBU Pool/PoP. Because the baseband processing hardware for the centralized architectures is located at the BBU pool or PoP, dimensions are done for the pool or PoP. In the D-RAN architecture, the dimensioning is performed per cell site.

In the baseband unit, the BBM hardware supposed to be containing three units, these are:

1. Capacity unit (CAP):

- The CAP unit provides baseband processing capacity for the system.
- The number of cells a CAP unit can handle is based on the cell's BW and MIMO configuration.
- More BW and MIMO configuration requires more baseband processing power and hence, requires higher CAP units.

2. Main Processing Unit (MPU):

- Responsible for processing control plane traffic and manages resources on the other BBMs.
- Its functions are providing transport links to the core network, clock reference, and maintenance links connecting to OMC.

3. Cabinet unit (CAB):

- Responsible for holding the CAP and MPU units
- Provides backplane for internal communication
- Interconnects the CAP and MPU to each other
- Provides air conditioning for the BBMs.

Hence, the BBM dimensioning is done for the three BBMs based on the flow chart shown in Figure 5.2. The flow chart illustrates how BBM is dimensioned and it is based on inputs cell-site data, network configuration data, as well as hardware and software provided by the operator. Data from cell sites provide inputs regarding cell configurations and control plane traffic at cell sites, while network configurations provide the number of cell sites and BBU pools necessary, while the HW and SW data specify the baseband modules' capacity limits for ensuring cell connectivity and controlling control plane traffic.

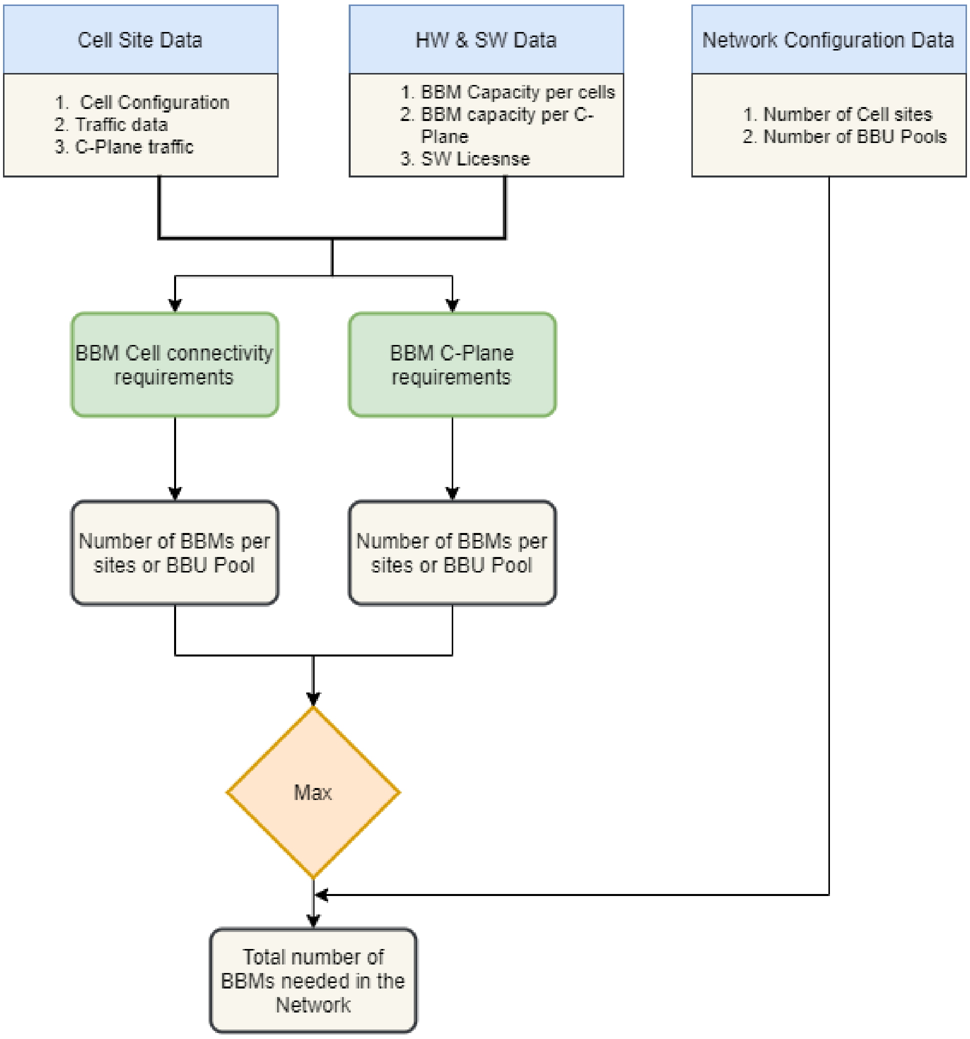


Figure 5.2: Flow chart for BBM dimensioning [23]

Dimensioning BBM units take into account both cell configurations and control plane traffic on the site during the calculation process. For BBM units, these two characteristics determine their dimensions requirement. Cloud RAN does not require control plane traffic requirements in the BBM dimensioning since this is mainly managed by the cloud servers and would not present a restrictive factor to BBM scaling. Furthermore, since the BBUs are located in the cloud, additional processing gains can also be achieved, such that using the average cell traffic for the dimensioning purpose rather than the peak traffic per site, as it is used in distributed architectures.

The two main requirements for the BBM module dimensioning are elaborated below:

1. Cell connectivity requirements:

i. Capacity unit (CAP):

- Each cell site has its own configuration of BW and MIMO, which have particular processing requirements.
- The CAP unit must provide adequate processing resources per site for the total baseband processing requirement of the cells. Higher BW and MIMO both require more processing resources per site.

ii. Main Processing Unit (MPU):

- For cell connectivity requirements, the CAP unit is the main responsible module. However, a minimum of one MPU module is required per cabinet.

iii. Cabinet Unit (CAB):

- The CAB unit is responsible for accommodating the CAP and MPU units.
- How many CAP and MPU units the CAB unit can handle is restricted by its capacity.

2. Control plane connectivity requirements:

i. Capacity unit (CAP):

- Connected UEs per cell and control plane load per connected UE determines the control plane traffic per cell site.
- CAP units have limited capacity for handling the control plane traffic hence the number of CAP units must fulfill the required control plane traffic on cell sites.

ii. Main Processing Unit (MPU):

- The MPU has two modes of configuration, which are the single-mode and dual-mode. The configuration is selected based on the control plane traffic on the site.

iii. Cabinet Unit (CAB):

- CAP units and MPU units in a CAB system are determined by how many cells can be supported per cabinet, that is, how many cells can be supported per CAP unit and the number of MPU needed to handle the control plane traffic.

The dimensioning is performed based on the requirements set for cell connectivity and control plane traffic for all the BBM units (CAP, MPU, and CAB). The BBM unit dimension generates the number of CAP, MPU, or CAB units needed per cell site or BBU pool based on the requirements. Once the cell connectivity and C-plane traffic requirements are met, the maximum number of BBM units can be selected, so that both requirements are met. After the dimensioning is done for BBM units per cell site or BBU pool, we can obtain the total number of BBM units required in the network by multiplying it with the total number of cell sites or BBU pools in the network. The result of the BBM dimensioning is the total number of BBM HW and software licenses needed with the forecasted traffic demand to determine the optimum number of network elements deployed per year in the study periods.

5.4.2 Cloud Server Dimensioning

In C-RAN, part of the baseband processing functions are virtualized into vBBUs or virtual network functions (VNFs) which implemented on generic cloud hardware. In this thesis, the NRT-RT functional split is assumed in which the NRT functions are executed on the COTS cloud HW and RT functions are executed on proprietary HW. This functional split will alleviate the burden on the Fronthaul link and meet the latency requirement set by the LTE protocol stack.

The VNFs in C-RAN contain multiple virtual machines (VMs) that process various parts of the virtualized baseband processing functions. To process the NRT baseband functions in the virtualized environment, it is assumed that the following VMs are deployed: Cell processing VM (CP VM), User processing VM (UP VM), OAM VM and Central eNB VM (CeNB VM). The VMs use and functions are described below:

1. Cell processing VM (CP VM):
   - The CP VM handles functions related to cell processing in the VNF.
2. User Processing VM (UP VM)
   - In the VNF, the UP VM handles user-related functions.
3. OAM VM
   - The OAM VM is responsible for processing the Operation, Administration, and Maintenance functions of the VNF.
4. Central eNB VM (CeNB VM)

- The CeNB VM handles functions related to the centralized resources and the eNB related functions in the VNF.

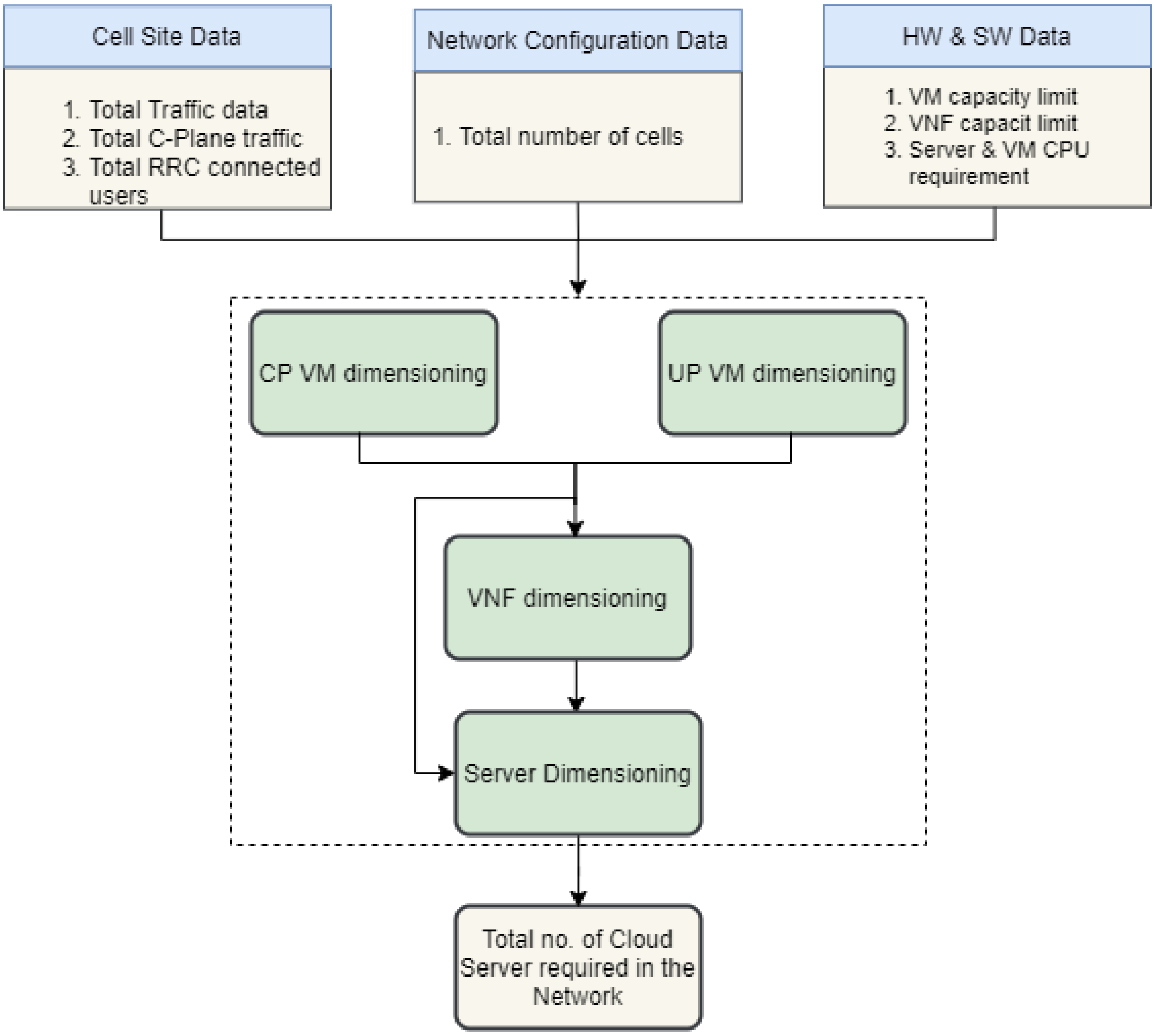


Figure 5.3: Flow chart for Cloud server dimensioning [23]

Hence, the cloud server dimensioning is done by using the input from the cell site data, network configuration data, and the HW and SW data based on the flow chart shown in Figure 5.3. A hardware and software specification defines the VM and VNF capacity limit and the number of cores for each VM and VNF as well as how many server processor cores are available.

Cloud server dimensioning starts with calculating the required virtual machines in the network, which takes place when the CP VM and UP VMs are dimensioned. Then the required number of VNF can be calculated in the VNF dimensioning based on the input from the CP VM and UP VM dimensioning result and network-related data. The number of OAM and CeNB VMs required in the network is supposed the same as the number of VNFs; therefore, no process of sizing is required. For better reliability and maintainability, the OAM and CeNB VMs are deployed in Active/standby mode. Lastly, the required number of cloud servers in the network is obtained by using the VMs and VNFs calculated from the dimensioning. The CP VM, UP VM, VNF, and Cloud server dimensioning are elaborated below in detail.

1. CP VM Dimensioning

The CP VMs handles functions related to the cell processing in the VNF and its dimensioning uses the cell site data, network configuration data, and HW and SW data as input. Dimensioning is based on the total number of cells, number of users concurrently connected to RRC, and traffic in the control plane. The HW and SW data specify the CP VM capacity limits for each parameter stated and used as a requirement for the CP VM dimensioning purpose. The CP VM requirements are discussed below:

i. Cell connectivity requirements

- It specifies the number of CP VMs required to handle the total number of cells in the network.

ii. Concurrent RRC connected user Requirements

- The RRC connected users requirement illustrates the number of CP VMs required to handle the total number of simultaneous RRC connected users in the network.

iii. Control plane traffic requirements

- The control plane traffic requirement illustrates the number of CP VMs required to handle the total control plane traffic in the network.

We obtain a number of CP VMs from the output of each requirement to satisfy their requirement. The maximum number of CP VMs from the output of the requirements is selected so that the CP VMs in the network can handle all the requirements. The result of the dimensioning is the total number of CP VMs needed in the network. The CP VM dimensioning uses the flow chart shown in Figure 5.4.

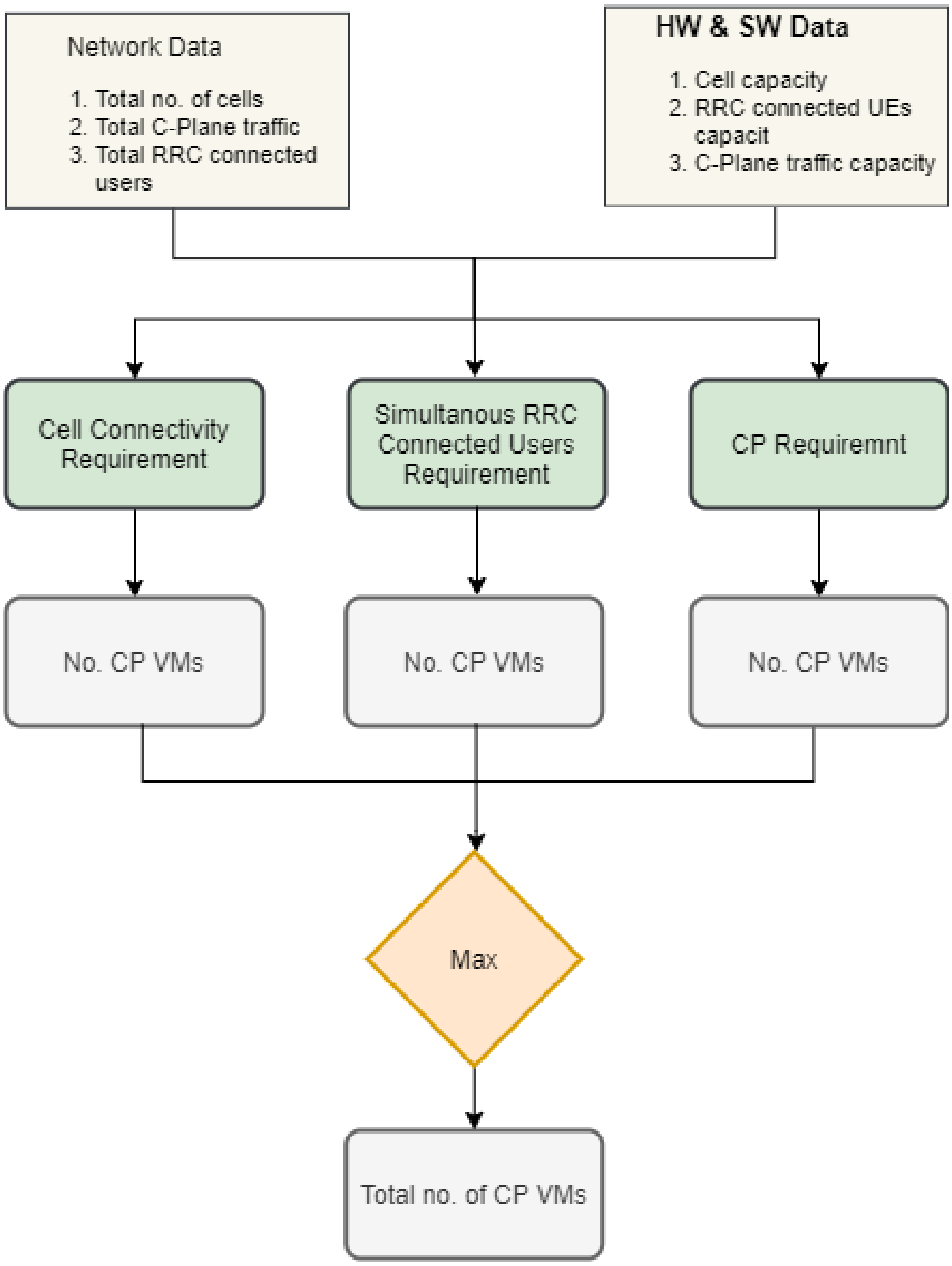


Figure 5.4: CP VM dimensioning [23]

2. UP VM Dimensioning

The UP VM is used for user-related processing in the virtualized BBUs hence the dimensioning is performed using the input from the cell site data, network configuration data, and HW and SW data. The total DL and UL throughput traffic, simultaneous RRC connected users, and the control plane traffic in the network are used for dimensioning. The HW and SW data specify the UP VM capacity limits for the parameters stated and used as a requirement for the UP VM dimensioning purpose. The UP VM dimensioning uses the flow chart shown in Figure 5.5.

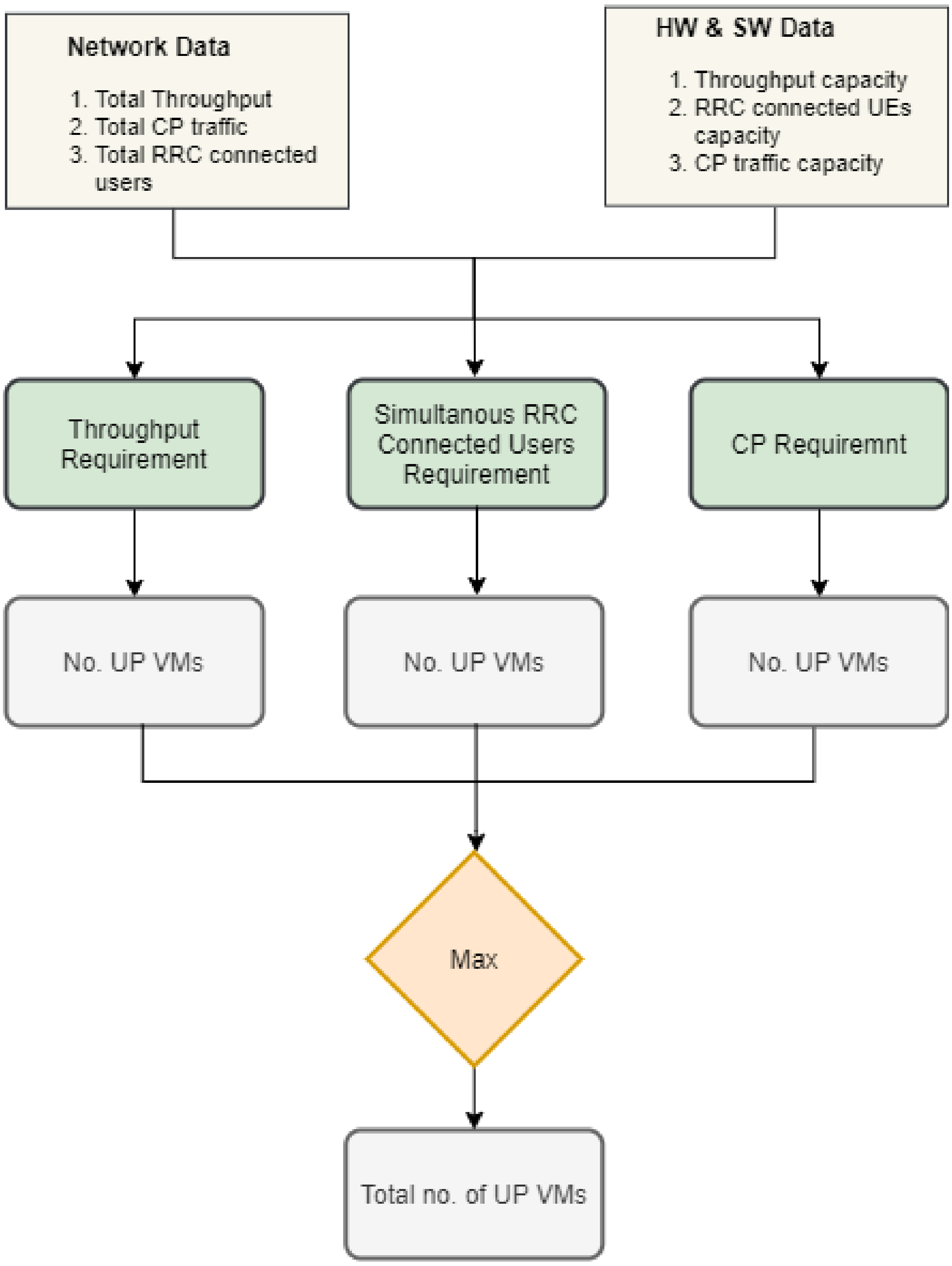


Figure 5.5: UP VM dimensioning [23]

The UP VM requirements are discussed below:

i. Throughput requirements

- It indicates how many UP VMs are necessary to handle the total DL and UL throughput traffic from all cell sites in the network.

ii. Concurrent RRC connected user Requirements

- The RRC connected users requirement illustrates the number of UP VMs required to handle the total number of concurrent RRC connected users in the network.

iii. Control plane traffic requirements

- The control plane traffic requirement illustrates the number of UP VM required to handle the total control plane traffic in the network.

We obtain a number of UP VMs from the output of each requirement to satisfy their requirement. The maximum number of UP VMs from the output of the requirements is selected so that the UP VMs in the network can handle all the requirements. The result of the dimensioning is the total number of UP VMs needed in the network.

3. VNF Dimensioning

VNF is virtualized network service consisting of various VMs. Most VNFs run in the VMs on common virtualized infrastructure software such as KVM, VMWare [59]. Because they have restrictions in terms of Cell connectivity and control plane traffic, the overall number of VNFs required in the network will be determined by the total number of cells, control plane traffic, and CP and UP VMs. The HW and SW data specify the VNF's capacity limit for the parameters stated and used as a requirement for the VNF dimensioning purpose. The VNF dimensioning uses the flow chart shown in Figure 5.6.

The VNF requirements are discussed below:
i. Control plane requirements

- The control plane traffic requirement defines the number of VNF required to handle the total control plane traffic in the network.

ii. Cell connectivity Requirements

- The number of VNFs necessary to manage the entire number of cells in the network is specified by the cell connectivity requirement.

iii. CP VM requirement

- This requirement specifies how many VNFs are necessary to handle the total number of CP VMs in the network.

iv. UP VM requirement

- It specifies the amount of VNFs necessary to handle the total number of UP VMs in the network.

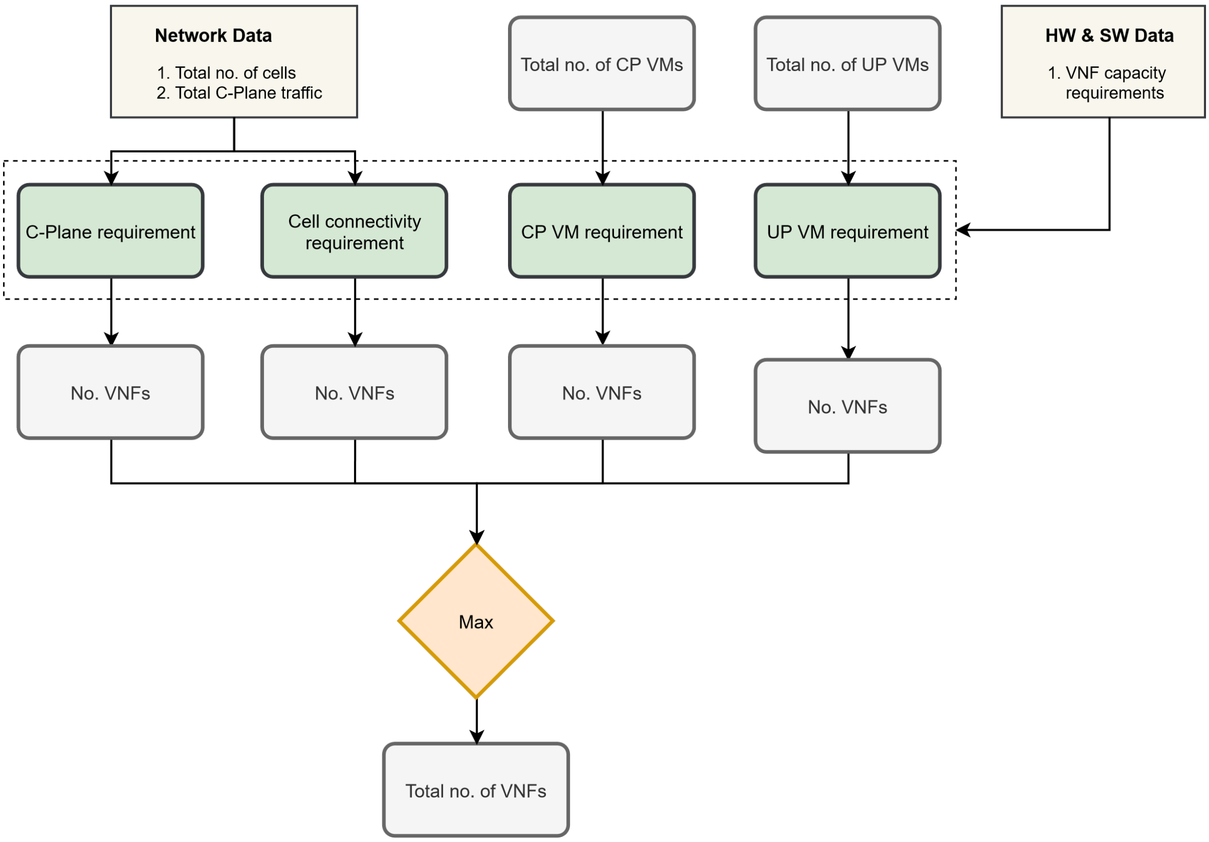


Figure 5.6: VNF dimensioning [23]

When a VNF is dimensioned, the number of VNFs required to meet the requirement is calculated. Out of these requirements, the maximum amount of VNFs is then selected to supporting all requirements for network dimensioning. The result of the dimensioning is the total number of VNFs needed in the network.

4. Server Dimensioning

Cloud server dimensioning requires the dimensioning of the physical server to get the total number of servers needed in the network. In the initial phase of server dimensioning, the VMs configuration per VNF is estimated by assigning CP and UP virtual machines to VNFs. The number of CP VMs per VNF (VNF_{CP}) is obtained as follow [23]:

$$VNF_{CP} = \frac{N_{CPVM}}{VNF_T} \tag{5.4.1}$$

Where 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.

The number of UP VMs per VNF (VNF_{UP}) is obtained as follow:

$$VNF_{UP} = \frac{N_{UPVM}}{VNF_T} \tag{5.4.2}$$

Where N_{UPVM} is the total number of CP VMs in the network and VNF_T is the total number of VNFs required in the network.

Once the number of N_{CPVM} and N_{UPVM} is obtained, we can compute the number of cloud servers needed per VNF (S_{VNF}) as follow:

$$S_{VNF} = \frac{VNF_{CP} * C_{CP} + VNF_{UP} * C_{UP} + C_{CeNB} + C_{OAM}}{C_{Server}} \tag{5.4.3}$$

Where the VNF_{CP} and VNF_{UP} are the total numbers of VMs per VNF, C_{CP}, C_{UP}, C_{CeNB}, and C_{OAM} are the required number of CPU cores per VMs and C_{Server} is the number of CPUs per server.

Lastly, the number of cloud servers needed in the network is computed as follow:

$$N_S = S_{VNF} * VNF_T \tag{5.4.4}$$

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 number of cloud servers required in the network is determined, the necessary network elements, for instance, switches, controllers, and server racks are obtained and included in the list of required network elements.

5.5 Small Cell Dimensioning

The term small cell refers to a type of radio access node that has low power and a small range between 10 and several hundred meters and they appear to be a very promising solution to scale network capacity especially in dense areas where capacity is very severe [72]. Small cells are widely deployed for hotspot areas in indoor and outdoor scenarios. A precisely placed small cell in high traffic demand area will result in most of its capacity being highly utilized, which shows a good ROI for the Operators investing in small cells [72].

Deploying two small cells per macro cell at a precise location provides enhanced performance in hotspot areas according to [73]. In addition, using a dedicated carrier for outdoor small cell deployment can achieve greater performance with three small cells per sector [74]. Based on these investigations as well as 3GPP technical recommendations of outdoor small cells, two small cells per macro-cell were assumed [75].

5.6 Cost Modeling Assumptions

The cost modeling performed in this thesis is discussed in detail in Chapter 3. Here the assumptions made on the cost modeling are presented below.

1. It is assumed that baseband software will be about the same for all architectures, or even more for Cloud RAN since less baseband hardware will be required in the network.
2. Since a functional split is assumed in the model, the cost of the Fronthaul in the Cloud RAN is assumed to be the same as the cost of the backhaul in the D-RAN. The Cloud RAN Fronthaul costs would have been significantly higher if a CPRI-based Fronthaul had been used instead.
3. As part of this use case, only rental costs for the cell tower and the floor space needed for baseband equipment are considered. As the operator has its own data center and core sites space, the rental costs for the data center were not included.
4. D-RAN capacity upgrade costs are assumed to be higher since the installation has to be completed at each site individually, significantly extending installation time and requiring more work than the centralized architectures.
5. In the study case, the annual OAM costs for network operation and troubleshooting, preventive maintenance, performance optimization, capacity analysis and planning, and software release upgrades are estimated from the operator's annual report and target literature for each of the architectures.
6. The CAPEX cost calculation does not include RF hardware, since it is assumed that it will remain the same in all architectures.

After the required number of BBMs and Cloud servers are obtained from network dimensioning [Section 5.4], the next step is to estimate the investment and operational costs required to deploy and operate the system. Cost values for CAPEX and OPEX (energy cost excluded) are reported in Table 5.1 and Table 5.2 based on ethio telecom project documentations, vendor documents, related literature and Internet sources. A 5% yearly price inflation rate is considered throughout the study periods. The annual energy costs (C_E) are derived from the power model [Section 3.3.2] by assuming cost per kWh (C_{kWh}) = \$0.09 [76].

Table 5.1: Assumed CAPEX and OPEX Costs (D-RAN, C-RAN) [23], [29], [35], [37], [77], [78]

No.	Component	Cost [k$]
1	CAP	50
2	COM	20
3	CAB	5
4	BB SW	10
5	BBM License	8
6	BH & FH link cost	5
7	Annual BH & FH cost per site	3
8	Annual Cell site rent (D-RAN, C-RAN)	5,3
9	Annual BBU pool rent (C-RAN)	10
10	Annual OAM (D-RAN, C-RAN)	15,10
11	Capacity upgrade (D-RAN, C-RAN)	2,1
12	HW & SW maintenace	4% & 5% of equipment

Table 5.2: Assumed CAPEX and OPEX Costs (Cloud RAN) [23], [29], [35], [37], [77], [78]

No.	Component	Cost [k$]
1	CAP	50
2	COM	20
3	CAB	5
4	BB SW	10
5	BBM License	8
6	BH & FH link cost	5
7	Cloud HW	200
8	Cloud SW	55
9	Annual BH & FH cost per site	3
10	Annual Cell site rent	3
11	Annual BBU pool rent	10
12	Annual OAM	10
13	Capacity upgrade	1
14	HW & SW maintenace	2% & 10% of equipment

Result and Analysis

In this section, Techno-economic analysis for the use case of ethio telecom was performed employing Cloud RAN TEA modeling tool developed to evaluate the costs of different RAN architectures. The use case is based on the data obtained from ethio telecom to analyze the costs of the three architectures (D-RAN, C-RAN & Cloud RAN). The analysis is done for a period of 6 years wherein the initial year 2021 ethio telecom has an existing D-RAN architecture. The architectures are assessed in terms of economic evaluation metrics within the study period in order to show, which RAN architecture performs best in terms of cost. As a convention from now on, D-RAN refers to Distributed RAN architecture, C-RAN refers to Centralized RAN architecture whereas Cloud RAN refers to Cloud-based RAN architecture.

The subsequent sections will present the model inputs that were used for the analysis, followed by a discussion of the use case's deployment option, network dimensioning result, market analysis and techno-economic evaluation results and discusses the observation on the results obtained.

6.1 Deployment Option

As per the scenario analysis discussed in Chapter 4, the formulated deployment scenarios for the Cloud RAN are presented here for further analysis. In this regard, two deployment scenarios have been formulated based on selected uncertainty extreme values. The formulated deployment options are also known as Small-scale deployment with low control plane traffic (SC1) and Small-scale deployment with high control plane traffic (SC2).

6.1.1 Small Scale Deployment

Based on the data from ethio telecom, 3 months of traffic data are collected and top sites with the highest data volume are selected for Cloud RAN deployment. The main aim of this deployment is to address the high data traffic demand of hotspot locations with Cloud RAN architecture as a centralized approach is very appealing for such kinds of scenarios since it simplifies the implementation of interference management techniques such as ICIC, eICIC, and CoMP. As part of this thesis, hotspot areas are identified in Bole Sub-city around Bole International Airport where dense buildings, shopping malls, entertainment malls, restaurants, and residential areas mainly cover the area. Figure 6.1 depicts the location of the existing site in the study area covering 2km by 2km area. The study area contains 21 macro base stations each with three sectored antennas. The sites are selected based on the factors: high traffic demand, cell site cell configuration, and fiber link availability. Two different traffic growth scenarios are evaluated for the deployment options depending on the control plane traffic growth forecast. According to these two scenarios, the maximum number of users per cell site determines the growth of control plane traffic and the control plane traffic load per connected device is assumed to be constant. As a result, it is expected that the number of devices will continue to grow, but the signaling frequency per connected devices will not change in the network. Hence, the following two scenarios are formulated.

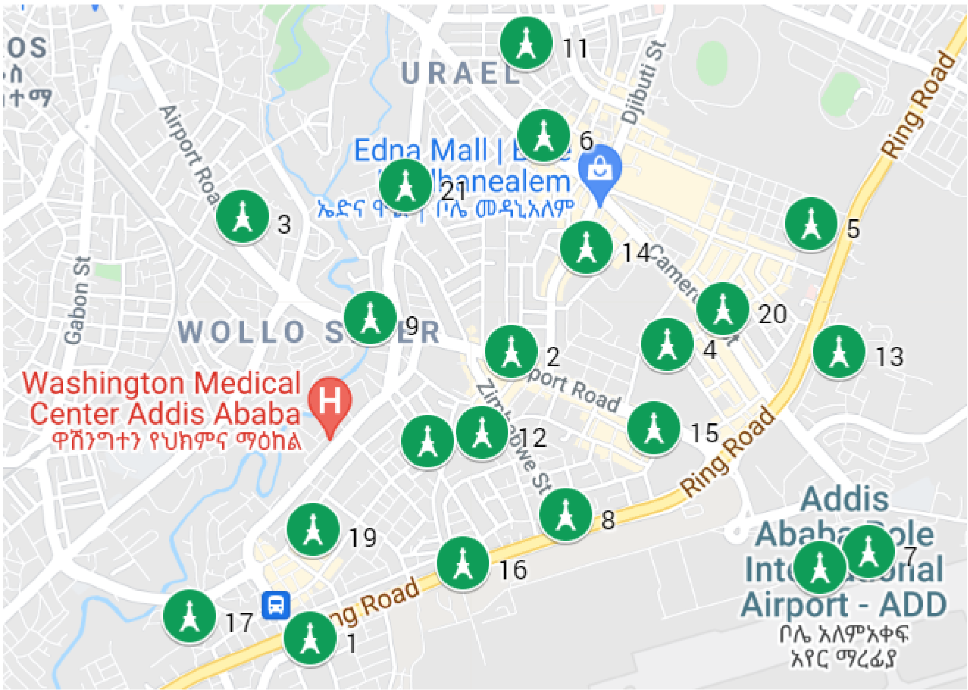


Figure 6.1: An operational LTE network with 21 eNBs (in total 63 sectors) around Bole area in the city center of AA.

1. Small Scale Deployment with Low Traffic Scenario (SC1)

In this scenario, 25% of the compound annual growth rate (CAGR) is assumed between the years 2022 to 2027 (Figure 6.4). Considering that 5G and other disruptive technologies such as the IoT are still a few years away, Scenario 1’s 25% CAGR is a reasonable expectation for device growth rate.

2. Small Scale Deployment with High Traffic Scenario (SC2)

In this scenario, 50% of CAGR is assumed between the years 2022 to 2027 (Figure 6.4). Although it is a high growth rate, it can still be realistic in the future. With the advent of the massive IoT, M2M communication, the number of connected devices will increase even more rapidly, and this number may increase significantly with the development of 5G, which enable various use cases such as autonomous vehicles, Augmented Reality (AR), and Virtual Reality (VR), smart city, industrial automation, video monitoring, and detection, etc.

6.2 Network Dimensioning Result

In this section, the results obtained from the Cloud RAN dimensioning process in Chapter 5 Section 5.4 are summarized. Assumption taken in the dimensioning processes are described as follow:

- The year 2021 is assumed to contain only D-RAN architecture and progressively centralize to Centralized RAN and Cloud RAN architecture. Hence, the BBUs gradually move from the cell sites to Centralized RAN then Cloud RAN BBU pools.
- It is assumed that all the RAN architectures have the same number of cell sites equipped with radio frequency capabilities.
- Cloud RAN BBU pool can handle tens or even hundreds of cell sites [79].
- Cloud RAN VNF can support up to 96 cells [23].

As described in Chapter 5 Section 5.4, the cell configuration per cell site will affect the cell connectivity requirements in the BBM and cloud server dimensioning process. In these cases, the processing resources required for baseband processing will be higher as there are more cells, higher BWs, and MIMO configurations are added to the cell. A current cell configuration for ethio telecom contains FDD type 20 MHz 2x2 MIMO and 20 MHz 4x4 MIMO cells. Over the study period, the cell configuration is forecasted to contain higher BW and MIMO configurations as shown in Figure 6.2.

Cloud server dimensioning refers to determining the required number of servers, which are needed to guarantee the baseband processing of LTE sub-frames within the deadline for the given number of cell sites. In addition, the cloud server dimensioning and the required software licenses depend on busy hour throughput and data volume per cell site. A linear forecasted method was used to forecast the cell site's BH throughput and data volume per day considering the growth of services, APPs, and city growth as shown in Tabel 6.1 and Figure 6.3.

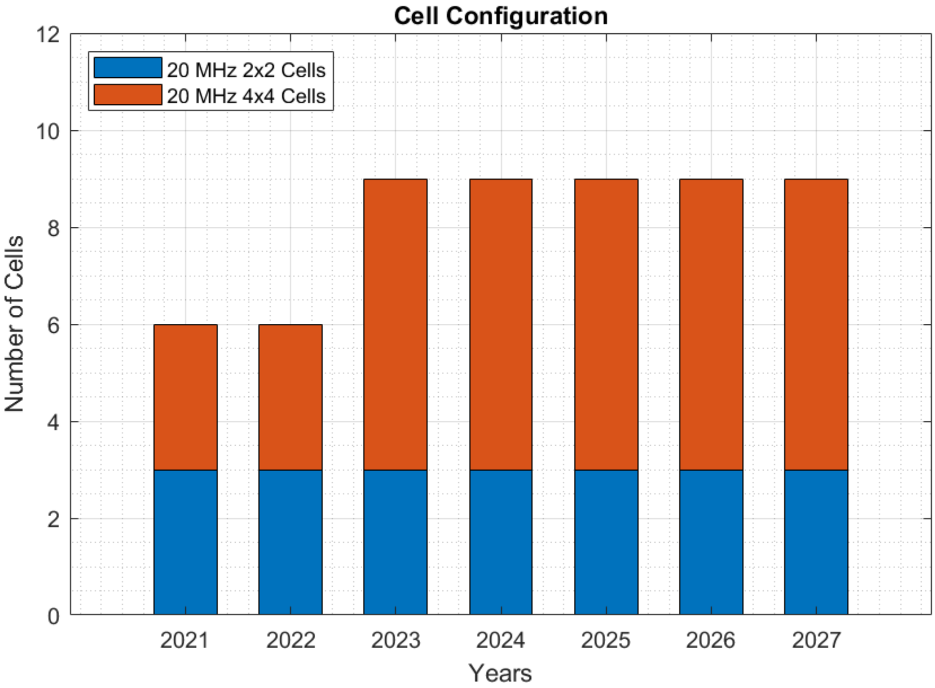


Figure 6.2: Cell sites cell configuration

Table 6.1: Cell site parameters

Parameters	Unit	2021	2022	2023	2024	2025	2026	2027
BH share of traffic per day per site	%	9%	9%	9%	9%	9%	9%	9%
UL share of total throughput (DL+UL)	%	5%	6%	6%	7%	7%	8%	9%
Average BH throughput per site	Mbps	11.85	13.04	14.34	15.77	17.35	19.08	20.99
Data Volume per site	GB/day	100.73	110.80	121.88	134.07	147.47	162.22	178.44

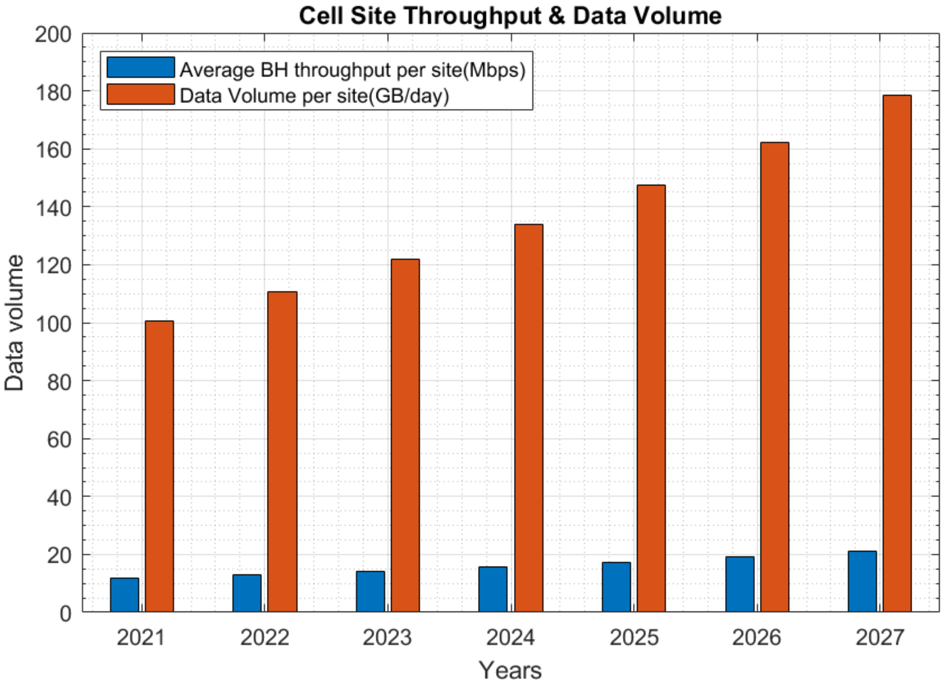


Figure 6.3: Cell site throughput and data volume forecast

The other key parameter in the network dimensioning is the control plane traffic, which affects the control-plane requirements in the dimensioning of BBMs and Cloud servers as discussed in Chapter 5 Section 5.4. In order to determine the growth of control plane traffic per cell site, there are two key parameters required. These are the maximum number of connected users per cell site and the control plane load per connected user. The connected user per cell site shows the maximum number of LTE devices connected to the cell sites. Based on the data collected from the operator, analysis is performed and the maximum connected users per cell site are predicted as shown in Figure 6.4. As per the analysis, the maximum connected UEs per cell site is 308 at the initial year and these numbers are assumed to increase based on the assumption that more devices are expected to be attached to cell sites in the future (such as smartphones, IoT devices, etc.). Even though more devices are forecasted to be attached to the network, the control plane load per each device is assumed to stay the same in the study period.

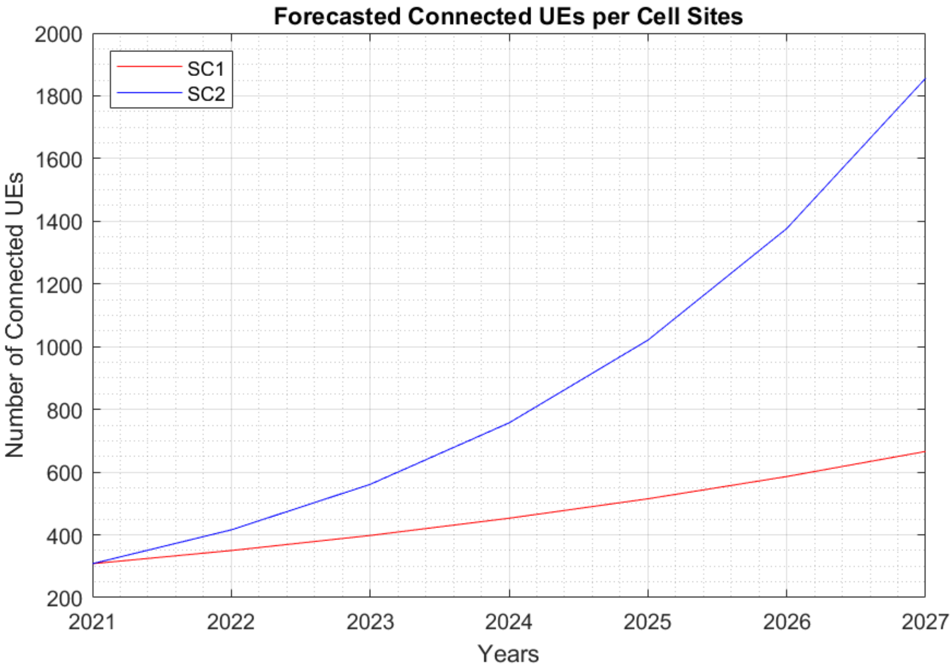


Figure 6.4: Forecasted maximum connected UEs per cell site

6.2.1 Small Cell Dimensioning Result

Small cell plays a key role in meeting the network demands of the future network and their deployment is very appealing for such a scenario to increase the network capacity with lower cost. In Chapter 5 Section 5.5, small cell dimensioning for the outdoor area is performed. To determine the required number of outdoor small cells research works [74], [66] and 3GPP recommendations [75] are employed. The selected area contains 21 macro base stations each with three sectors hence a total of 63 sectors. Based on the discussion the number of small cells

Table 6.2: Summary of the result of Network dimensioning for SC 1

Network Configuration (Scenario 1)								
RAN Architectures	**Attributes**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
D-RAN	Total No. of D-RAN cell sites	63	126	138	150	162	174	189
Centralized RAN	Total no. of Centralized RAN sites	0	126	138	150	162	174	189
	No. of BBU Hotel/PoP	0	2	2	3	3	3	3
	Centralized RAN sites served per PoP	0	63	69	50	54	58	63
Cloud RAN	Total no. of Cloud RAN sites served by BBU Pools/PoP	0	126	138	150	162	174	189
	No. of BBU Pools/PoP	0	2	2	3	3	3	3
	No. of Cloud RAN sites served per BBU Pool/PoP	0	63	69	50	54	58	63

Table 6.3: Summary of the result of Network dimensioning for SC 2

Network Configuration (Scenario 2)								
RAN Architectures	**Attributes**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
D-RAN	Total No. of D-RAN cell sites	63	158	177	196	215	234	253
Centralized RAN	Total no. of Centralized RAN sites	0	158	177	196	215	234	253
	No. of BBU Hotel/PoP	0	3	3	3	3	4	4
	Centralized RAN sites served per PoP	0	53	59	65	72	59	63
Cloud RAN	Total no. of Cloud RAN sites served by BBU Pools/PoP	0	158	177	196	215	234	253
	No. of BBU Pools/PoP	0	3	3	3	3	4	4
	No. of Cloud RAN sites served per BBU Pool/PoP	0	53	59	65	72	59	63

obtained are 126 and 189 for scenario 1 and scenario 2 respectively.

The results obtained in the network dimensioning process are summarized in Table 6.2 & Table 6.3 and the macro BS and small cells deployed are shown in Figure 6.5. Based on the discussions in Chapters 5 & 6 the number of cell sites required for each architecture is determined and the number of cell sites migrated to centralized architecture is decided based on the availability of resources.

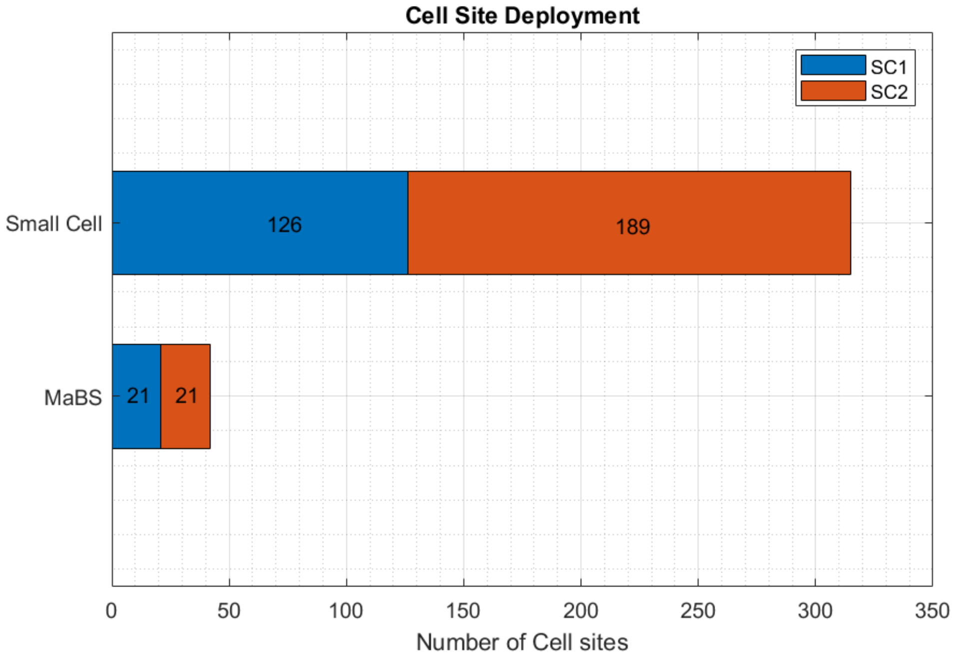


Figure 6.5: Macro BS and Small Cell deployment

6.3 Marketing Analysis

The number of subscribers and ARPU are determined based on the input data obtained from ethio telecom and employing forecasting and data analysis techniques [4], [80]. The number of users for the study period is forecasted using the bass model for the two scenarios [81], [82]. The ARPU is projected based on the data obtained from ethio telecom and applying the linear regression method for the study periods and a market share of 100% is assumed within the study period. In Figure 6.6 and Figure 6.7, it can be seen that subscriptions and ARPU both continue to grow.

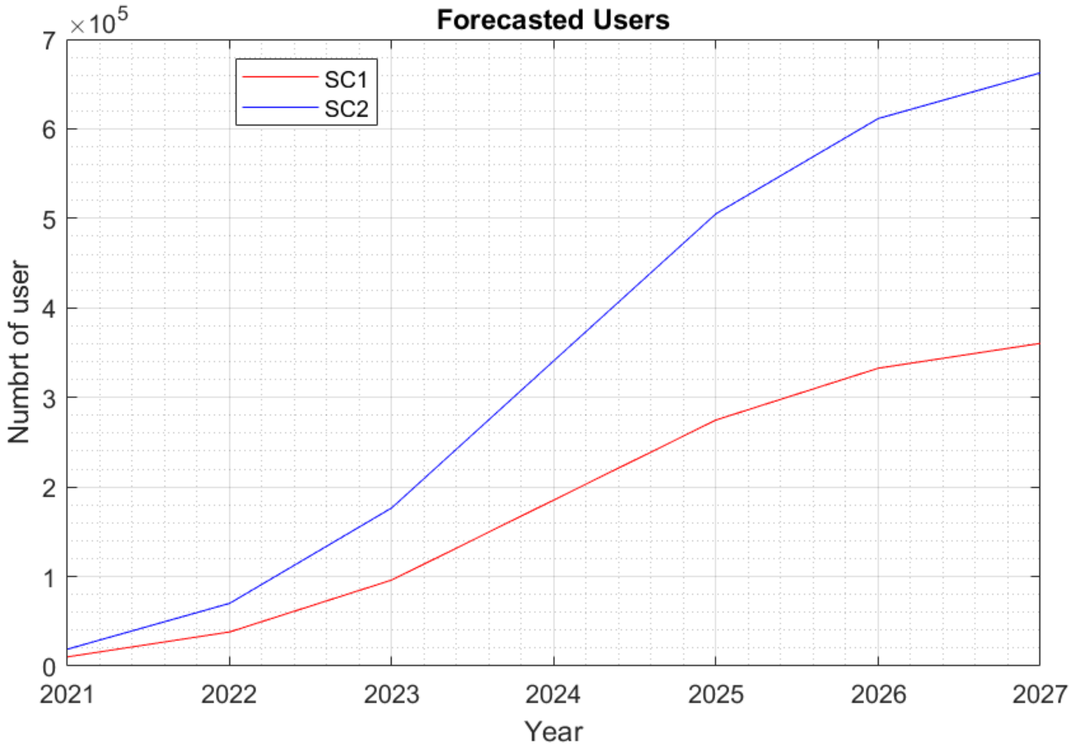


Figure 6.6: LTE user forecast

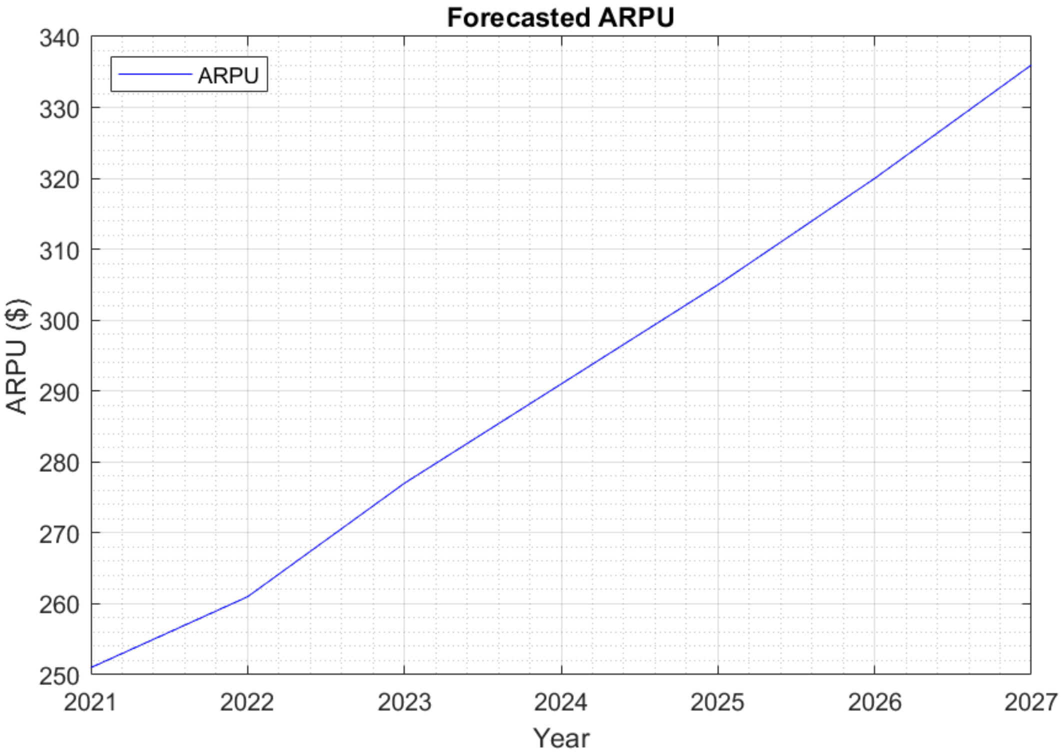


Figure 6.7: ARPU trend and forecast

6.4 Techno-economic Analysis

The Techno-economic evaluation is performed for the two scenarios and discussed below using the key economic evaluation metrics such as CAPEX, OPEX, TCO, and CF.

6.4.1 Small Scale Deployment with Low Traffic Growth

In scenario 1 with low traffic growth, 25% of the compound annual growth rate (CAGR) is assumed between the years 2022 to 2027. The cost position of each RAN architecture is described below.

1. CAPEX

For CAPEX evaluation, various data sources are considered vendor (Huawei, Ericsson & ZTE), ethio telecom project documentation (LTE/ LTE-A), cost database from industry-standard, related literature, and other operators' experience. The result of the network dimensioning is the starting point to calculate the total cost of the equipment required for each architecture. The succeeding figures show the results of the evaluation.

The required baseband processing hardware for each architecture is shown in Figure 6.8. In the low traffic scenario, comparing the BB processing hardware requirements between the architectures, D-RAN requires more BB processing hardware due to the dimensioning performed for peak traffic load (i.e., busy hour traffic) while C-RAN has a slightly reduced amount since BB processing hardware are centralized into central location, the hardware can be better optimized to handle as per their capacity. In comparison with the D-RAN architecture, Cloud RAN decreases the number of BBMs required however, additional cloud servers (vBBU pools) are included in the network infrastructure. In contrast, the difference between Cloud RAN and C-RAN with the addition of cloud servers is not as large. Cloud RAN better utilizes the BB processing hardware due to the pooling gain achieved from centralization however, in a low traffic growth scenario, Cloud RAN cannot benefit from cloud hardware better scaling for the control plane traffic.

The yearly CAPEX trends for each architecture are depicted in Figure 6.9. The initial investment for the Cloud RAN is high as compared to the other architectures due to the expensive cloud servers deployment required in the first year. As shown, the investment cost decreases over the study period for all architectures as this trend is expected due to the deployment cost of new technology is high at the beginning and decrease over the study period.

The CAPEX cost contribution of each architecture is shown in Figure 6.10. The BBMs took the highest share of the investment for all architecture. In the low traffic scenario, C-RAN attains

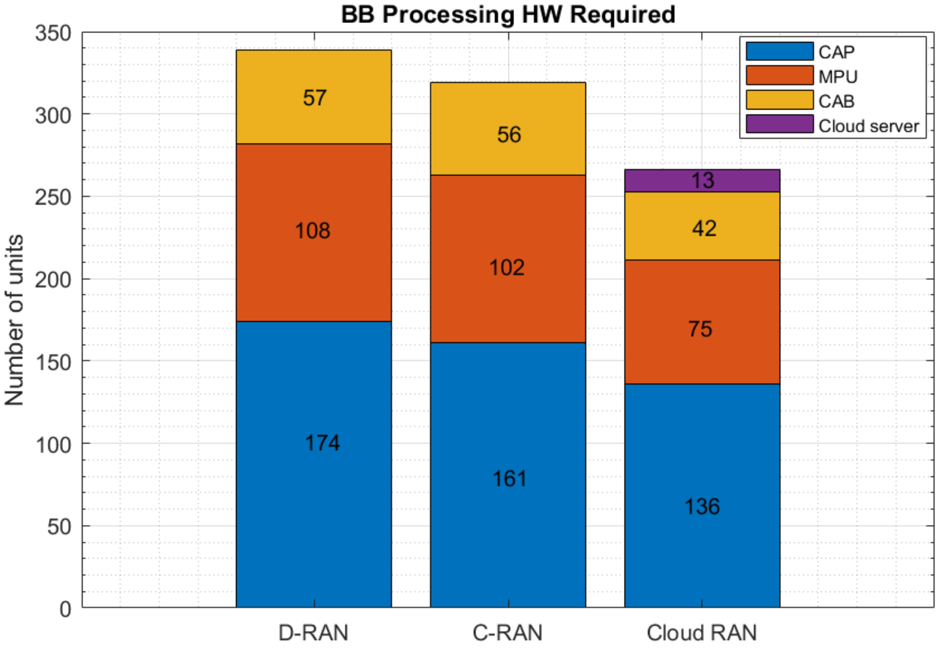


Figure 6.8: Required BB processing hardware for each architecture SC1

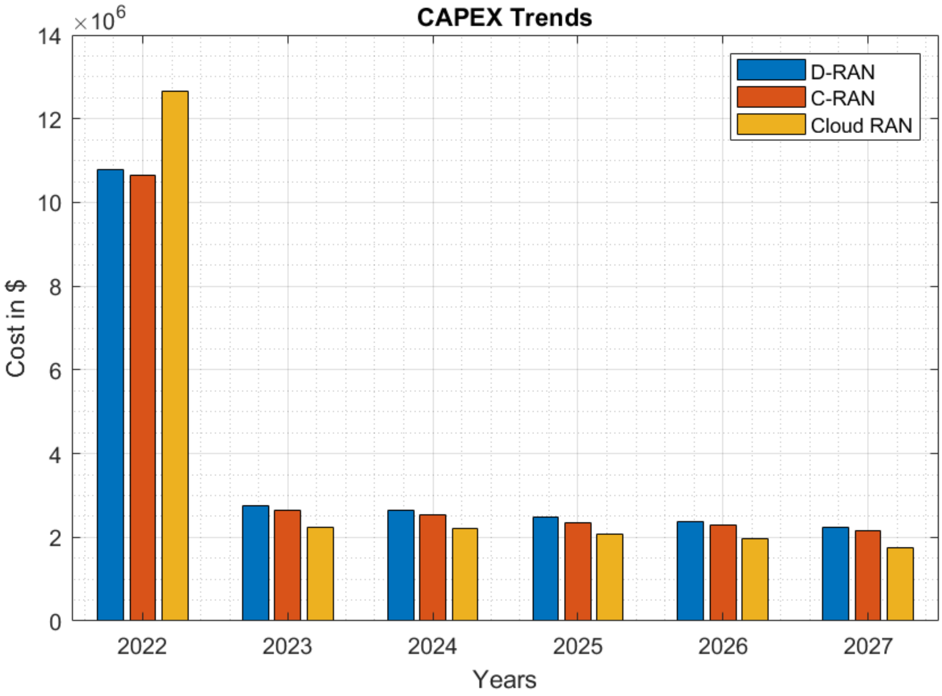


Figure 6.9: CAPEX cost trends for each architecture SC1

the lowest CAPEX as compared to D-RAN with a 1.14% lower cost. Cloud RAN shows higher CAPEX as compared to D-RAN with 1.83% higher costs. The main reason behind the increase in CAPEX cost in the Cloud RAN architecture is that the BBM hardware savings were not enough to offset the addition of expensive cloud servers and cloud software. C-RAN managed to reduce the number of required BBMs without investing in additional cloud servers, resulting in the lowest CAPEX.

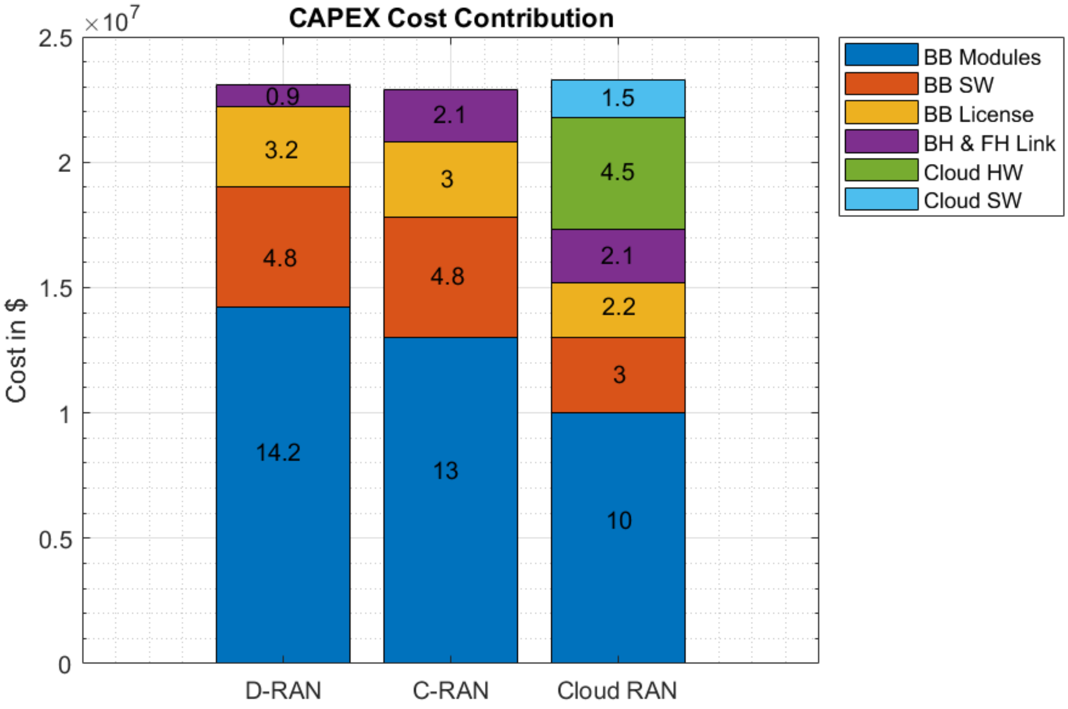


Figure 6.10: CAPEX cost contribution SC1

2. OPEX

For OPEX evaluation various data sources are considered in service LTE network in AA, cost database form industry-standard, related literature, and others Operators experience.

The OPEX cost trend is shown in Figure 6.11 for all architectures. As it can be seen, OPEX costs are an ongoing cost and it increases as time goes on due to the increase in the number of network elements, new equipment required to be installed each year in order to handle the growing capacity demand. The operational cost of distributed architecture is higher than that of centralized architectures. After 4^{th} year, the operational cost of Cloud RAN starts to decrease as it reduces the baseband upgrade cost significantly. Centralizing the BBU benefits a lot as site visit costs are reduced significantly.

The OPEX cost contribution of each architecture is shown in Figure 6.12. According to the analysis of SC 1 in terms of OPEX, due to the reduction in maintenance, site rent, energy, and operation costs, the centralized architectures achieve better OPEX savings. C-RAN achieved the lowest OPEX cost than D-RAN with 13.9% lower costs and Cloud RAN achieved lower

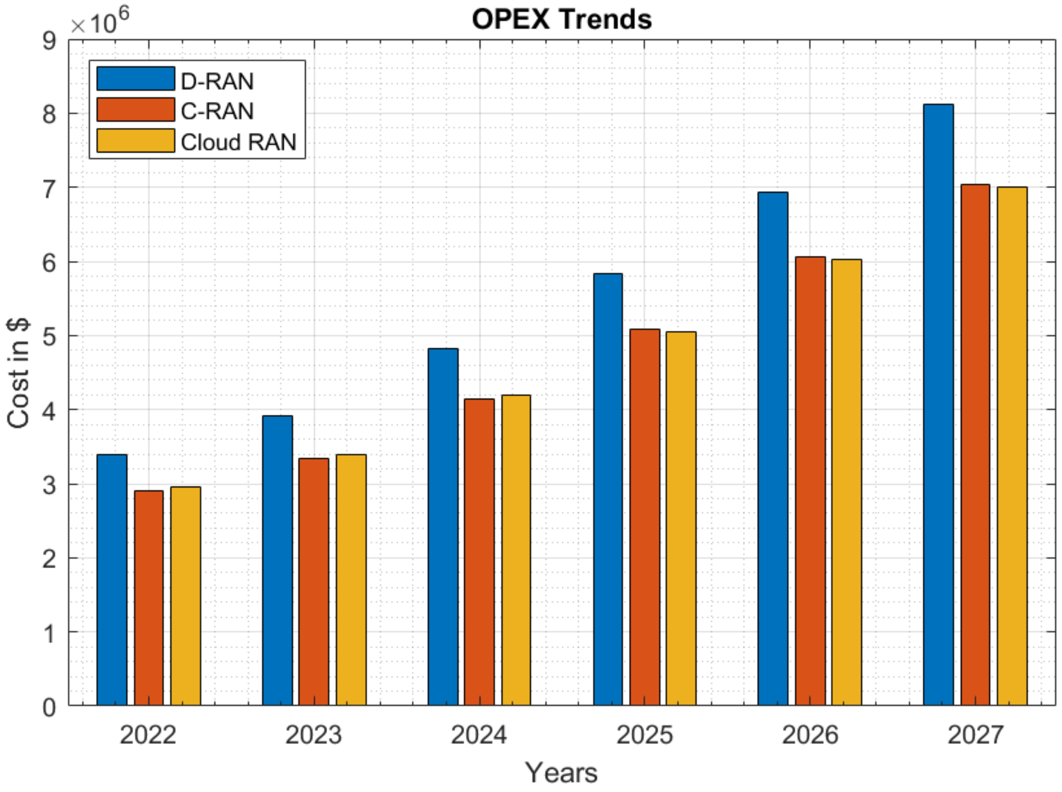


Figure 6.11: OPEX cost Trends SC1

OPEX than D-RAN with 13.7% lower costs. The majority of the OPEX savings originate from reduced maintenance, site rent, and capacity upgrade costs. These are primarily due to more centralized vBBU locations, which are easier to access, require fewer site visits, and are cost-effective to operate. The SW maintenance cost of Cloud RAN is higher when compared to the other two architectures due to additional expensive software in Cloud RAN.

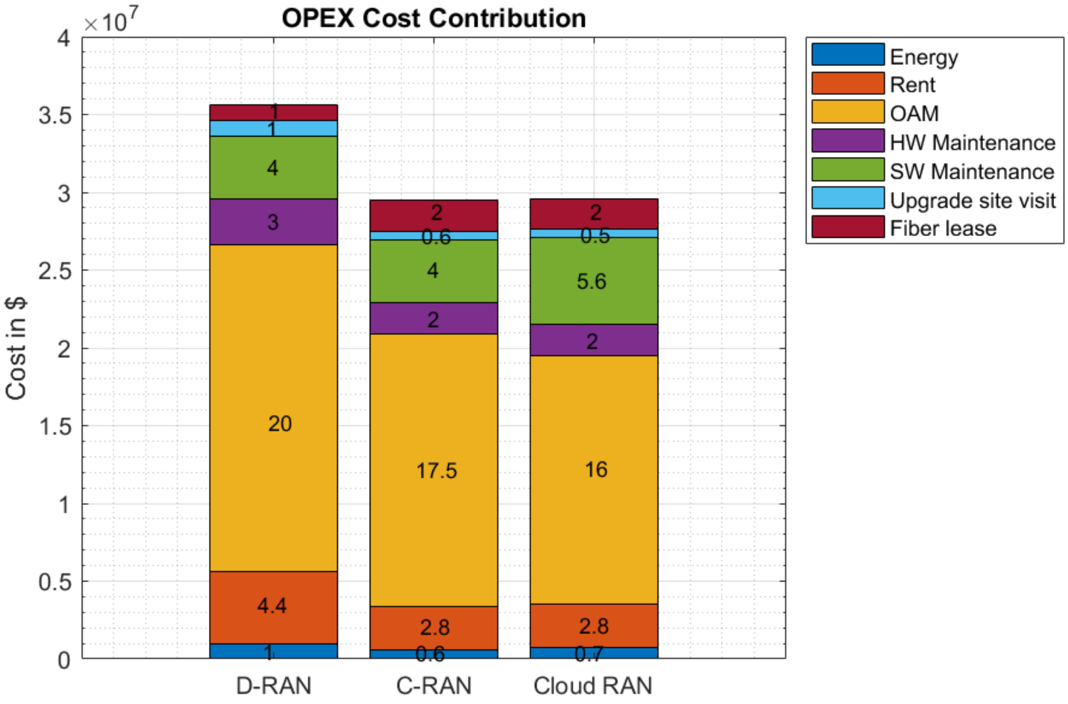


Figure 6.12: OPEX cost breakdown SC1

3. Total Cost of Ownership (TCO)

Figure 6.13 shows the Cumulative TCO trends over the study period for each architecture for low traffic growth scenario. Over the course of the study period, the cost of the network is stable. C-RAN architecture shows a better cost position than the other architectures and becomes more economical within the study period. The Cloud RAN architecture achieves a lower TCO than D-RAN after 3^{rd} year and starts to be more cost-effective afterward. The initial TCO of Cloud RAN is higher due to having higher CAPEX at the beginning.

For the low traffic growth scenario, the TCO cost saving that can be achieved in the architectures compared to the distributed architecture is shown in Figure 6.14. C-RAN proved to be the most cost-effective architecture in terms of TCO. C-RAN attains the lowest TCO than D-RAN with 7.9% lower TCO. A lower TCO is also achieved by Cloud RAN with a TCO of 5.2% lower than D-RAN. Cloud RAN architecture did not succeed in attaining better TCO in a low traffic growth scenario than the other architectures.

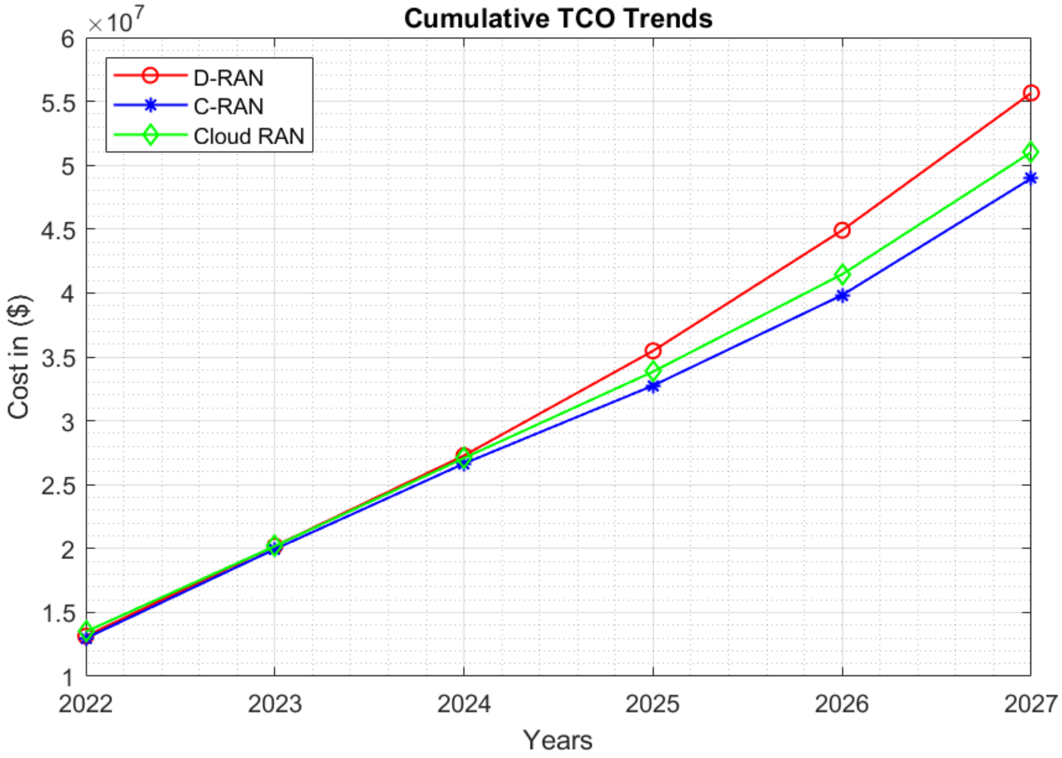


Figure 6.13: Cumulative TCO trends for the architectures over the study period in SC1

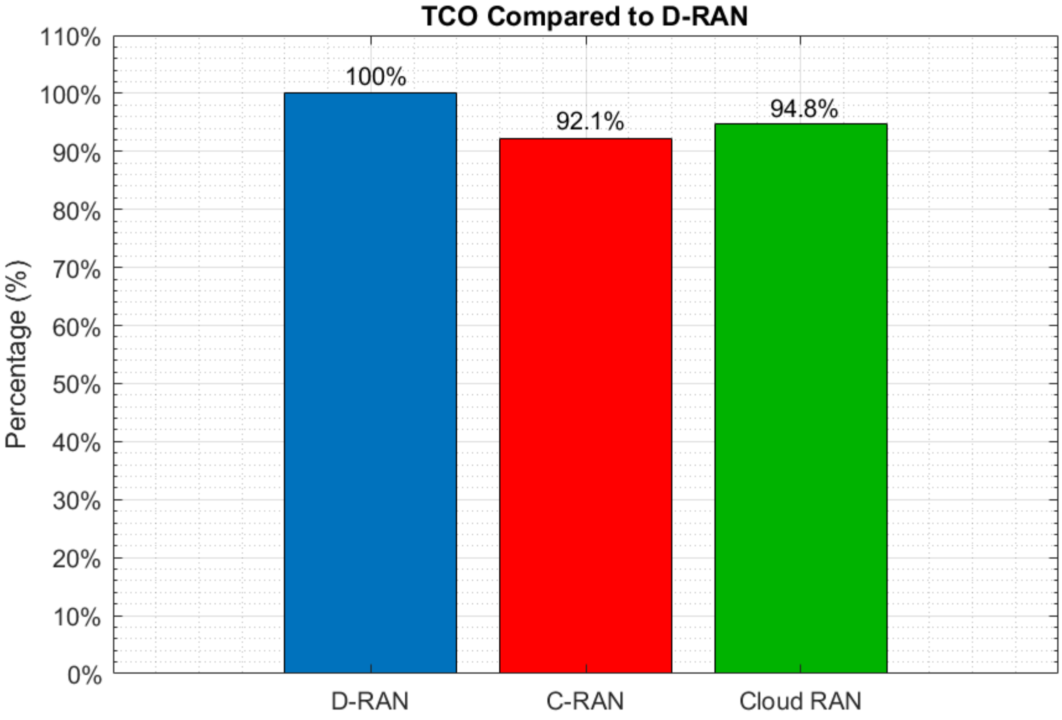


Figure 6.14: TCO change comparison SC1

4. Techno-economic Evaluation

The techno-economic analysis is used to evaluate the economic feasibility of each architecture. The techno-economic analysis is based on the result obtained from the technical and cost model and defined discount rate (10%) to provide economic metrics such as NPV, IRR, and payback period. The method used is the cash flow (CF) and cumulative cash flow (CCF) analysis and is discussed below. Figure 6.15 shows the cash flow analysis for D-RAN, C-RAN, & Cloud RAN respectively.

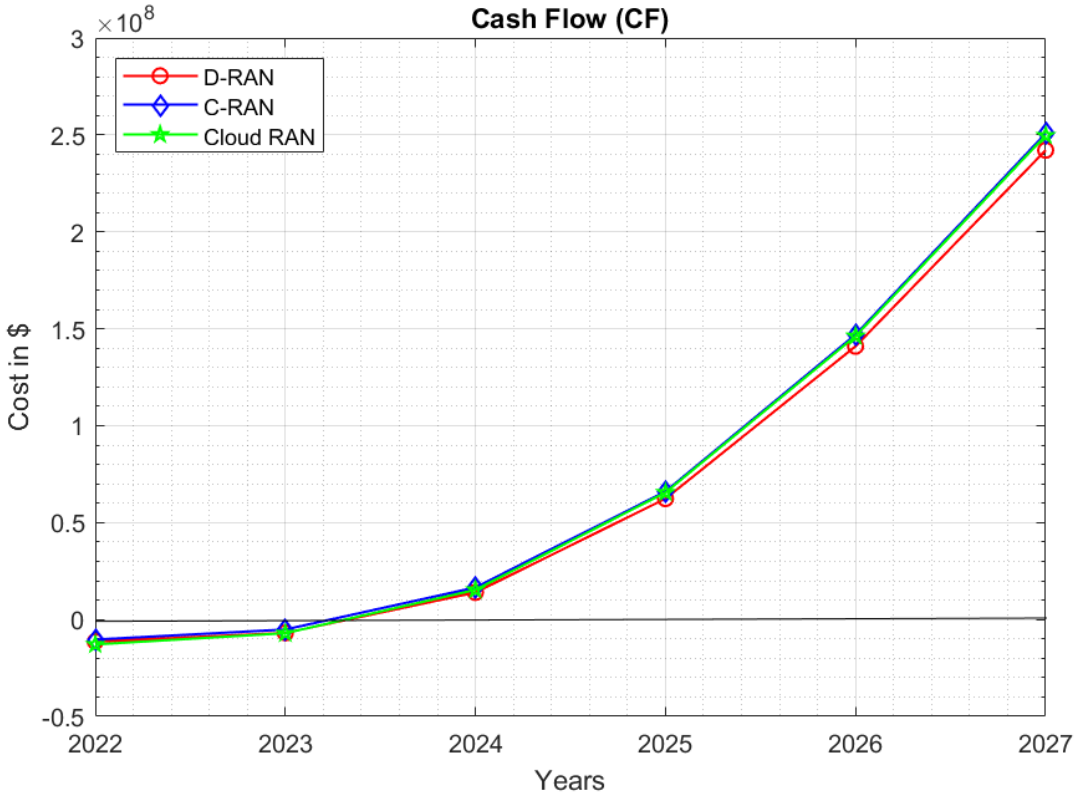


Figure 6.15: Cash flow analysis of Scenario 1 for all architectures

In Figure 6.15, Scenario 1 cash flow analysis for D-RAN, C-RAN, & Cloud RAN is shown using the CAPEX, OPEX & revenue obtained from previous sections for low traffic scenarios. Similarly, the result of the cumulative cash flow (CCF) trends within the study period for each architecture is shown in Figure 6.16 to illustrate their relative standing. After the 3rd year, the CCF approaches zero and increases exponentially for the rest of the study period.

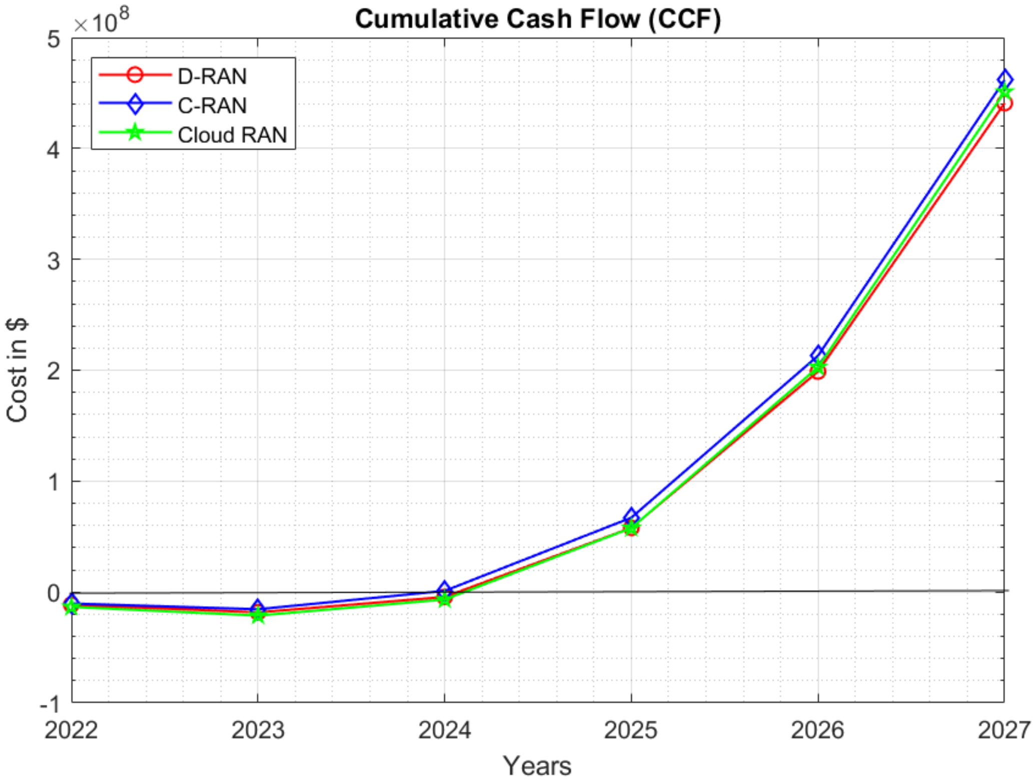


Figure 6.16: Cumulative cash flow analysis of SC1

5. NPV, IRR, & PP

The other economic metrics used to evaluate the economic feasibility of investment are NPV, IRR, & PP. Figure 6.17 shows the result of the NPV analysis for all the architectures based on the yearly cost evaluation considering the 10% discount rate and revenue projection. The NPV value was negative until the 3^{rd} year of deployment for all the architectures, whereas after the 3^{rd} year all the architectures show positive NPV value with \$237.56, \$253.01, and \$251.43 for D-RAN, C-RAN, and Cloud RAN respectively. Hence, all architecture can be considered economically viable. The C-RAN deployment has the lowest TCO among all the architectures also NPV analysis shows that C-RAN deployment has the highest profitability in low traffic scenarios.

The other economic metric used is the internal rate of return (IRR). IRR is a discount rate that is used for project analysis or capital budgeting which makes the net present value (NPV) of future cash flows equal to zero. Investments with higher IRR and NPV values are assumed to be better investments. If two systems have equal ROI periods, IRR and then NPV will be used for comparison. In Figure 6.18, the IRR value obtained for all architectures is greater than 10% (assumed discount rate) i.e., 68.2%, 72.5%, and 69.5% for D-RAN, C-RAN, and Cloud RAN respectively. Thus, all architectures would be financially viable in the future. C-RAN achieved higher IRR value than the other architectures.

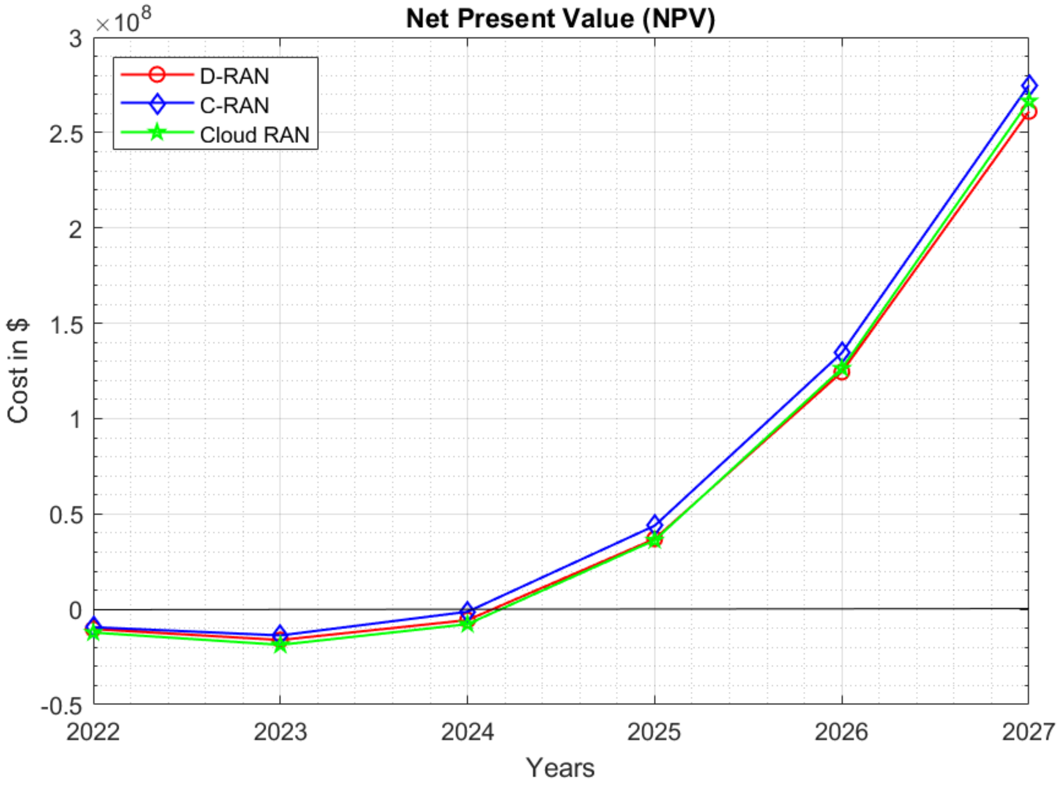


Figure 6.17: Net present value (NPV) SC 1

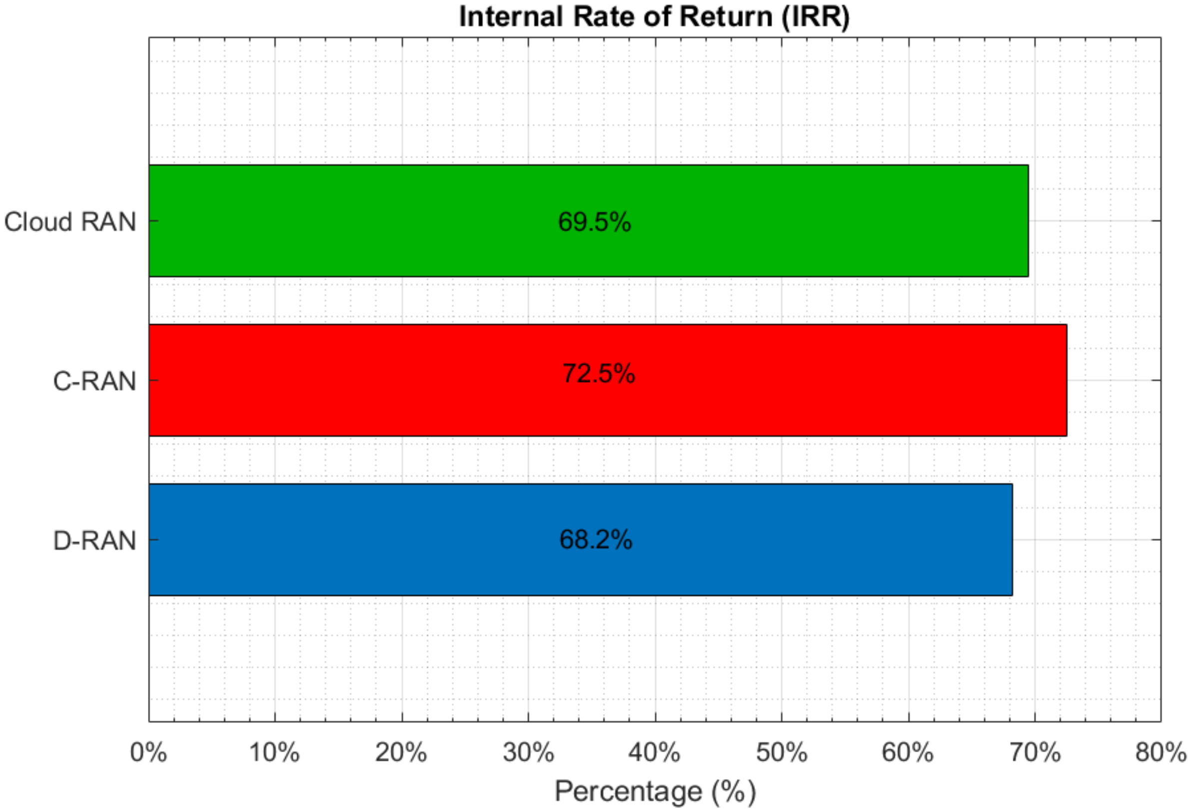


Figure 6.18: Internal rate of return (IRR) SC1

The payback period is the time in which the cumulative incomes are equal to the initial investments. It is one of the ways to rate the effectiveness of investment and evaluate how quickly the system and equipment purchased return their investment. As shown in Figure 6.19, the payback period obtained for D-RAN, C-RAN, and Cloud RAN are 3.14, 2.94, and 3.04 respectively. This means, C-RAN achieved the lowest return on investment period, which is 2.94 years.

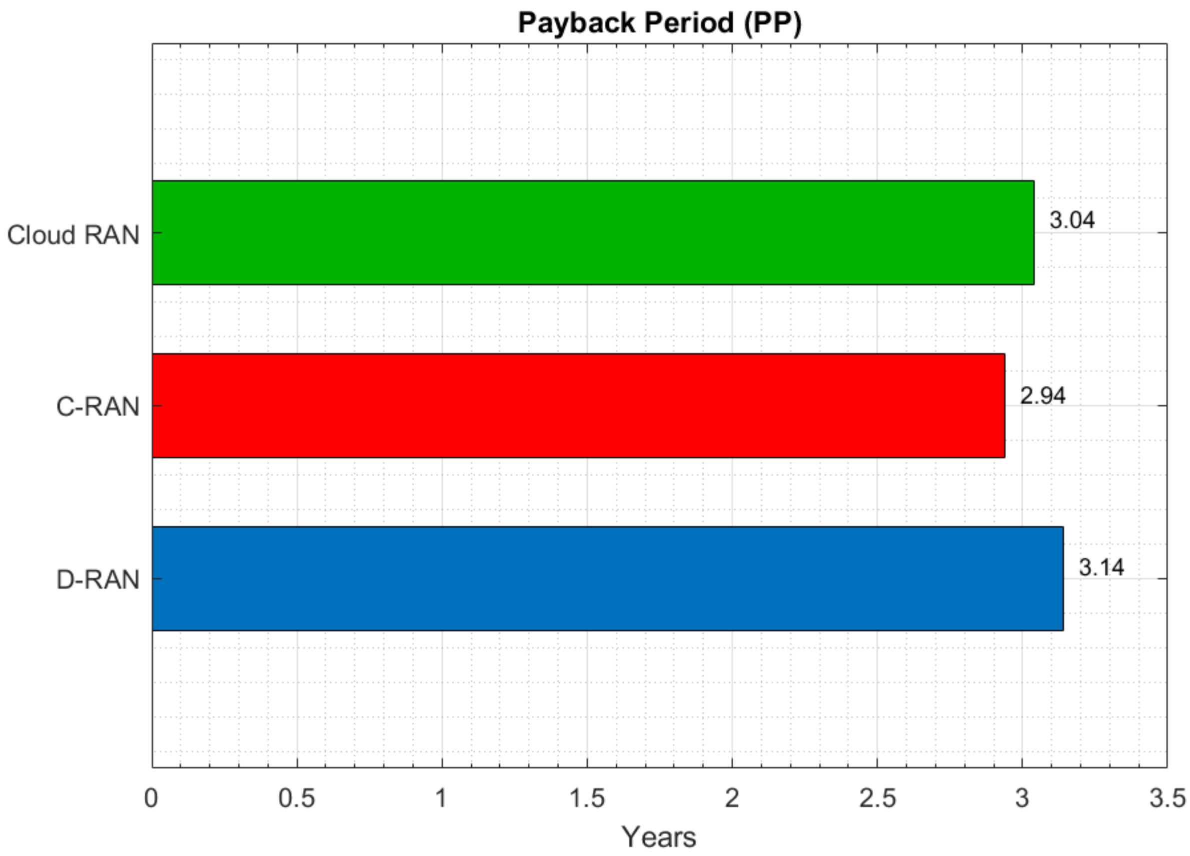


Figure 6.19: Payback period (PP) SC1

When ROI is a key factor to the operator, the scenario with the shortest payback period will be selected. However, if ROI is not a key factor and the decision is to choose long-term cost savings, the scenario with a greater IRR or NPV will be preferable.

Table 6.4 summarizes all the economic indicators used for decision-making. The findings in the summary table show that, positive NPV values, higher IRR values than the defined discount rate (10%), and payback period for all architectures. The result indicates that C-RAN attained better value with all economic indicators and it is economically viable within the study period for scenario 1.

Table 6.4: Summary of TEA for SC 1

Architectures	NPV ($Mil)	IRR (%)	Payback Period (Years)
D-RAN	**$237.56**	**68.2%**	**3.14**
C-RAN	**$253.01**	**72.5%**	**2.94**
Cloud RAN	**$251.43**	**69.5%**	**3.04**

6.4.2 Small Scale Deployment with High Traffic Growth

In scenario 2 with high control plane traffic growth, 50% of the Compound annual growth rate (CAGR) is assumed between the years 2022 to 2027. The cost position of each RAN architecture is described below.

1. CAPEX

The required baseband processing hardware for each architecture is shown in Figure 6.20. As it can be seen in the high traffic scenario, Cloud RAN architecture allows for better scaling of the required baseband processing hardware. Comparing the BBM units needed in the architectures, D-RAN requires more baseband processing hardware due to the baseband resources are assigned statically to cell sites whereas C-RAN reduces slightly the required BBMs. Cloud RAN better utilizes the required BBMs due to the pooling gain obtained from centralizing and virtualizing the baseband units. Based on a comparison between the respective distributed architectures and the Cloud-based RAN architecture, the Cloud RAN reveals a significant improvement in scaling of cloud servers than the vendor-locked BBMs under high traffic growth scenarios. Cloud RAN reduces the amount of BB processing hardware needed by 40-50% when compared to D-RAN architecture due to the multiplexing gain implemented in network dimensioning as well as the highly increasing traffic growth permits Cloud RAN to better scale the baseband processing hardware required.

In a high traffic scenario, the yearly CAPEX cost for each architecture is depicted in Figure 6.21. The initial investment for the Cloud RAN is high as compared to the other architectures due to the expensive cloud servers deployment required in the first year. As shown, the investment cost decreases over the study period for all architectures as this trend is expected due to the deployment cost of new technology is high at the beginning and decrease over the study period.

The CAPEX cost contribution of each architecture is shown in Figure 6.22. In the high traffic scenario, Cloud RAN attains the lowest CAPEX as compared to D-RAN with a 14.5% lower cost. C-RAN attains 1.9% lower CAPEX costs than D-RAN. CAPEX savings come mainly from

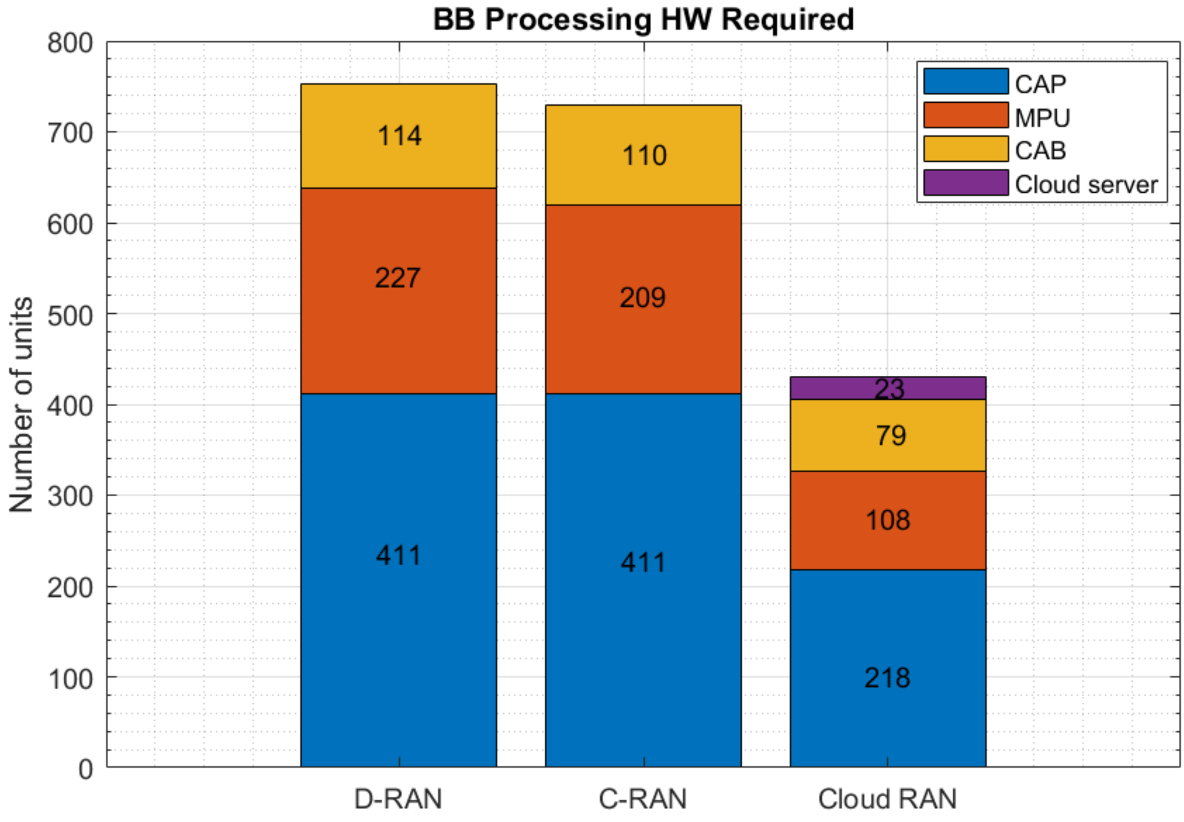


Figure 6.20: Required BB processing HW SC2

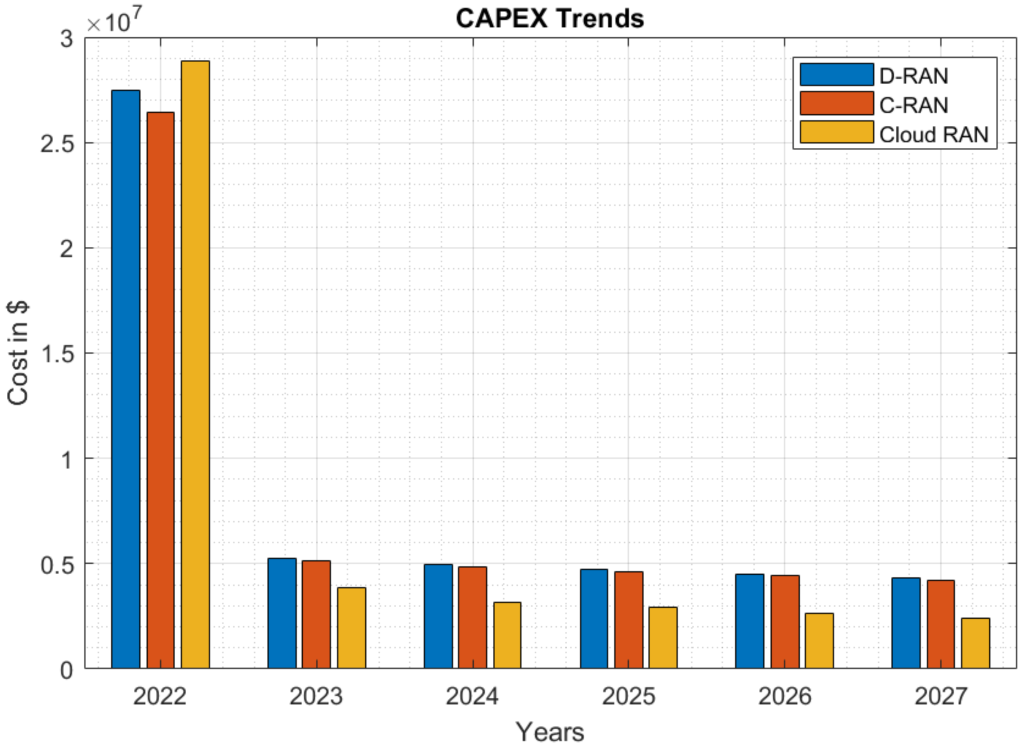


Figure 6.21: CAPEX Trends SC2

cloud servers better hardware scaling and a reduction in equipment required for the vBBU. Virtualizing the baseband processing functions into the cloud makes it possible to use non-proprietary hardware and BBU pooling. In addition to increasing vBBU's efficiency, the BBU pool requires less baseband processing capacity and thus less hardware required. Therefore, enhancing the network capacity is significantly cost-effective with cloud hardware than the proprietary BBUs since the BBU savings compensate for the costs incurred by additional cloud servers and software in high traffic scenario. Besides lowering CAPEX costs, reducing equipment required can also result in shorter deployment times and greater flexibility in equipment placement.

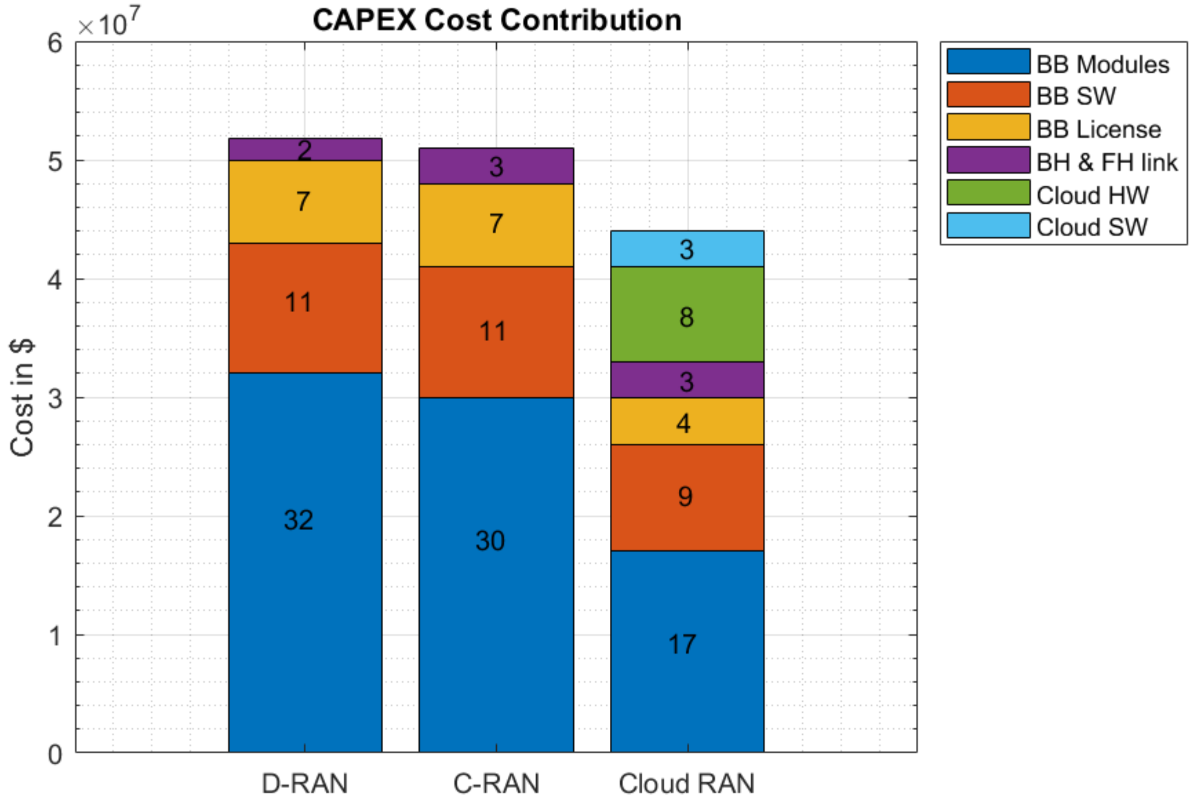


Figure 6.22: CAPEX Cost contribution SC2

2. OPEX

The OPEX cost trend is shown in Figure 6.23 for all architectures. As it can be seen, OPEX costs are an ongoing cost and it increases as time goes on due to the increase in the network capacity, new equipment is required to be installed each year to handle the growing traffic demand. The operational cost of the distributed architecture is higher than that of centralized architectures. Cloud RAN attains the lowest OPEX costs throughout the study periods as it reduces the baseband upgrade cost and hence reduces site visit costs significantly in the high traffic scenario.

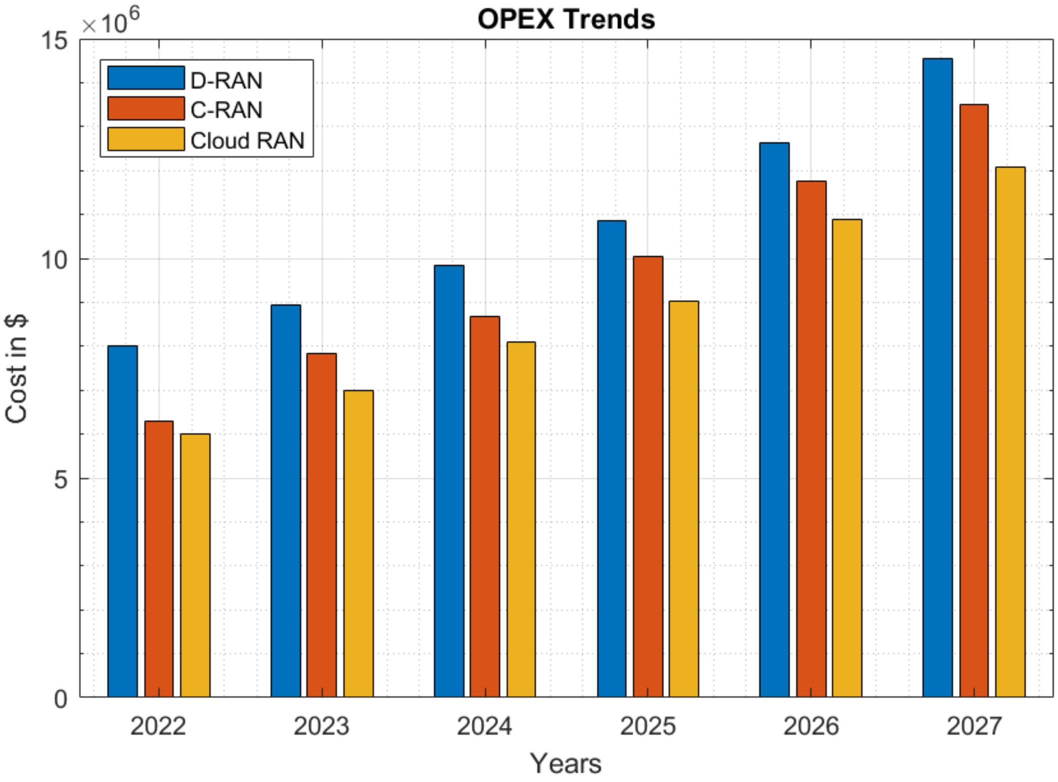


Figure 6.23: OPEX Trends SC2

The OPEX cost contribution of each architecture is shown in Figure 6.24. In a high traffic scenario, Cloud RAN attained better OPEX savings. Cloud RAN achieved the lowest OPEX cost than D-RAN with 21.1% lower costs and C-RAN achieved lower OPEX than D-RAN with 12.4% lower costs. The savings in operational costs of Cloud RAN are mostly attributable to the reduction of maintenance, site rent, energy, and operation costs associated with centralized locations, which are less expensive to operate. Centralizing and virtualization of the baseband units into the cloud significantly reduces the baseband capacity upgrade, energy, and site rent costs due to a reduction in equipment and fewer site visits needed. In most areas, Cloud RAN was able to reduce costs, with the exception of the higher software maintenance costs associated with Cloud RAN due to its more expensive software. Based on the analysis of the cumulative energy consumption of the baseband processing hardware for the different RAN architectures, Cloud RAN has less CO_2 emission as opposed to the traditional RAN, making it the most environmentally friendly and green architecture. It successfully reduced energy consumption by 35% over D-RAN.

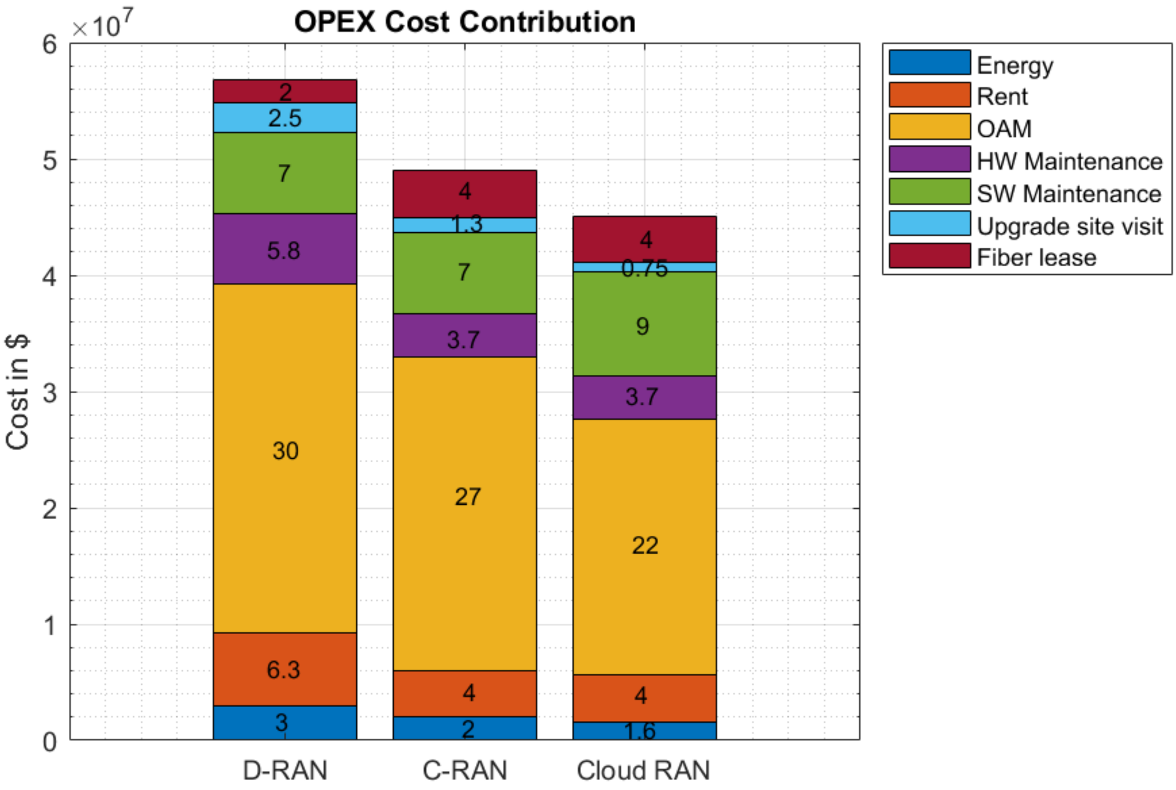


Figure 6.24: OPEX Cost contribution SC2

3. Total Cost of Ownership (TCO)

Figure 6.25 shows the Cumulative TCO trends over the study period for each architecture for high traffic growth scenario. The TCO trend indicates that the cost did not differ significantly until year three between the architectures. When the connected user per cell site grows rapidly, the cost of the distributed architecture rises faster than the Cloud RAN architecture. This makes the Cloud RAN architecture the most economically viable architecture when compared to the distributed architecture.

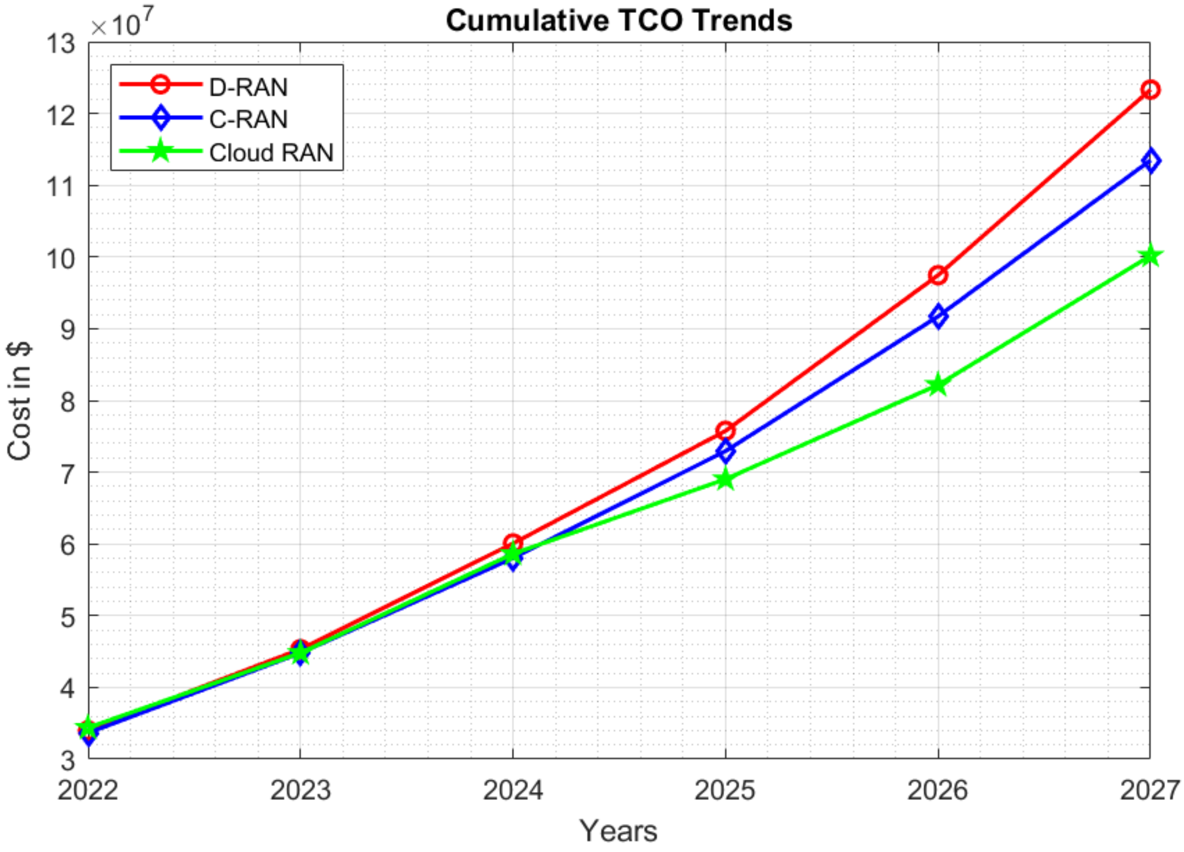


Figure 6.25: Cumulative TCO trends for the architectures over the study period in SC2

For the high traffic growth scenario, the TCO cost saving that can be achieved in the architectures compared to the distributed architecture is shown in Figure 6.26. Cloud RAN proved to be the most cost-effective architecture in terms of TCO in high traffic scenarios. Cloud RAN attains the lowest TCO than D-RAN with 16.2% lower TCO. C-RAN also attain lower total cost than D-RAN with 5.8% lower TCO.

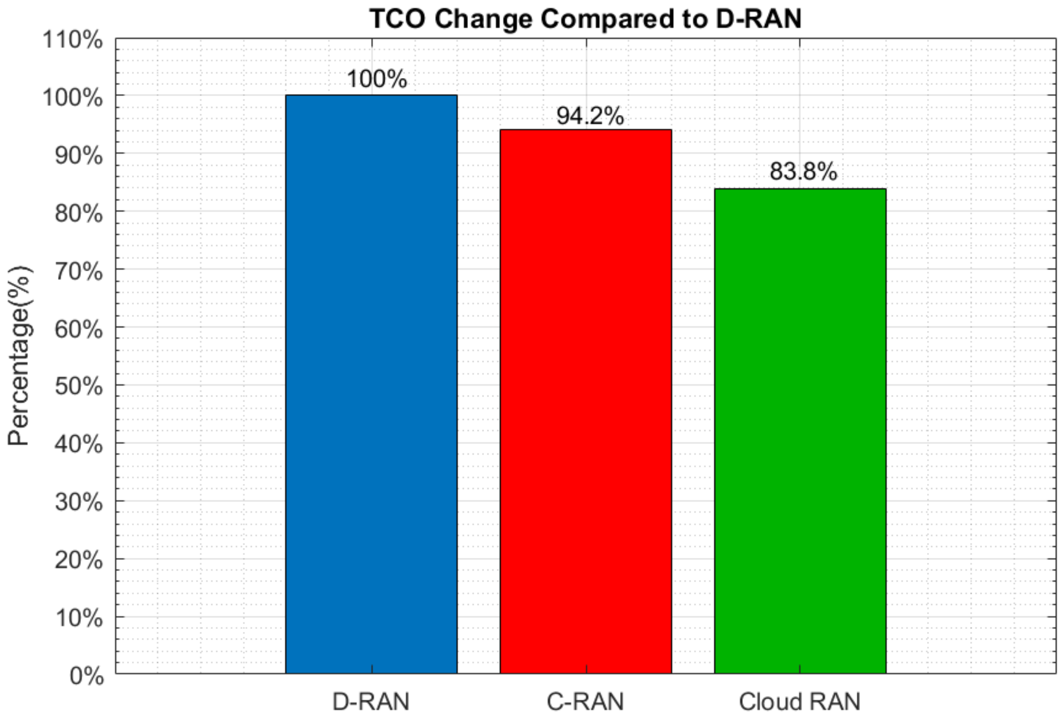


Figure 6.26: TCO Compared to D-RAN SC2

4. Techno-economic Evaluation

In Figure 6.27, the cash flow analysis for D-RAN, C-RAN, & Cloud RAN is shown using the CAPEX, OPEX & revenue obtained from previous sections for high traffic scenarios. Likewise, the result of the cumulative cash flow (CCF) trends within the study period for each architecture is shown in Figure 6.28 to illustrate their relative standing. After 3.5 years, the CCF approaches zero and increases exponentially for the rest of the study period.

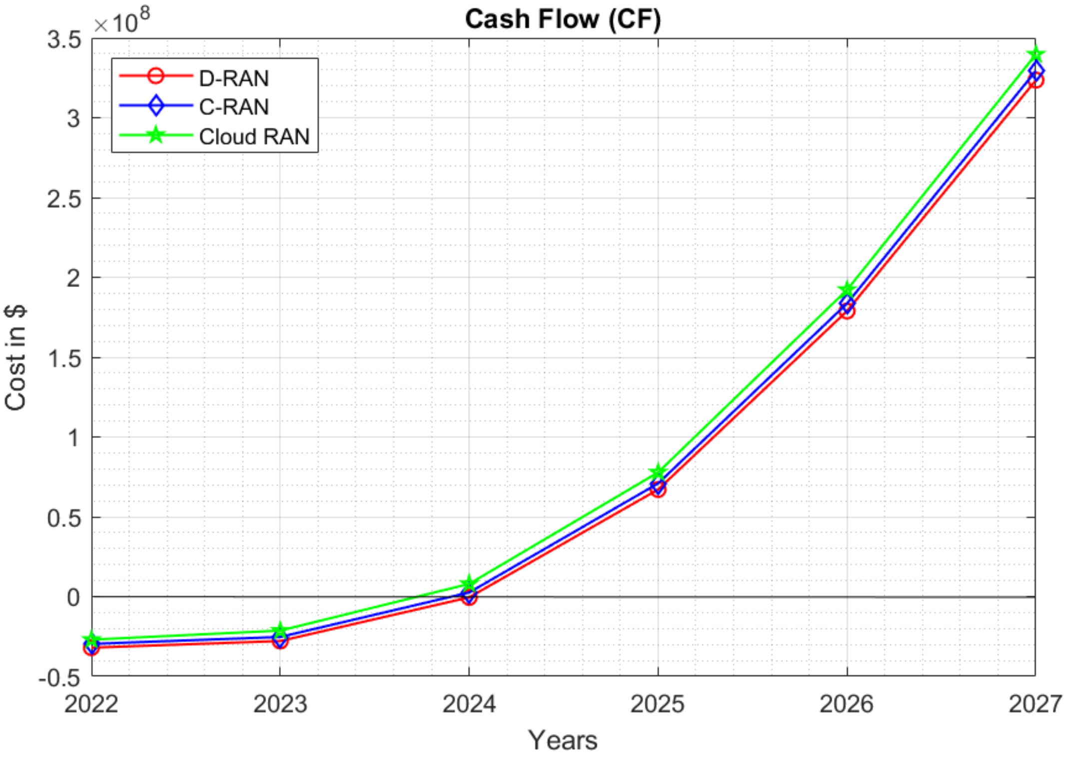


Figure 6.27: Cash flow analysis of SC2

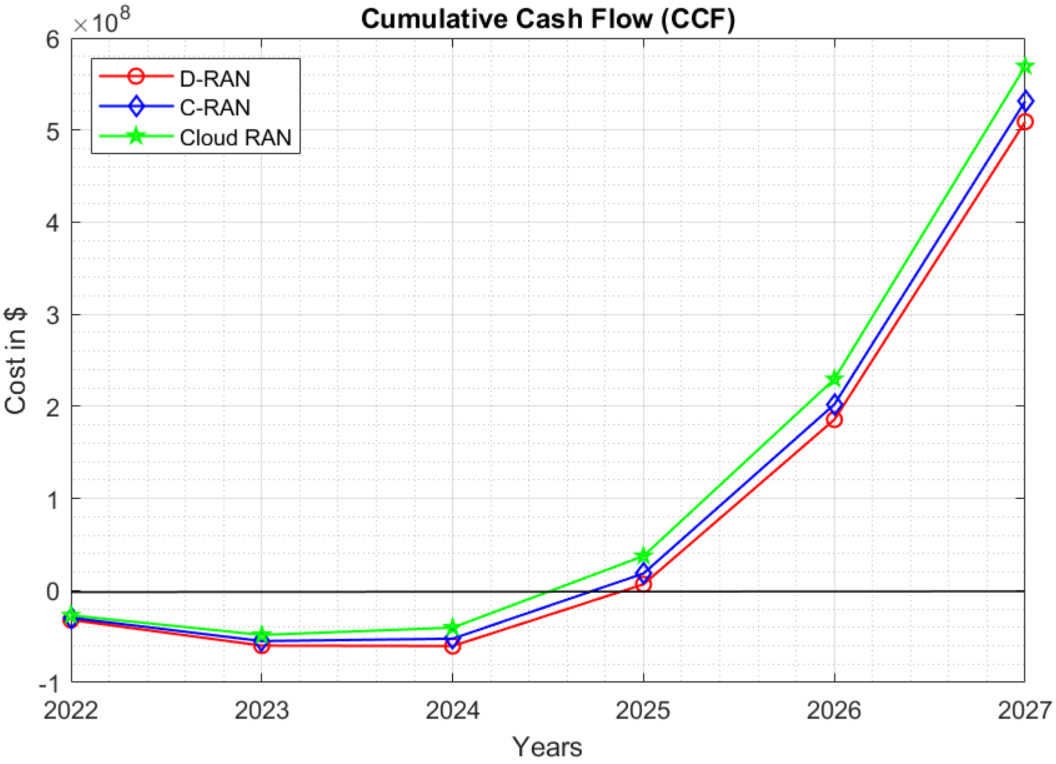


Figure 6.28: Cumulative Cash Flow analysis of SC2

5. NPV, IRR, & PP

Figure 6.29 shows the result of the NPV analysis for all the architectures based on the yearly cost evaluation considering the 10% discount rate and revenue projection. The NPV value was negative until year 3.5 of deployment for Cloud RAN and around 4 years for the other architectures, whereas after year 4 all the architectures show positive NPV values with $234.80, $251.09, and $285.78 for D-RAN, C-RAN, and Cloud RAN respectively. The recorded greater than zero or positive NPV values shows that each architectures are economically feasible within the study period. The Cloud RAN deployment has the lowest TCO among all the architectures and higher positive NPV value showing that Cloud RAN deployment has the highest profitability in high traffic scenarios. This is because of the cost-saving attained due to better scalability in cloud hardware and improved performance in Cloud RAN.

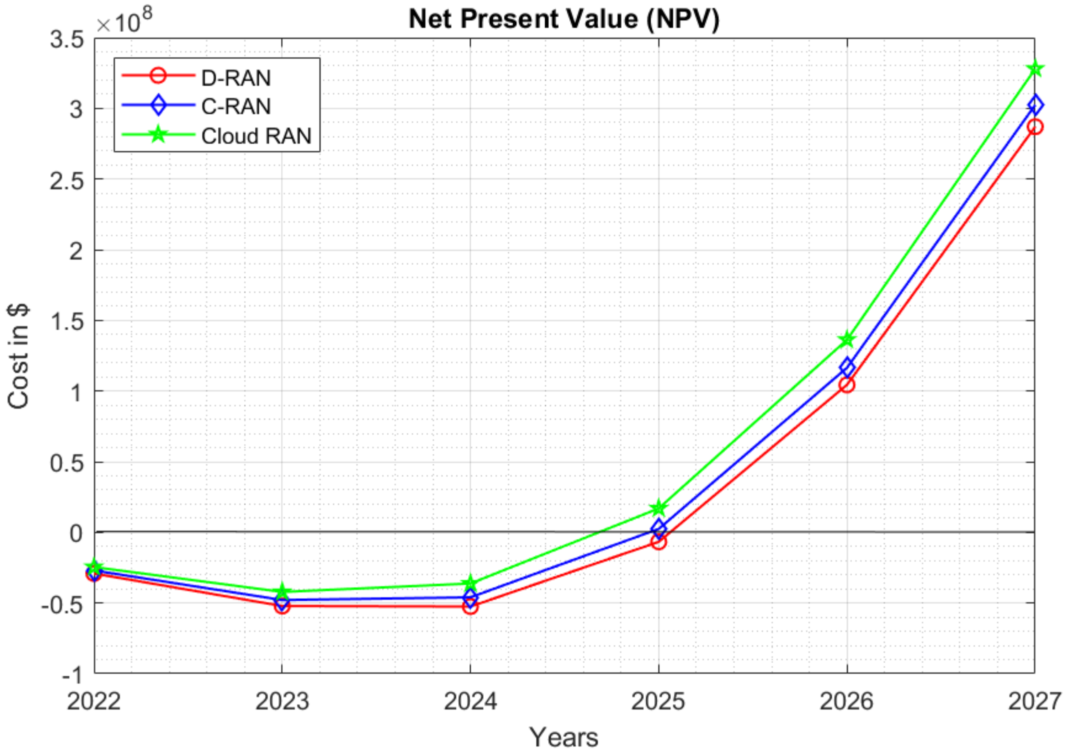


Figure 6.29: NPV SC2

The other economic metric used is the internal rate of return (IRR). Figure 6.30 shows that the result of the IRR value obtained for all architectures is greater than 10% i.e., 41.5%, 44%, and 50.4% for D-RAN, C-RAN, and Cloud RAN respectively. As a result, all architectures would be financially viable. Projects/investments with higher IRR values are assumed to be better investments. Hence, Cloud RAN achieved higher IRR value than the other architectures and become attractive investment.

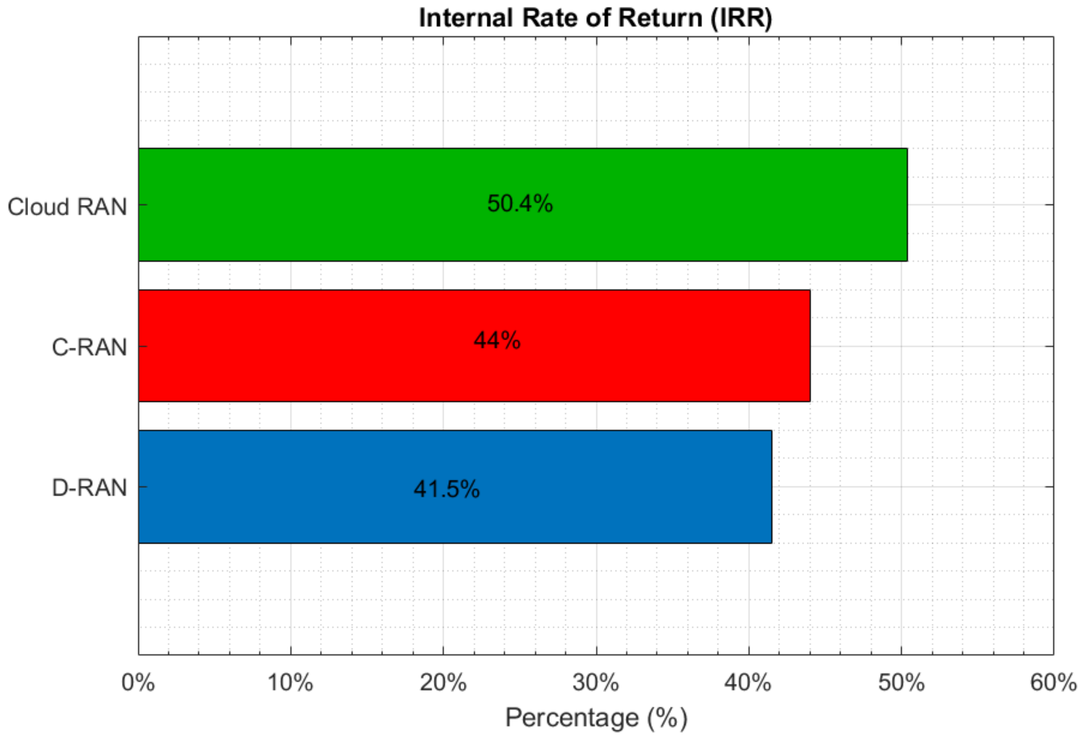


Figure 6.30: IRR SC2

As shown in Figure 6.31, the payback period obtained for D-RAN, C-RAN, and Cloud RAN are 4.16, 3.95, and 3.5 respectively. This means, Cloud RAN achieved the lowest return on investment period, which is 3.5 years.

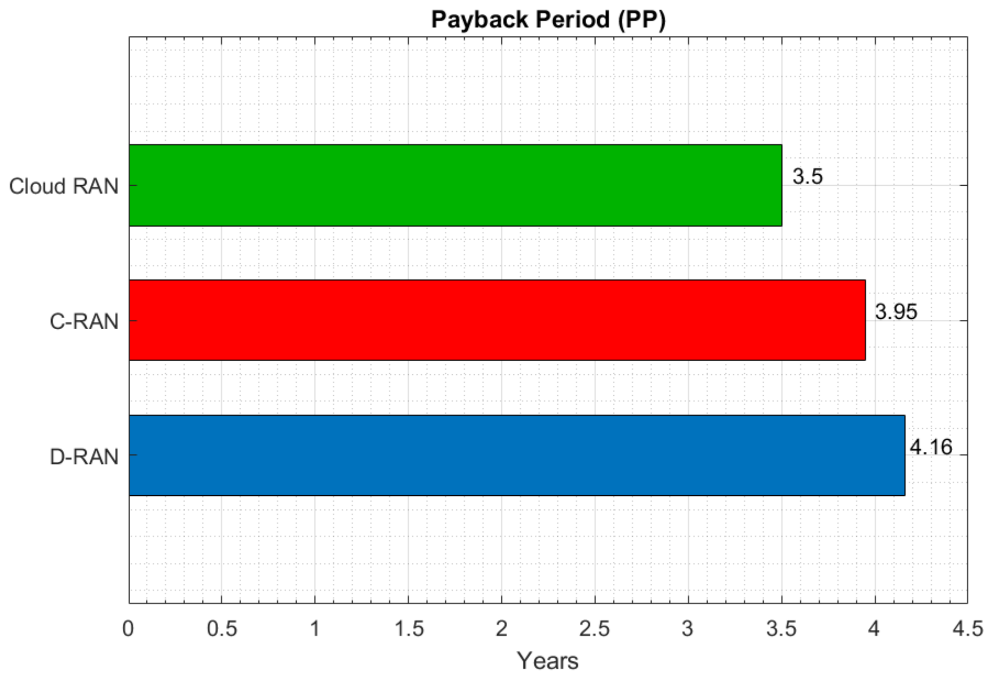


Figure 6.31: PP SC2

Table 6.5: Summary of TEA for SC 2

Architectures	NPV ($)	IRR (%)	Payback Period (Years)
D-RAN	$234.80	41.5%	4.16
C-RAN	$251.09	44.0%	3.95
Cloud RAN	$285.78	50.4%	3.50

Table 6.5 summarizes all the economic indicators used for decision-making. Based on the results in the table, positive NPV values, higher IRR values than the defined discount rate (10%), and payback period for all architectures are depicted. When comparing comparable projects with payback periods, those with larger cash inflows in the earlier periods generally ranked higher. In addition, several studies suggest that investments with a payback time of between 3 and 4 years ($\leq$ 3.5 years) over a period of six years are profitable and feasible. Therefore, Cloud RAN attained better value with all economic indicators and it is economically viable within the study period. This shows that the time required to return the investment for Cloud RAN deployment for high traffic growth scenario in Addis Ababa is 3.5 years.

Conclusion and Future Works

7.1 Conclusion

The explosion in mobile data traffic coupled with continuous demands for higher data rates, and low-latency connectivity are putting strain on network capacity, while also requiring the development of cost-efficient and energy-efficient solutions. This necessitates a deep rethink and revolution on mobile network design, and more specifically on the RAN architecture. In light of its superior performance and lower cost, Cloud RAN is a fundamental component of next-generation mobile networks (such as 5G). Cloud RAN mobile networks implement the concept of NFV to follow the IT trend toward cloud computing, virtualization, and automation.

However, selecting a Cloud RAN deployment use case is challenging for the mobile operator due to the many aspects that have to be considered. Technologies differ in complexity, features, performance, and cost, so choosing the right option requires a strategic decision. Meanwhile, ethio telecom tends to deploy mobile network infrastructures vendor-oriented without performing fully localized techno-economic assessments. These will lead to observed systems performance problems such as under-utilization and wastage of resources, poor network performance, and poor quality of service while the network is in operation. Techno-economic analyses are therefore very important for determining the feasibility of Cloud RAN deployment scenarios from a technical and economic level.

In this thesis, a comprehensive review of Cloud RAN is performed based on standards, reports, expert opinions, and stat-of-the-art literature and developed potential Cloud RAN deployment options for Addis Ababa city through scenario planning methods. Out of the formulated four scenarios, two scenarios are selected for further investigation based on the extrema values. Network dimensioning was performed for a 6-year study period based on the developed Cloud RAN deployment scenarios.

The CAPEX, OPEX, TCO, and revenue for each deployment scenario has been modeled, and the economic feasibility of each deployment scenario has been evaluated using economic decision-making metrics such as NPV, IRR, and PP using a 10 % discount rate. The techno-economic model was implemented on MS Excel and Matlab based on the modified TERA model in order to comprise the input parameters used.

The following conclusions are drawn from the result:

1. The benefits of centralized deployment of baseband processing hardware over the distributed proprietary-based BBUs, encouraged operators to migrate to Cloud RAN due to it simplifies site acquisition, reduces the costs associated with site rentals, scales resources easily, utilizes resources more effectively, and consumes less energy than the traditional RAN. Cloud RAN can provide a treasured value to operators by combining the processing resources of multiple base stations onto a cloud server or a data center and is considered a key enabler of 5G mobile networks. Hence, ethio telecom will be recommended to deploy Cloud RAN in its future deployments.

2. The result of SC 1 in terms of baseband processing hardware requirement shows that D-RAN requires more baseband processing hardware while C-RAN has a slightly reduced amount. Cloud RAN better utilizes the baseband processing hardware due to the pooling gain obtained from centralization. However, in a low control plane traffic growth scenario, Cloud RAN cannot benefit from cloud hardware better scaling for the control plane traffic.

3. Regarding the CAPEX and OPEX results in SC 1, C-RAN architecture attains a better cost position than the Cloud RAN architecture. In comparison with the D-RAN architecture, Cloud RAN incurs more CAPEX. In terms of OPEX, C-RAN attains the lowest costs, and Cloud RAN attains lower costs than their rival D-RAN. Therefore, Cloud RAN is not the most advantageous option from a cost perspective, given the low predicted traffic growth.

4. The result from the TCO model in the study period in SC 1 shows that C-RAN attains lower TCO and becomes cost-efficient than the other architectures. Cloud RAN architecture did not succeed in attaining better TCO in a low traffic growth scenario than the C-RAN architectures.

5. SC 1 cash flow analysis result shows that the payback period of D-RAN, C-RAN, and Cloud RAN are 3.14, 2.94, and 3.04 years respectively. The C-RAN arrives at ROI period earlier than the others. The difference with Cloud RAN is 1.2 months. In cases where ROI is important, operators should select the scenario with the shortest payback period.

6. From net present value results, it can be seen that all scenarios have internal rates of return that are higher than the defined discount rate (10%), showing that all architectures are feasible within the study period. For the D-RAN, C-RAN, and Cloud RAN, their respective IRR values are 68.2%, 72.5%, and 69.5%. As can be seen from the results, C-RAN is ranked first, D-RAN is ranked last and Cloud RAN is ranked second.

7. The six years study period in SC1 shows that all architectures have positive NPV figures, which indicates all deployments are feasible with the study period. All the architectures had negative NPV values until the third year of deployment, however after the third year the NPV values are all positive with \$237.56, \$253.01, and \$251.43 for D-RAN, C-RAN, and Cloud RAN respectively. The C-RAN architecture offers a superior NPV value to others, D-RAN architecture is the least effective, and Cloud RAN is ranked at the second level. In cases where the operator does not place high importance on ROI and is more interested in long-term profitability, it can select the solution with the highest IRR or NPV.

8. Based on results for SC 2, the Cloud RAN solution proved to be the most cost-effective architecture in high traffic growth scenario. Due to the enhanced scaling of cloud hardware in Cloud RAN architecture, the CAPEX and OPEX costs were reduced significantly over the distributed architectures with 14.5% and 21.1% cost savings respectively for high traffic growth. In addition, Cloud RAN has shown the ability to deliver greener RAN architecture (i.e., consumes less energy and decreases CO_2 emissions), due to its improved hardware utilization level.

9. The result from the TCO model in the study period in SC 2 shows that Cloud RAN proved to be the most cost-effective architecture in terms of TCO in high traffic scenarios than the other architectures. Cloud RAN achieved the lowest TCO than D-RAN with 16.2% lower TCO.

10. Results of SC 2 cash flow analysis show that the payback period of D-RAN, C-RAN, and Cloud RAN are 4.16, 3.95, and 3.5 years respectively. The Cloud RAN architecture arrives at ROI period earlier than other architectures.

11. SC 2 NPV result demonstrates that Cloud RAN achieved the highest positive NPV value showing that the most economical RAN architecture in a high traffic growth scenario with \$234.80, \$251.09, and \$285.78 values for D-RAN, C-RAN, and Cloud RAN respectively. Similarly, the IRR value of Cloud RAN is also higher than the other architectures with 41.5%, and 44%, and 50.4% values for D-RAN, C-RAN, and Cloud RAN respectively.

12. In a scenario where the traffic growth is expected to grow rapidly, moving to Cloud RAN architecture is cost-efficient, as shown by the result of the TEA model.

In summary, cell configuration and traffic growth expectation largely affected the result of the TEA analysis. Based on these parameters, the amount of baseband processing hardware necessary in a network can be dictated. In cases where the control plane traffic becomes the prevailing parameter for network dimensioning, Cloud RAN architecture leverages better hardware scaling. The most significant change in the output of the analysis comes as a result of varying these parameters. Therefore, for high traffic growth forecast, Cloud RAN architecture becomes the most cost-efficient architecture.

7.2 Future Work

This thesis significantly investigates the Cloud RAN deployment scenarios for Addis Ababa, Ethiopia from a techno-economic perspective under different scenarios that can help to understand Cloud RAN's possible benefits. The techno-economic analysis mainly emphasizes on the costs and economic values of the different RAN architectures. Some suggestions for future research are provided based on the results of this thesis and the experience gained while performing it.

1. The techno-economic analysis implemented in this thesis considers the NRT-RT split of RAN functionalities. Cloud RAN's cost-benefit ratio is significantly affected by the level of centralization and virtualization of baseband functions. In order to fully exploit the potential of the Cloud RAN architecture, considering fully centralized Cloud RAN is imperative. The deployment of fully centralized Cloud RAN will allow for higher resource utilization and lead to great CAPEX and OPEX savings.
2. The implemented techno-economic evaluation of the Cloud RAN approach in this study was limited to the LTE network based on the formulated deployment scenarios. It can be further investigated for next-generation mobile networks such as 5G mobile, which requires detailed consideration of various parameters.
3. Additionally, QoS and QoE parameters, as well as potential revenue streams from Cloud RAN deployments such as resource leasing, are not considered. Hence, studying how these factors influence the costs, as well as the potential revenue streams that might emerge, could be part of future research areas into Cloud RAN.
4. The BBU pool placement optimization to find the optimal number and location of BBU pools, and aggregators, such that all the RRUs are connected to a pool and the TCO of the

network can be minimized. Hence, the optimization of the BBU pool placement should be considered in architectural design and cost analysis.

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Appendices

Techno-Economic Analysis of Cloud RAN Deployment Scenarios: in the Context of Ethio Telecom

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***Abstract*—The explosive mobile traffic growth, as well as rapid deployment of innovative wireless technologies and services, have all put significant strain on network capacity in the radio access network (RAN). Mobile network operators (MNOs) are considering Cloud-based RAN (C-RAN) deployment to address this capacity challenge while improving cost, energy usage, deployment flexibility and network management. Efficient deployment of C-RAN requires selecting suitable deployment scenarios and a thorough understanding of both its technical and economic aspects in the context of the RAN service area. Such techno-economic study has not been undertaken in the context of Addis Ababa, Ethiopia and it is required to scientifically understand viable deployment of RAN architecture in Addis Ababa. In this paper, potential C-RAN deployment scenarios are formulated using scenario planning method. For selected scenarios in the context of Addis Ababa, a thorough techno-economic analysis is performed applying a modified TERA framework by assuming 6 years study period and a 10% discount rate. The achieved result shows that C-RAN cost benefits are dependent on traffic growth expectations. In the high traffic growth forecast, C-RAN achieved significant cost benefits as shown with all economic metrics.**

***Index Terms*—LTE, 5G, RAN, Cloud RAN, Virtualization, TERA Model, Cost Modeling, Techno-Economic Analysis**

I. INTRODUCTION

A. Motivation

Mobile data traffic has been growing exponentially due to the proliferation of mobile devices and services. Several sources reveal that mobile data traffic continues to grow explosively owing to the released new kinds of mobile services such as ultra-high definition (UHD) video, self-driving cars, wearable devices, virtual reality (VR), augmented reality (AR) and ubiquitous access to high-speed cloud content anytime [1]. A report from Ericsson mobility also shows that the global mobile data traffic will reach 300 EB per month in 2026 from where it was 58 EB per month at the end of 2020 which is a growth by a factor of 5 according to the report [2]. The same report also shows that mobile data traffic will continue to grow in Sub-Saharan Africa with the largest growth rate. Furthermore, mobile data traffic growth in Ethiopia has been notable, especially in the capital Addis Ababa [3], [4]. As the mobile data grows over time, this forecast presents some very real challenges for mobile network operators (MNO) to address the high capacity demand both economically and scalable allowing for future growth.

The part of the mobile network infrastructure that needs modification to handle such growth is the radio access network (RAN). RAN consists of base stations and user equipment that provides wide-area wireless connectivity between end-user and core networks as well as network availability and high data rate to end-users. RAN systems typically have the highest costs since deploying and managing base stations gets really complex and expensive. For instance, MNOs spend 60-80% of CAPEX on RAN equipment [5], [6] to meet the increasing demand for mobile subscriptions and data traffic, and 60% of the total cost of ownership (TCO) on the RAN operation expenses [5]. Furthermore, to meet the increasing data demand with a satisfactory user experience, adding more cells, or the capacity of each cell may need to be increased. However, this results in increased costs as well as energy consumption in which 72% of power consumption comes from cell sites [5]. Therefore, to meet the future requirements of high capacity demand, massive connections and energy efficiency, an advanced wireless network architecture is necessary. Cloud radio access network (C-RAN) is a promising wireless access network paradigm that has the potential to improve spectral efficiency, energy consumption as well as costs based on the cloud computing concept by centralizing and virtualizing the baseband processing into the cloud which can be implemented on the commercial-off-the-shelf (COTS) hardware [7].

Despite the tremendous advantages, an effective deployment of C-RAN requires selecting the most suitable deployment scenarios and having a detailed knowledge of its technical and economic aspects. Yet, there has been no such techno-economic study conducted in Addis Ababa, Ethiopia, which is essential to understand viable deployment of C-RAN architecture in Addis Ababa.

In this paper, potential deployment scenarios are formulated for Addis Ababa based on scenario planning method that is presented in [8]. The techno-economic analysis (TEA) is performed for the selected scenarios by using modified TERA model that is implemented in MS Excel and MATLAB. The TEA is undertaken considering 6 years study period and a 10% discount rate. The TEA result shows that C-RAN economic benefits are highly dependent on traffic growth expectation.

B. Related Works

The centralization of baseband functions into a central location in C-RAN architecture attracted significant attention in academic and industrial communities because of its flexibility, scalability, performance improvement, coordination across cells and costs. Even though C-RAN provides prominent advantages and opportunities, its deployment brings challenges to MNOs. The recent progress of C-RAN centralization and its challenges are presented in [9], [10], [11], [12]. Fully centralizing all the network functions in the baseband unit to a central location requires a throughput of around 160 Gbps (as it is envisioned in 5G) [13]. To achieve this throughput the allowed latency requirements are tight, between 10 to 250 µs [14], [15]. Transmitting in-phase and quadrature signal (IQ) samples between remote radio unit (RRU) and baseband unit (BBU) via the Fronthaul link requires a high bandwidth hence data compression and aggregation techniques should be implemented at BBU and RRU to limit the Fronthaul bandwidth. By splitting the baseband functions for instance integrating the layer 1 functions (Physical layer) with the RRU, can reduce the required Fronthaul transport link by 40% [14]. In order to attain a better advantage from the C-RAN, fully centralizing the baseband function is recommended however due to limited Fronthaul link capacity issue, this might not be possible. Therefore, MNOs should consider these tradeoffs and their use cases while selecting the functional split that reduces the burden on the Fronthaul link as well as meets their requirements.

Multiplexing gain can be achieved when resources are aggregated into a single pool and shared. In C-RAN, centralizing the BBUs into a pool enhance cooperation techniques which in turn increases the multiplexing gain [16]. Various studies investigated the multiplexing gain achieved from aggregating the BBUs into a central pool. The author in [17] evaluated the multiplexing gain achieved for different functional splits in terms of cost and energy efficiency. Their result indicates that for fully centralized C-RAN, significant multiplexing gain can be achieved from baseband resources (thus energy and cost-savings) even though, the required Fronthaul capacity is the highest. Moving part of baseband processing functions from BBU pool to cell sites, the multiplexing gain achieved on the BBU pool decreases. However, multiplexing gain can be achieved on the Fronthaul link when traffic becomes variable bit rate [17]. In [18] investigated the multiplexing gain achieved and showed that by aggregating multiple cells into a single BBU pool a significant gain can be obtained. In [19] the authors compared the multiplexing gain based on the tele traffic approach. Their result indicates that 1.2–1.6 gain can be obtained based on the percentage of 30% / 70% office to residential cell sites ratio. This number can grow to 4 by taking into consideration specific traffic patterns and assuming the number of cell sites serving different areas.

To evaluate the cost position of the C-RAN architecture, a detailed investigation of the cost model is required. The study conducted in [20] examines the cost benefits of different RAN architectures distributed RAN (D-RAN), centralized RAN, Cloud D-RAN, and Cloud C-RAN. The author evaluated each architecture in terms of TCO within a 5-year study period to identify the most cost-efficient RAN architecture. The result reveals that C-RAN cost benefits are highly dependent on the Control-plane traffic growth. For high control-plane traffic growth expectation, Cloud C-RAN achieved better cost benefits and become economically viable solution.

A study conducted in [21] investigated the techno-economic analysis on the integration of SDN/NFV based C-RAN architecture in 5G mobile networks for the case of Sweden. The paper provided a cost model to estimate network costs for the proposed 5G architecture in comparison with the corresponding costs of legacy network architecture. The qualitative analysis performed reveal that the proposed SDN/NFV based C-RAN architecture provides significant cost saving. The considered CAPEX and OPEX costs could be reduced by 68% and 63% respectively compared to the legacy network and the TCO could be reduced by 69% compared to the legacy network. However, the model did not considered the network traffic and does not provide a detailed emphasis on the implemented hardware, and the baseband pooling gain is not considered in the model which has a high impact on the benefits of C-RAN deployment.

In order to formulate a techno-economic analysis of C-RAN, all the network costs should be taken into account. In most studies as in [14], [20], [22], [23] the evaluation metrics implemented is only Total Cost of Ownership. The study in [24] provides a comprehensive techno-economic framework for 5G RAN and transport networks and used TCO and other economic feasibility metrics for comparison. The author argues that TCO alone is not enough in order to show the profitability of different architectures and other economic evaluation metrics such as NPV and cash flow analysis should be taken into consideration. The authors' business feasibility assessment indicates that low TCO does not always lead to high profits because, for long-term projects, the point of time the project is invested in affects significantly the overall profit of the projects. The study in [23] analyzed the migration of LTE/LTE-A networks to C-RAN and proposed an ILP algorithm for the transition with minimal investment using the existing infrastructure. The authors tried to show the economic benefit of employing the existing legacy network infrastructures during migration to C-RAN. The authors found that significant savings could be acquired by using the existing network infrastructure during migration to C-RAN. The study in [14] investigated the cost-effective migration of D-RAN architecture to C-RAN using time and wavelength division multiplexing (TWDM) based Fronthaul with functional splitting features. The authors formulated an ILP based optimization method to reduce the TCO of C-RAN with fully centralized and partially centralized network functions. Their result shows that partially centralizing the network functions bring about better TCO than the fully centralized C-RAN with a lower return period for the investment.

Most of the studies conducted so far mostly emphasized on deploying wireless networks for next-generation mobile networks based on C-RAN architecture from the scratch relying on the traffic demand of a specific network. Even though the studies bring better insight into the deployment of C-RAN, how MNOs possessing existing network infrastructure (e.g., LTE/LTE-A networks, transport network, site location, etc.) can easily migrate to C-RAN architecture without losing those infrastructures resources with minimum TCO is not widely addressed as required. MNOs can reuse the existing network infrastructure for the deployment of C-RAN so that they can save a significant amount of costs.

From the mentioned literature, it is inevitable to evaluate new technology viability from a technical and economic perspective. Most of the literature reviewed, used TCO to analyze the cost position of C-RAN and assessed the cost-saving obtained. However, to evaluate the economic feasibility of complex technical systems, in addition to TCO, economic decision making metrics such as net present value (NPV), internal rate of return (IRR) and payback period (PP) should be evaluated and it is the main task of this study. Moreover, this paper presents a detailed techno-economic evaluation of the C-RAN to illustrate the differences in the costs of the different architectures based on the developed scenarios.

The remainder of this paper is structured as follow. Section 2 provides background to C-RAN, the evolution of base station architecture in the cellular network, explain C-RAN fundamentals, the main components in the architecture, and its advantages. The implemented C-RAN architecture is also discussed. Formulation of potential C-RAN deployment scenarios are discussed in Section 3. Section 4 presents the methodology, assumptions and parameter values for the techno-economic analysis. Section 5 discusses the results of the techno-economic analysis. Finally, Section 6 concludes the paper with some ideas for future work.

II. C-RAN OVERVIEW

C-RAN is a network architecture where baseband resources are consolidated into a centralized pool of cloud computing-based, shared and virtualized BBUs. Figure 1 shows the general architecture of C-RAN. The centralized deployment of the BBUs simplifies site acquisition and reduces the number of equipment required at cell sites, reducing costs associated with rentals, energy usage, and equipment rooms. Collaboration between BBUs further improves performance at cell edges significantly. C-RAN becomes the best solution in solving the challenges with the traditional RAN as well as its features make it the next generation RAN architecture [7], [9], [11]. This section introduces cellular base station (BS) architecture evolution and the basis of the C-RAN concept.

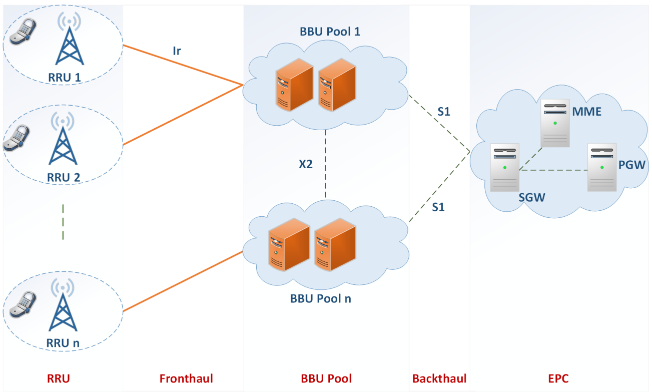


Fig. 1. General C-RAN Architecture in LTE Network.

A. Base Station Architecture Evolution

In order to understand the RAN architecture for the next generation of mobile systems (such as 5G), it is important to look back to previous and current RAN developments. This section will describe the architectural evolution of BS briefly.

1) Traditional BS Architecture: The traditional BS architecture combines the functions of the baseband and radio units into a single base station. As shown in Figure 2, the antenna is typically placed near the radio modules due to the high losses experienced by coaxial cables used to connect them. Mobile network deployments using this architecture were common in the 1G and 2G eras [16].

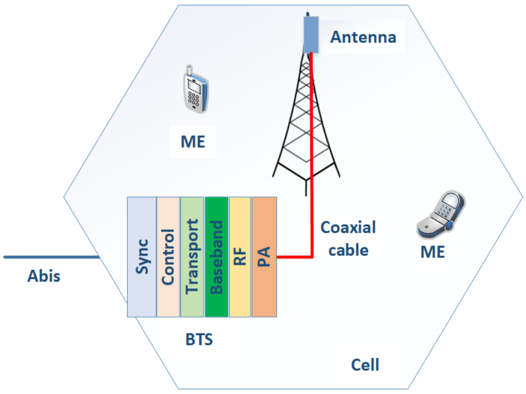


Fig. 2. Traditional Macro Base Station.

2) Distributed BS Architecture (D-RAN): In D-RAN architecture, the conventional base station is split into two components called BBU and RRU as shown in Figure 3. The BBU is responsible for baseband and higher layer processing and allocates resources dynamically to RRUs depending on network requirements. The RRU is responsible for radio frequency (RF) related function and consists of RF transmit and receive components such as power amplifier (PA), duplexers, low noise amplifier (LNA), and analog-to-digital converter (ADC) and digital-to-analog converter (DAC) . BBU and RRU are collocated at the macro site and their interconnection is using fiber cable and also a microwave connection. The interface between the BBU and RRU is termed a Common public radio interface (CPRI). The adoption of fiber cable provides numerous advantages such as greater bandwidth, lesser noise, decreased power requirements, and more network coverage than copper cabling [16], [25]. The distance between RRU and BBU can be stretched up to 40 km, however, the distance is limited due to the processing and propagation delay that occurred between them [16]. The D-RAN is introduced during 3G network deployment and is widely adopted and exploited by LTE and LTE-A. In this architecture, the BBU equipment can be placed in a more convenient, easily accessible place, enabling cost savings on-site rental and maintenance compared to the traditional RAN architecture.

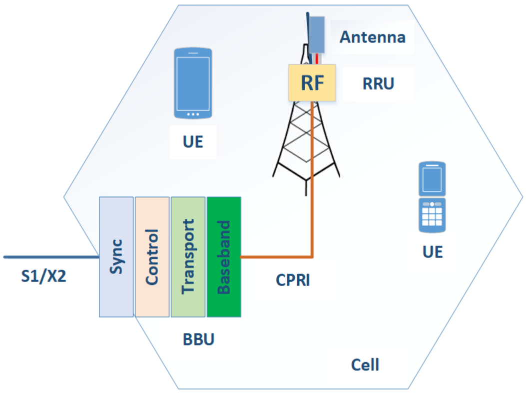


Fig. 3. D-RAN Architecture.

3) Centralized RAN Architecture: The existing D-RAN architecture brings many advantages by utilizing the existing fiber-optic network between the cell site and central office. In Centralized RAN, the BBUs are moved from the cell sites to a central location also known as BBU Hotel or Point of presence (PoP) [26] as shown in Figure 4. The RRUs at the cell sites are connected to the BBU Hotel via a CPRI Fronthaul transport network. This architecture makes RRUs easy to install on rooftops or streetlights, thus providing efficient cooling [25]. Centralizing the baseband unit into a central location allows more efficient maintenance, it provides the ability to maintain multiple BBUs in a single location, thereby improving Mean Time to Repair (MTTR) and cutting visits to cell sites significantly [26]. Moreover, the energy used by air-conditioning and other equipment on the premises can be reduced which leads to a reduction in energy consumption [25], [26].

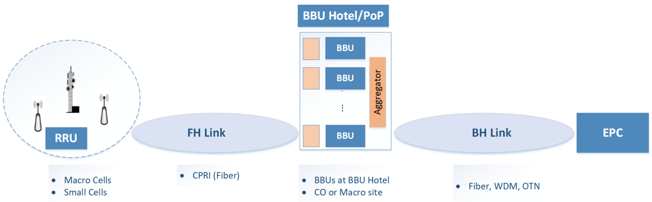


Fig. 4. Centralized RAN Architecture.

4) Cloud-based RAN Architecture (C-RAN): With the progress from 4G to 5G, there will be a significant increase in base station density, causing increased site acquisition costs and network construction costs. Further, dense deployment of base stations creates severe co-channel interference at cell edges, which negatively affects the user experience. These challenges were addressed with the development of the C-RAN.

In C-RAN, cloud computing is incorporated into the RAN architecture enabling BBU virtualization which allows operators to offer RAN as a service (RANaaS) by sharing BBU resources [16], [20]. Since C-RAN is based on an open platform, it opens the possibility for new revenue streams with technologies such as Mobile Edge Computing (MEC). Initially, C-RAN focuses on two principles: the centralization of baseband processing and the virtualization of it as shown in Figure 5. With centralization, network performance can be optimized, energy consumption can be decreased and spectrum can be efficiently used. Likewise, virtualizing baseband processing will results in resource sharing and reduction of both CAPEX and OPEX costs [9].

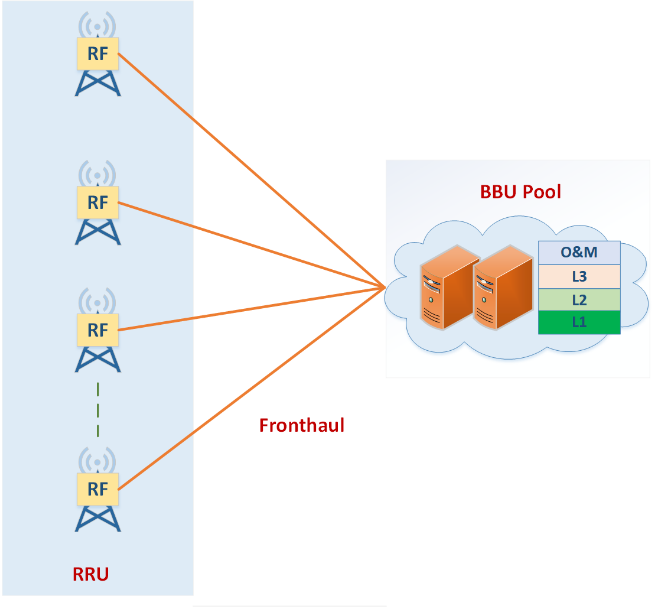


Fig. 5. C-RAN Architecture.

B. C-RAN Components

The C-RAN architecture consists of the following main components: BBU Pool, RRU, and a transport network known as Fronthaul. Figure 5 shows the C-RAN architecture and its components are described below.

BBU Pool: A BBU pool consists of multiple BBUs arranged in a cloud, each serving several RRUs. The virtualized BBUs at the BBU pool is responsible for processing the baseband functions (Layer 1 to 3). A BBU can be located at a cell site, in a BBU Pool, or a data center, depending on the C-RAN architecture, centralization level and functional split implemented

[20], [27]. A BBU pool can be entirely filled by different BBUs and their signal processing resources are shared and dynamically allocating them to the RRUs depending on the current network demand [27], [28].

RRU: RRU is located at cell sites and provides signal coverage for the cell sites. RRU comprises RF transmit and receive components and performs the functions such as ADC and DAC conversion, power amplification, LNA, filtering, antenna module, interface adaptation, and provide fiber interface [16], [20], [27].

Fronthaul: A Fronthaul network is a transport network, which connects the remote RRUs and BBU pool and is responsible for carrying the Fronthaul links to provide low latency and high capacity links [27]. There are different technologies used for C-RAN Fronthaul, including wireless and optical fiber. The most commonly used is a fiber-optic network with CPRI or enhanced CPRI (eCPRI) [29] and Open Base Station Architecture Initiative (OBSAI) protocols [30].

C. C-RAN Functional Splits

Initially, it was planned that C-RAN would incorporate fully centralized baseband processing. In this scenario, most base station functions would be performed centrally, while only RF functions were handled at distributed sites. Fully centralized BBU provides a maximum gain in multiplexing and easy implementation of coordinated multipoint transmission and reception (CoMP) schemes while reducing operating costs at radio sites. However, fully centralizing the baseband function and transporting the radio samples between the RRU and BBU requires high bandwidth and low latency interconnection network. This may not be cost-efficient and may even offset the benefit gained by centralizing the baseband processing. To overcome this deficiency without sacrificing the benefits of centralized processing, different functional splits are proposed for central and remote processing units in C-RAN [20], [31].

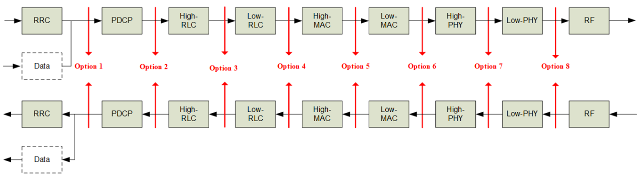


Fig. 6. Function Split between central and distributed unit [32].

An effective implementation and deployment of a C-RAN depends on the functional split between the central and distributed unit. There are several options studied by 3GPP as shown in Figure 6. For C-RAN eight functional split options (Option 1 to 8) are realized where option 8 is the fully centralized solution. Currently, options 2 (PDCP) and Option 3 (Upper RLC) are the most appealing functional splits, which split functionalities into non-real-time (NRT) and real-time (RT) functions as the optimal trade-off between flexibility and performance. According to the NRT-RT split, NRT functions will be performed at the centralized site and RT functions will be performed at the distributed sites [32].

D. Advantages of C-RAN

C-RAN technology has concrete and measurable advantages over the current RAN architecture, which primarily deal with reducing operators' operating costs. The following are some of them discussed briefly.

1) CAPEX and OPEX saving: With Cloud RAN, there will be substantial Savings both in terms of CAPEX and OPEX as upgrades and maintenance costs can be reduced. The Centralization & virtualization of the BBUs as well as relocating site support equipment from the cell sites to BBU pools significantly reduces the required network elements at the cell sites, which in turn reduces the CAPEX. Virtualization allows for the use of generic hardware and thus lowers the cost of equipment. The main source of OPEX savings is energy savings, reduced maintenance costs, and a lesser site visit. Furthermore, because of the lesser footprint required per cell site, the costs of renting and constructing sites decrease [5], [33].

2) Flexibility in Capacity and Spectral Efficiency Improvement: Cloud RAN brings another advantage in network capacity and spectral efficiency improvement. Due to its centralized architecture, it is easily scalable, which simplifies the process of upgrading the capacity of the networks. It can also be easy to connect more RRUs to the Cloud to provide greater coverage over a greater area or split the cell for higher capacity gain. Furthermore, Cloud RAN makes it easier to implement joint processing and scheduling, enabling the mitigation of inter-cell interference and an increase in spectral efficiency [5], [20], [33].

3) Reduce Energy Consumption: In Cloud RAN, BBUs, air conditioning, and site support equipment are centralized, reduced, and better utilized. This enables easy sharing of site support facilities leading to power consumption reduction. C-RAN can benefit from virtualization, which reduces energy consumption significantly. In addition, during low traffic hours, the vBBUs can be scaled down by turning off the BBU resources to reduce power consumption so that resources can be better utilized [20], [33].

E. Challenges of C-RAN

Although Cloud RAN brings many opportunities discussed above, it also faces challenges that need to be addressed. Below are some of them briefly discussed.

1) Fronthaul Transport Network: With the Cloud RAN architecture, the optical links between RRU and BBU Pool carry a tremendous amount of IQ samples, which brings a huge overhead on the Fronthaul link. Furthermore, the Fronthaul network must also meet stringent requirements for latency, jitter, and cost efficiency when it comes to transporting the IQ samples [7]. Costs associated with building large optical fiber Fronthaul networks to support Cloud RAN can make it unappealing in comparison to other RAN architectures. However, a potential solution could be used to reduce the capacity required such as IQ data compression. Therefore, the heavy burden on the Fronthaul link can be lowered [7], [20].

2) BBU Cooperation, Interconnection, and Clustering: In order to support CoMP, base stations should collaborate on sharing data, scheduling at the base station, and integrating channel feedback information. With centralized architecture, a large number of BBUs are located at a single location, which has a high risk of a single point of failure if Cloud fails, which increases the need for security and reliability [10]. The connectivity solutions of BBUs should be reliable and must provide a high bit rate, low latency, cost-efficient solution, and offer a flexible topology for interconnecting RRUs [16]. Clustering cells effectively in BBU pools is also crucial for both achieving multiplexing gains and preventing the transport network from being overloaded. BBU pools should be composed of cells from a variety of traffic areas such as the office, residential, and business areas such that the number of BBUs and RRUs within the pool is maximized [7].

3) Base station Virtualization Technology: Virtualizing the base station is one of the most challenging aspects of processing radio signals in real-time while meeting strict constraints. Nowadays, the baseband functions are processed more efficiently on custom silicon than on general-purpose processors. The real-time processing requirements of wireless networks make base station virtualization much more difficult than in traditional IT data center settings [7], [20].

F. Implemented C-RAN Architecture

In this study, C-RAN architecture implemented is based on the NRT-RT functional split, where NRT functions are performed on COTS cloud hardware and RT functions are executed on proprietary hardware [34] as shown in Figure 7. Therefore, C-RAN BBUs comprise both proprietary baseband hardware and a cloud server based on COTS hardware. As shown in Figure 7, the RRUs are located at the cell sites and contain the macrocells and small cells. Whereas the BBUs are moved to the BBU pools or data centers based on the distance between the RRU and BBU. To connect RRUs and BBUs in the C-RAN, a fiber optics Fronthaul network is needed. The Midhaul link between BBU pool and edge cloud uses IP/MPLS. Conversely, the centralization of the proprietary baseband hardware allows for more efficient use of the hardware, as well as simpler updating and management. It also reduces the space requirements at cell sites compared to D-RAN.

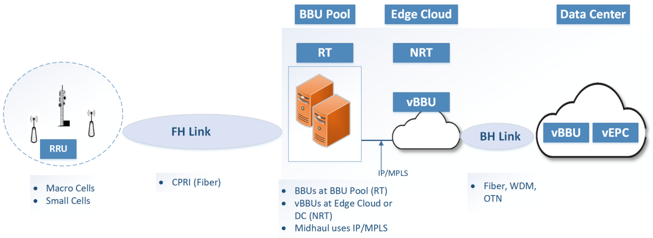


Fig. 7. Implemented C-RAN Architecture.

III. C-RAN DEPLOYMENT SCENARIOS FOR ADDIS ABABA

A. Scenario Planning Method

Scenario planning is a tool used for exploring, analyzing, and managing uncertainties and disruptiveness of emerging technologies [8], [35], [36]. To formulate and analyze the deployment of C-RAN for the context of Addis Ababa, Ethiopia various data sources are evaluated such as Ethio telecom documents, reports and strategies, related works of literature, standards, and expert opinions. From the available literature, Schoemaker's method is selected as the most convenient one for this study. The ten-step process presented in [8] was implemented but out of the ten steps, the following processes are selected for the purpose of this study: Defining time frame, Scope and Stakeholders identification.

The factors and trends that affect the C-RAN deployment are organized based on the PESTLE (Political, Economic, Social, Technological, Legal and Environmental) framework [37]. Through various literature, a survey of previous and existing RAN architectures, ethio telecom strategies and reports, project reports, expert opinions and discussion, and vendor opinions are included to identify the factors that significantly affect the C-RAN deployment in the context of Addis Ababa, Ethiopia. The factors and trends identified are assumed to be influencing the C-RAN deployment process positively or negatively and are summarized in Table I.

From the selected key trends, several uncertainties including deployment options and traffic growth expectation are identified and their correlation is analyzed in the correlation matrix forming step. The final scenarios are constructed based on opinions and interviews with ethio telecom experts to contextualize the identified uncertain events to the local context. The two key uncertainties were used and crossed to form a scenario matrix. Lastly, four internally consistent and plausible scenarios are constructed based on the most important uncertain events in the C-RAN implementation see [38] for details. The other selected uncertainties most of them are interrelated and support the scenarios developed.

B. Potential C-RAN Deployment Scenarios for Addis Ababa

The formulated potential C-RAN deployment scenarios based on the selected uncertain events are shown in Figure 8.

The C-RAN is designed to provide an alternative network architecture for next-generation mobile networks in order to address the requirements of the mobile services. Its deployment is suitable for most typical scenarios, including macro cells, micro cells, and Pico cells as well as indoor coverage. C-RAN deployment options can be either medium scale or small-scale deployment that can be implemented progressively or fully. The choice of medium scale or small scale deployment of C-RAN has to be investigated in depth since it is dependent on the resource availability, CAPEX and OPEX costs, C-RAN features, capacity, human power, time and vendor choice.

Traffic demand growth in the network serves as an input for the network dimensioning requirement calculation. The

TABLE I
SCENARIO PLANNING FOR C-RAN - PESTLE ANALYSIS

No.	PESTLE Analysis	Factors/Trends
1	Political	Government interest in regulative control
		Spectrum usage and allocation
		Competition policy
		Site acquisition
2	Economical	High costs of network elements, and running cost
		Energy consumption becomes a cost driver in wireless network
		Pricing policy
		Revenue decoupling
3	Social	User behavior change towards new technologies
		High demand for mobile data service
		Availability & reachability of service desire
		Internet users shift to wireless access from wired access
		Growing high data usage APPs
		End-user awareness on QoE
		Security, trust, and privacy
4	Technological	Technological improvement (e.g., computing power)
		C-RAN implementation depends on the choice of the functional split
		Service shift from hardware-based toward Cloud-based
		Network architecture evolves towards centralized, Cloud, cognitive, and clean processes.
		Challenges with the deployment of HetNet, Indoor traffic
		Challenges of the required high bandwidth Fronthaul
		Mobile data traffic exponential growth due to the proliferation of new devices, services.
		Vendors role
		Incompetency of current RAN architecture.
		OTT services, Content provides
		Cloud features bring new business opportunities
5	Legal	Law to enforce venue owners to install macro and small sites
		Safety laws
6	Environmental	Increasing environmental awareness
		Availability of alternative energy source
		Green ICT

number of connected user equipment (UEs) per cell site, the signaling frequency of these devices, and the control plane load per UE are used to compute the total control plane traffic in the network. These parameters will help to predict the traffic growth in the network and are used as an input for network dimensioning. In addition, these parameters determine the number of mobile devices connected to the network. Hence, traffic demand growth has to be forecasted as precisely as possible for efficient resource utilization, enhancement of quality of service (QoS) and quality of experience (QoE), reduction of CAPEX and OPEX costs, and generation of reasonable revenue.

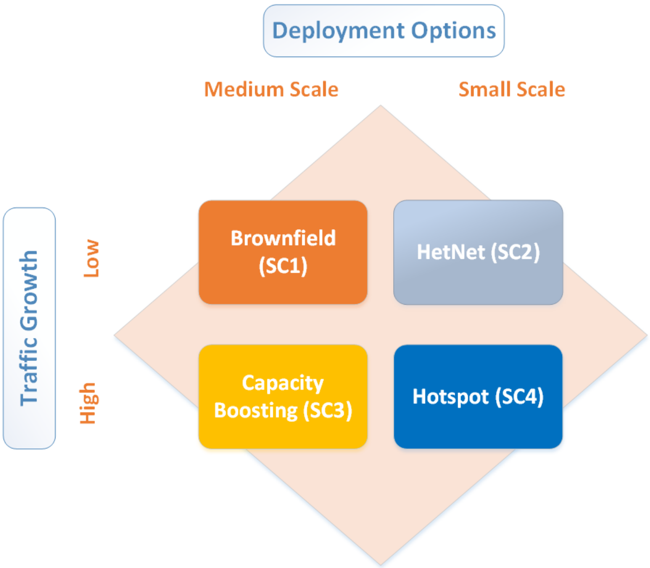


Fig. 8. Scenario planning for C-RAN - Scenario Matrix.

IV. C-RAN TECHNO-ECONOMIC MODELING AND ASSUMPTIONS

A techno-economic model is a framework used to analyze the economic feasibility of the technologies considering all the system parameters based on the framework from the model is derived. For the analysis, the TERA framework is modified to comprise the input parameters and follows the flow chart in Figure 9. The model consists of marketing, technical and economic parts. The formulated scenarios are implemented based on the developed tool.

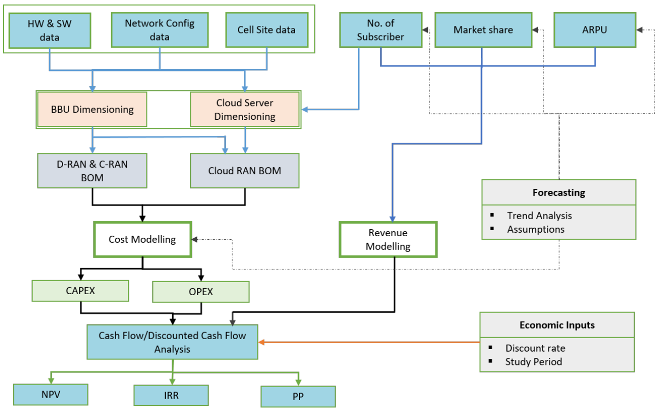


Fig. 9. Modified and Implemented TEA Mode.

The techno-economic analysis is performed for a period six years. The service to be provided and the target subscribers for the service are defined over the study period. Based on the combination of yearly subscribers and average revenue per user (ARPU), revenue is calculated for each year. For network dimensioning, three datasets are collected from ethio telecom. These datasets are cell-site data, network configuration data, and Hardware and Software data. The cost for calculating the CAPEX for the used hardware (HW) and software (SW) licenses is derived from literature, vendors, and previous ethio telecom LTE and LTE-A project documents. The OPEX cost including OAM, site rent, HW maintenance, SW maintenance, energy consumption, capacity upgrade and fiber lease are computed based on literature and ethio telecom data. For the analysis, a 10% discount rate is used and the standard economic metrics such as TCO, cash flow (CF), discounted cash flow (DCF), NPV, IRR and PP are calculated based on the modified TEA tool.

A. *Marketing Forecast and Economic Inputs*

The number of subscribers and ARPU are determined based on the three years input data record obtained from ethio telecom and employing forecasting and data analysis techniques [3], [39]. The number of subscribers for the study period is forecasted using the bass model for the two scenarios [40], [41]. The ARPU is projected based on the data obtained from ethio telecom and applying the linear regression method for the study periods and a market share of 100% is assumed within the study period. In addition, study period and discount rate defined for the economic input.

B. *Network Dimensioning*

The network dimensioning performed for the three RAN architectures D-RAN, Centralized RAN and C-RAN based on data collected from ethio telecom LTE network. In D-RAN and Centralized RAN architectures, the network dimensioning performed using a proprietary HW per-site basis for the baseband module (BBM), whereas the C-RAN architecture utilizes both proprietary and COTS HW for the BBM and Cloud server dimensioning respectively. The network dimensioning performed in this study adopted from [20], [27] and contextualized into the local context. The baseband and cloud software licenses calculated based on the network configuration data and user traffic data. Hence, the output of the network dimensioning is the number of baseband processing hardware and software licenses required for the three architectures on yearly basis.

1) ***BBM Dimensioning:*** C-RAN aims at consolidating the baseband processing of the radio signals emerging from different RRUs into a central office called BBU pool/PoP. Because the baseband processing hardware for the centralized architectures is located at the BBU pool or PoP, the dimensioning done for the BBU pool or PoP. In the D-RAN architecture, the dimensioning performed per cell site. In the baseband unit, the BBM hardware assumed to be containing three units, these are:

- **Capacity Unit (CAP)**: The CAP unit provides baseband processing capacity for the system. The number of cells a CAP unit can handle is based on the cell's BW and MIMO configuration. More BW and MIMO configuration requires more baseband processing HW and hence, requires higher CAP units.
- **Main Processing and control Unit (MPU)**: Responsible for processing control plane traffic and manages resources on the other BBMs. It also provides transport links to the core network, clock reference and maintenance links connecting to operation and maintenance center (OMC).
- **Cabinet Unit (CAB)**: Responsible for holding the CAP and MPU units, provides back-plane for internal communication of CAP and MPU units.

Hence, the BBM dimensioning done for the three BBM units based on the flow chart shown in Figure 10.

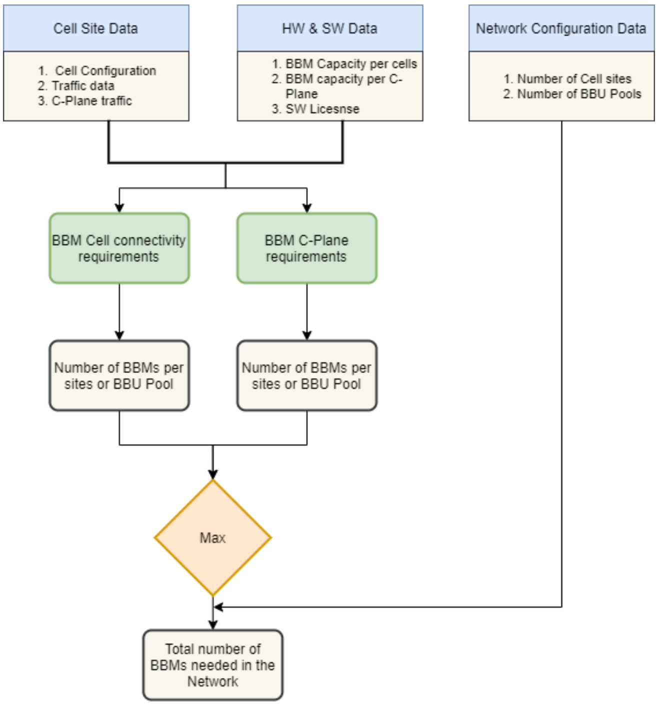


Fig. 10. Flow chart for BBM dimensioning [20].

2) ***Cloud Server Dimensioning:*** In C-RAN, part of the baseband processing functions are virtualized into virtualized BBUs (vBBUs) or virtual network functions (VNFs) which are implemented on generic cloud HW. In this study, the NRT-RT functional split is assumed in which the NRT functions are executed on the COTS cloud HW and RT functions are executed on proprietary HW. This functional split will alleviate the burden on the Fronthaul link and meet the latency requirement set by the LTE protocol stack.

The VNFs in C-RAN contain multiple virtual machines (VMs) that process various parts of the virtualized baseband processing functions. To process the NRT baseband functions in the virtualized environment, it is assumed that the following VMs are deployed: Cell processing VM (CP VM), User processing VM (UP VM), OAM VM and Central eNB VM (CeNB VM). Hence, the cloud server dimensioning is performed by using input from the cell-site data, network configuration data, and the HW and SW data based on the flow chart shown in Figure 11.

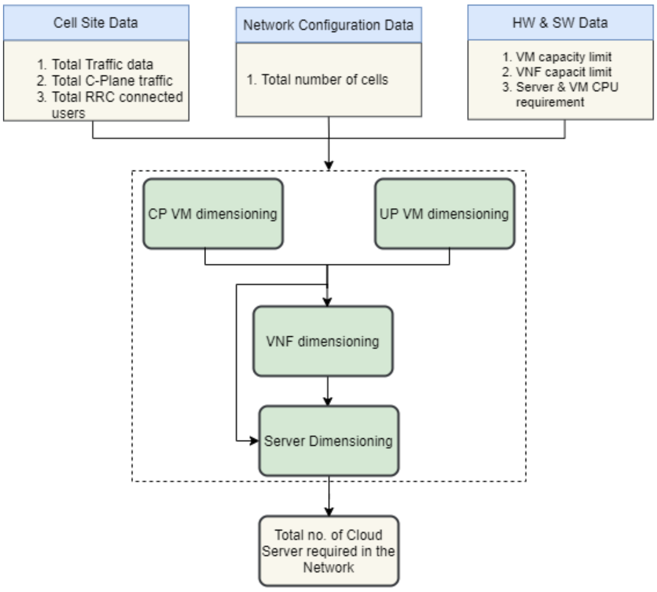


Fig. 11. Flow chart for Cloud server dimensioning [20].

3) ***Small Cell Dimensioning:*** Small cell plays a key role in meeting the capacity demands of the future network in hotspot areas in indoor and outdoor scenarios and their deployment is very appealing for such a scenario to increase the network capacity with lower cost. In this study, hotspot areas are selected based on LTE KPI reports and building density of Addis Ababa is analyzed. To determine the required number of outdoor small cells the studies in [42], [43] and 3GPP recommendations [44] are used. The selected area contains 21 macro base stations each with three sectors hence a total of 63 sectors.

C. Cost and Revenue Modeling

1) ***Cost Modelling:*** The cost of the network is one of the main elements for measuring the feasibility of C-RAN deployment scenarios. The costs of building and operating a radio access network can be split into capital expenditures (CAPEX) and operational expenditures (OPEX). Based on each year's required network elements, network configuration data and cost data, the cost calculations are performed. Calculations for CAPEX and OPEX represent the costs associated with implementing and operating the C-RAN and modelled using Eq. (1) and (2) respectively [20].

$$CAPEX = \sum_{i,j}^{T} N_j^i * (C_{BBM} + C_{BBSW} + C_{BBLC} + C_{CHW} + C_{CSW} + C_{FL}) * (1 + I_j)^{(i-1)} \quad (1)$$

Where: j ϵ list of CAPEX items (BBM, BBSW, BBLC, CHW, CSW, FL), N_j^i is the number of item j in the year i, C_{BBM} is the cost of BBM units, C_{BBSW} is the cost of baseband software, C_{BBLC} is the cost of baseband license, C_{CHW} is the cost of a cloud HW, C_{CSW} is the cost of cloud SW, C_{FL} is the cost of BH & FH link in year i, I is the yearly price inflation and T is the study period.

$$OPEX = \sum_{i}^{T} (C_{OAM}^i + C_E^i + C_{SR}^i + C_{HW}^i + C_{SW}^i + C_{UP}^i + C_{FR}^i) * (1 + P_i)^{(i-1)} \quad (2)$$

Where: C_{OAM}^i, C_E^i, C_{SR}^i, C_{HW}^i, C_{SW}^i, C_{UP}^i, and C_{FL}^i are costs of OAM, energy, site rent, HW & SW maintenance, capacity upgrade and fiber lease respectively in the year i, P_i is the yearly price inflation rate in the year i and T is the study period.

The total cost of ownership (TCO) is the sum of CAPEX and OPEX costs. According to the deployed architecture, i.e., D-RAN, Centralized RAN, and C-RAN, the TCO is modeled as shown in Eq. (3).

$$TCO = \sum_{i}^{T} (CAPEX_i + OPEX_i) \quad (3)$$

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.

2) ***Revenues Modelling:*** Revenue is calculated based on the number of subscribers, average revenue per user, and market share. The revenue is modeled as shown in Eq. (4).

$$R_T = N_S * ARPU * M_S \quad (4)$$

Where: R_T is the total revenue generated, N_S is the predicted number of subscribers, ARPU is the average revenue per user, and M_S is the C-RAN market share.

D. Techno-economic Evaluation Metrics

For the techno-economic evaluation, CF, DCF, NPV, IRR and PP are used.

1) ***Cash Flow (CF):*** refers to how much cash is received and disbursed within the study period. Based on the outputs from the cost and revenue model, the CF modeled mathematically as shown in Eq. (5) [36], [43]:

$$CF = \sum_{i}^{T} (R_T - C_T)_i \quad (5)$$

Where: CF is the cash flow, R_T is total revenue C_T is total cost of the network (TCO), T is the study period.

2) ***Discounted Cash Flow (DCF):*** DCF is a method of calculating the present value of a company's future cash flows in order to arrive at a current estimate of its fair value, using a discount rate. DCF modeled mathematically as shown in Eq. (6) [36], [43]:

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \dots + \frac{CF_i}{(1+r)^i} \quad (6)$$

Where: DCF is the discounted cash flow , CF is cash flow for the given year, CF_1 is for year one, CF_2 is for year two, CF_i is for additional years, i is the study period, and r is the discount rate.

*3) **NPV**:* NPV is used to evaluate the feasibility of the investment. NPV is modelled as shown in Eq. (7) [36], [45], [46]:

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+r)^i} \tag{7}$$

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

*4) **IRR and PP**:* The IRR and PP are two commonly used measures when evaluating a project in addition to NPV. In project analysis or capital budgeting, the IRR is a discount rate that makes the NPV of future cash flows equal to zero. Whereas, PP is the number of years it takes before the cumulative incomes equal the initial investments [36]. The IRR and PP are modelled as shown in Eq. (8), Eq. (9) [47]

$$NPV = \sum_{i}^{T} \frac{CF_i}{(1+IRR)^i} = 0 \tag{8}$$

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

$$PP = LP + [\frac{Abs(CCF)}{CF}] \tag{9}$$

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

V. RESULT AND ANALYSIS

In this section, Techno-economic analysis for the use case of ethio telecom was performed employing Cloud RAN TEA modeling tool developed to evaluate the costs of different RAN architectures. The use case is based on the data obtained from ethio telecom to analyze the costs of the three architectures (D-RAN, Centralized RAN & Cloud RAN). The analysis is done for a period of 6 years where in the initial year 2021 ethio telecom has an existing D-RAN architecture. The architectures assessed in terms of economic evaluation metrics within the study period in order to show, which RAN architecture performs best in terms of cost. As a convention in this section, D-RAN refers to Distributed RAN architecture, C-RAN refers to Centralized RAN architecture whereas Cloud RAN refers to Cloud-based RAN architecture.

Based on the data from ethio telecom, 3 months of traffic data are collected and top sites with the highest data are volume selected for Cloud RAN deployment in Addis Ababa. The main aim of this deployment is to address the high data traffic demand of hotspot locations with Cloud RAN architecture, as a centralized approach is very appealing for such kinds of scenarios. As part of this study, hotspot areas are identified in Bole Sub-city around Bole International Airport where dense buildings, shopping malls, entertainment malls, restaurants, and residential areas mainly cover the area. Figure 12 depicts the location of the existing site in the study area covering 2km by 2km area. The study area contains 21 macro base stations each with three sectored antennas. The sites are selected based on the factors: high traffic demand, cell configuration and fiber link availability.

Fig. 12. An operational LTE network with 21 eNBs (in total 63 sectors) around Bole area in the city center of AA.

Two different traffic growth scenarios for the deployment options are evaluated depending on the control plane traffic growth forecast for the Operator. According to these two scenarios, the maximum number of connected users per cell site determines the growth of control plane traffic and the control plane traffic load per connected device is assumed to be constant. As a result, it is expected that the number of devices will continue to grow, but the signaling frequency will remain the same in the network with in study period. Hence, the following two scenarios are formulated:

1) Small-scale deployment with low traffic growth expectation scenario (SC 1): 25% compound annual growth rate (CAGR) is assumed between the years 2022 to 2027 Figure 13.
2) Small-scale deployment with high traffic growth expectation scenario (SC 2): 50% CAGR is assumed between the years 2022 to 2027 Figure 13.

The results obtained in the network dimensioning process are summarized in Figure 14 & 15. Based on the discussions in [38] the number of cell sites required for each architecture is determined and the number of cell sites migrated to centralized architecture is decided based on the availability of resources.

For CAPEX and OPEX calculation various data sources are considered such as vendors (Huawei, Ericsson & ZTE), ethio telecom project documentation (LTE/ LTE-A), cost database from industry-standard, related literature, and other operators' experience. The CAPEX calculation does not include RF hardware, since it is assumed that it will remain the same in all architectures.

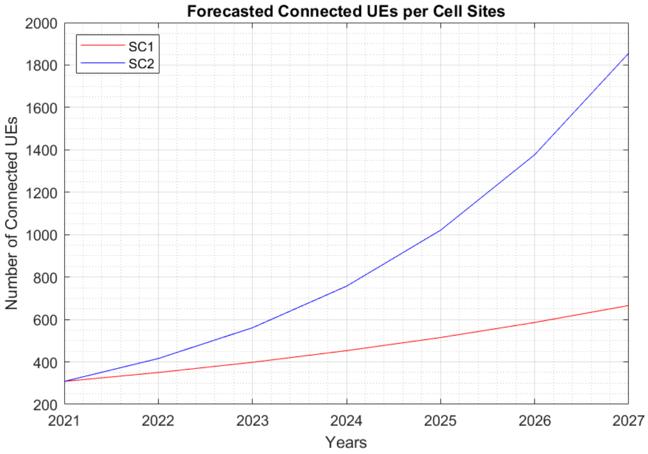
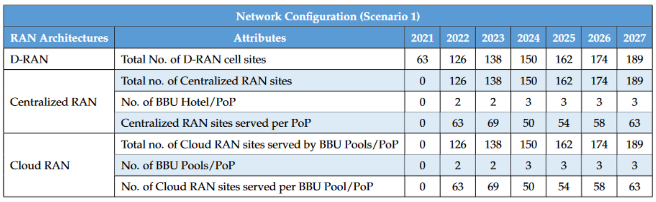
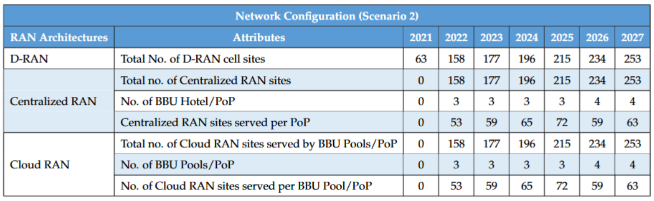


Fig. 13. Forecasted maximum connected UEs per cell site.



Network Configuration (Scenario 1)								
RAN Architectures	**Attributes**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
D-RAN	Total No. of D-RAN cell sites	63	126	138	150	162	174	189
Centralized RAN	Total no. of Centralized RAN sites	0	126	138	150	162	174	189
	No. of BBU Hotel/PoP	0	2	2	3	3	3	3
	Centralized RAN sites served per PoP	0	63	69	50	54	58	63
Cloud RAN	Total no. of Cloud RAN sites served by BBU Pools/PoP	0	126	138	150	162	174	189
	No. of BBU Pools/PoP	0	2	2	3	3	3	3
	No. of Cloud RAN sites served per BBU Pool/PoP	0	63	69	50	54	58	63

Fig. 14. Summary of the result of Network dimensioning for SC 1.



Network Configuration (Scenario 2)								
RAN Architectures	**Attributes**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
D-RAN	Total No. of D-RAN cell sites	63	158	177	196	215	234	253
Centralized RAN	Total no. of Centralized RAN sites	0	158	177	196	215	234	253
	No. of BBU Hotel/PoP	0	3	3	3	3	4	4
	Centralized RAN sites served per PoP	0	53	59	65	72	59	63
Cloud RAN	Total no. of Cloud RAN sites served by BBU Pools/PoP	0	158	177	196	215	234	253
	No. of BBU Pools/PoP	0	3	3	3	3	4	4
	No. of Cloud RAN sites served per BBU Pool/PoP	0	53	59	65	72	59	63

Fig. 15. Summary of the result of Network dimensioning for SC 2.

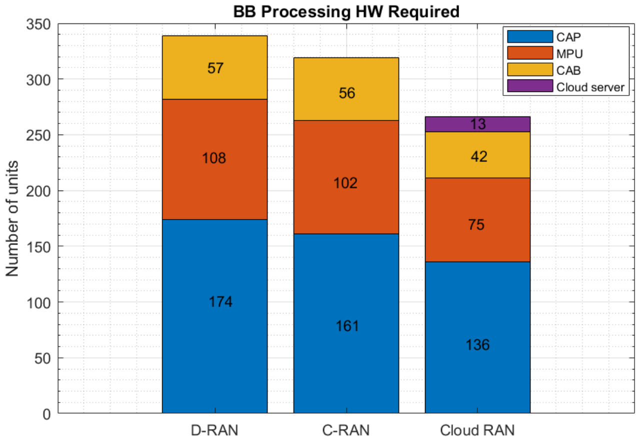


Fig. 16. Required baseband processing HW SC 1.

A. *Small-scale Deployment with Low Traffic Growth Scenario (SC 1)*

The result of the network dimensioning is the starting point for calculating the cost of the equipment for each architecture. The required baseband processing hardware for each architecture is shown in Figure 16. Comparing the baseband processing hardware requirements between the architectures, D-RAN requires more baseband processing hardware while C-RAN has a slightly reduced amount. Cloud RAN also reduced the required BBM but additional cloud servers have been added to the infrastructure. Cloud RAN better utilizes the BB processing hardware due to the pooling gain achieved from centralization however, in a low traffic growth scenario, Cloud RAN cannot benefit from cloud hardware better scaling for the low traffic growth.

In the low traffic scenario, C-RAN attains the lowest CAPEX as compared to D-RAN with a 1.14% lower cost. Cloud RAN shows higher CAPEX as compared to D-RAN with 1.83% higher costs. The main reason behind the increase in CAPEX cost in the Cloud RAN architecture is that the BBM hardware savings were not enough to offset the addition of expensive cloud servers and cloud software. C-RAN managed to reduce the number of required BBMs without investing in additional cloud servers, resulting in the lowest CAPEX as shown in Figure 17.

The analysis of SC 1 in terms of OPEX shows that, due to the reduction in maintenance, site rent, energy and operation costs, the centralized architectures achieve better OPEX savings. C-RAN achieve the lowest OPEX cost than D-RAN with 13.9% lower costs and Cloud RAN achieved lower OPEX than D-RAN with 13.7% lower costs. The majority of the OPEX savings originate from reduced maintenance, site rent and capacity upgrade costs. These are primarily due to more centralized vBBU locations, which are easier to access, require fewer site visits, and are cost-effective to operate. The SW maintenance cost of Cloud RAN is higher when compared to the other two architectures due to additional expensive software in Cloud RAN Figure 18.

Figure 19 shows the Cumulative TCO trends over the study period for each architecture for low traffic growth scenario. Over the course of the study period, the cost of the network is stable. The C-RAN architecture is the most cost-efficient architecture than the others and becomes more economical within the study period, whereas the D-RAN architecture is the most expensive architecture within the assessed study period. The initial TCO of Cloud RAN is higher due to having higher CAPEX at the beginning.

For the low traffic growth scenario, the TCO cost saving that can be achieved in the architectures compared to the distributed architecture is shown in Figure 20. C-RAN proved to be the most cost-effective architecture in terms of TCO. C-RAN attains the lowest TCO than D-RAN with 7.9% lower TCO. A lower TCO is also achieved by Cloud RAN with 5.2% lower than D-RAN. Cloud RAN architecture did not succeed in attaining better TCO in a low traffic growth scenario than the other architectures.

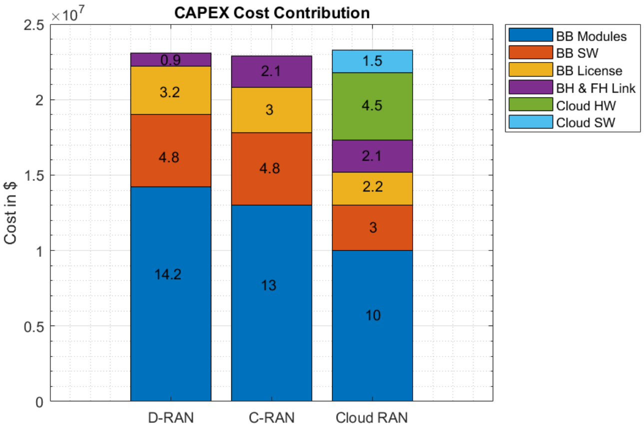


Fig. 17. CAPEX cost contribution SC 1.

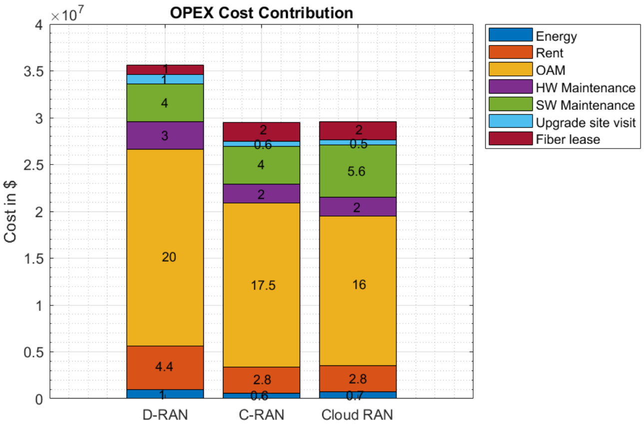


Fig. 18. OPEX cost breakdown SC 1.

Figure 21 shows the result of the NPV analysis for all the architectures based on the yearly cost evaluation considering a 10% discount rate and revenue projection. The NPV value was negative until the 3^{rd} year of deployment for all the architectures, whereas after the 3^{rd} year all the architectures show positive NPV values with $237.56, $253.01, and $251.43 for D-RAN, C-RAN, and Cloud RAN respectively. Hence, all architecture can be considered economically viable.

Table II summarizes all the economic indicators used for decision-making. The findings in the summary table show that, positive NPV values, higher IRR values than the defined discount rate, and payback period for all architectures. The result indicates that C-RAN attained better value with all economic indicators and it is economically viable within the study period for SC 1.

B. Small-scale Deployment with High Traffic Growth Scenario (SC 2)

The required baseband processing hardware for each architecture is shown in Figure 22. As it can be seen in the high traffic scenario, Cloud RAN architecture allows for better scaling of the required baseband processing hardware. Comparing the BBM units needed in the architectures, D-RAN requires more baseband processing hardware due to the baseband resources are assigned statically to cell sites whereas C-RAN reduces slightly the required BBMs. Cloud RAN better utilizes the required BBMs due to the pooling gain obtained from centralizing and virtualizing the baseband units. Based on a comparison between the respective distributed architectures and the Cloud-based RAN architecture, the Cloud RAN reveals a significant improvement in scaling of cloud servers than the vendor-locked BBMs under high traffic growth scenarios. Cloud RAN reduces the amount of baseband

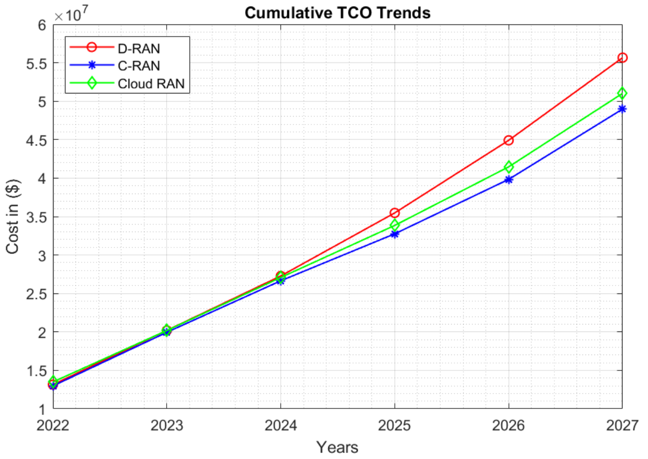


Fig. 19. Cumulative TCO trends for the architectures over the study period in SC 1.

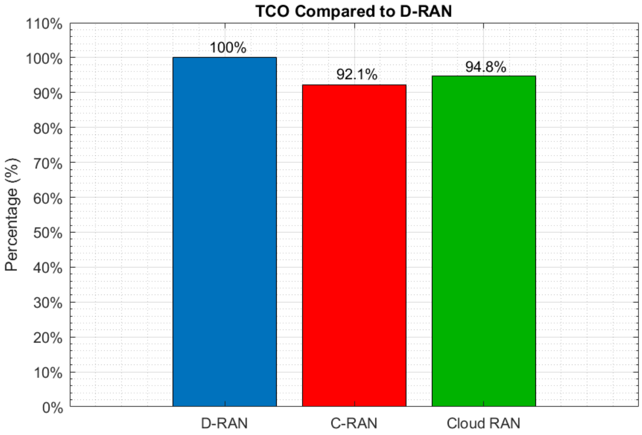


Fig. 20. TCO change comparison SC 1.

TABLE II
SUMMARY OF TEA FOR SC 1

Architectures	NPV ($Mil)	IRR (%)	Payback Period (Years)
D-RAN	$237.56	68.2%	3.14
C-RAN	$253.01	72.5%	2.94
Cloud RAN	$251.43	69.5%	3.04

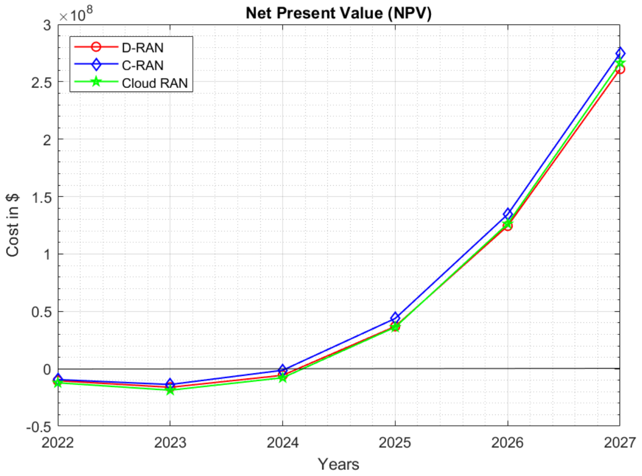


Fig. 21. Net present value (NPV) SC 1.

processing hardware needed by 40-50% when compared to D-RAN architecture due to the multiplexing gain implemented in network dimensioning as well as the highly increasing traffic growth permits Cloud RAN to better scale the baseband processing hardware required.

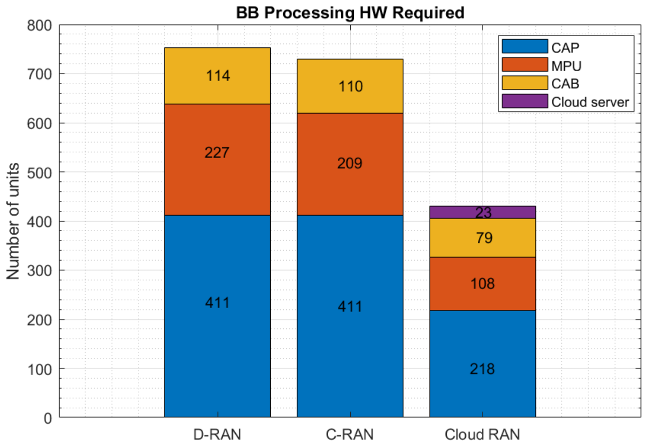


Fig. 22. Required baseband processing HW SC 2.

The CAPEX cost contribution of each architecture is shown in Figure 23. In the high traffic scenario, Cloud RAN attains the lowest CAPEX as compared to D-RAN with a 14.5% lower cost. C-RAN attains 1.9% lower CAPEX costs than D-RAN. CAPEX savings come mainly from cloud servers better hardware scaling and a reduction in equipment costs in the vBBU. Virtualizing the baseband processing functions into the cloud makes it possible to use non-proprietary hardware and BBU pooling. In addition to increasing vBBU's efficiency, the BBU pool requires less baseband processing capacity and thus less hardware required. Therefore, enhancing the network capacity is significantly cost-effective with cloud hardware than the proprietary BBUs since the BBU savings compensate for the costs incurred by additional cloud HW and SW in high traffic scenario. Besides lowering CAPEX costs, reducing equipment required can also result in shorter deployment times and greater flexibility in equipment placement.

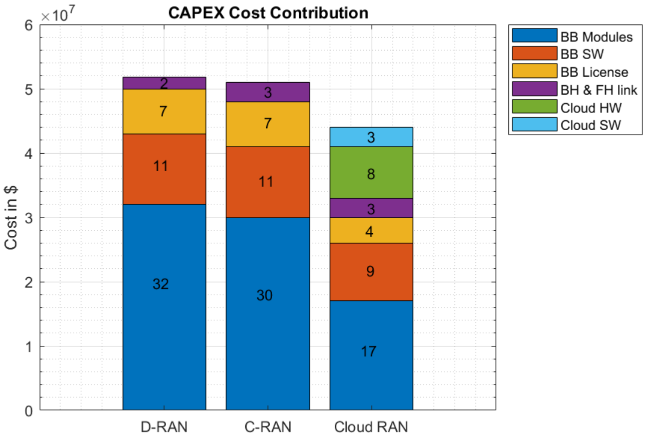


Fig. 23. CAPEX Cost contribution SC 2.

The OPEX cost contribution of each architecture is shown in Figure 24. In a high traffic scenario, Cloud RAN attains better OPEX savings. Cloud RAN achieve the lowest OPEX cost than D-RAN with 21.1% lower costs and C-RAN achieved lower OPEX than D-RAN with 12.4% lower costs. The savings in operational costs of Cloud RAN are mostly attributable to the reduction of maintenance, site rent, energy, and operation costs associated with centralized locations, which are less expensive to operate. Centralizing and virtualization of the baseband units into the cloud significantly reduces the baseband capacity upgrade, energy, and site rent costs due to a reduction in equipment and fewer site visits needed. In most areas, Cloud RAN was able to reduce costs, with the exception of the higher software maintenance costs associated with Cloud RAN due to its more expensive software. Based on the analysis of the cumulative energy consumption of the baseband processing hardware for the different RAN architectures, Cloud RAN has less CO_2 emission as opposed to the D-RAN, making it the most environmentally friendly and green architecture. It successfully reduced energy consumption by 35% over D-RAN.

Figure 25 shows the Cumulative TCO trends over the study period for each architecture for high traffic growth scenario. The TCO trend indicates that the cost did not differ significantly until year three between the architectures. When the connected user per cell site grows rapidly, the cost of the distributed architecture rises faster than the Cloud RAN architecture. This makes the Cloud RAN architecture the most economically viable architecture when compared to the distributed architecture.

For the high traffic growth scenario, the TCO cost saving that can be achieved in the architectures compared to the distributed architecture is shown in Figure 26. Cloud RAN proved to be the most cost-effective architecture in terms of

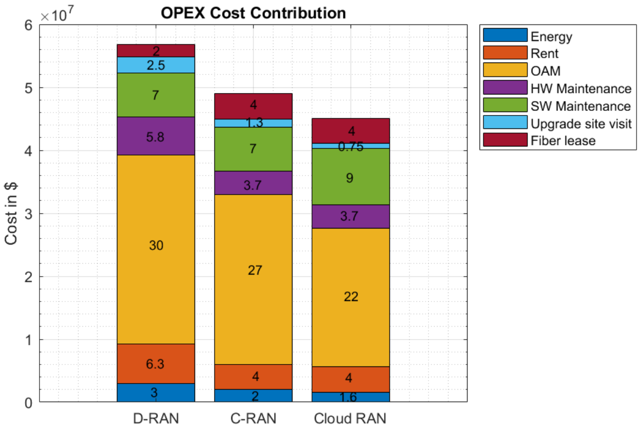


Fig. 24. OPEX Cost contribution SC 2.

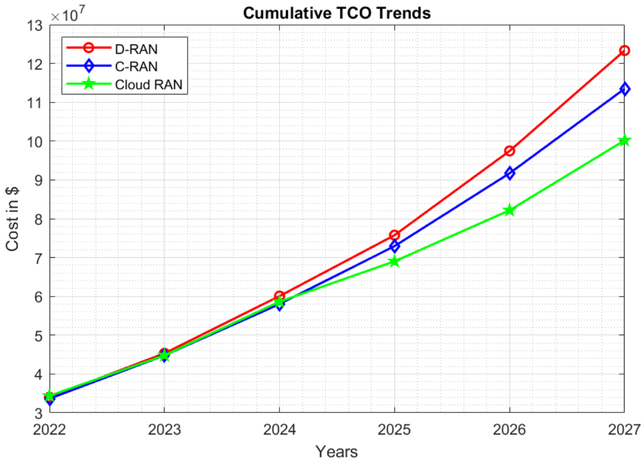


Fig. 25. Cumulative TCO trends for the architectures over the study period in SC 2.

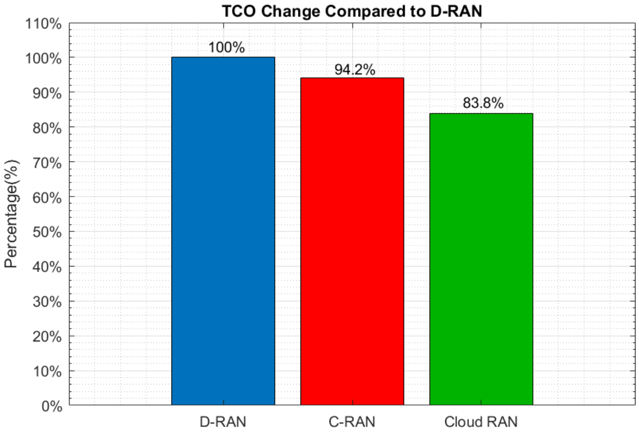


Fig. 26. TCO Compared to D-RAN SC 2.

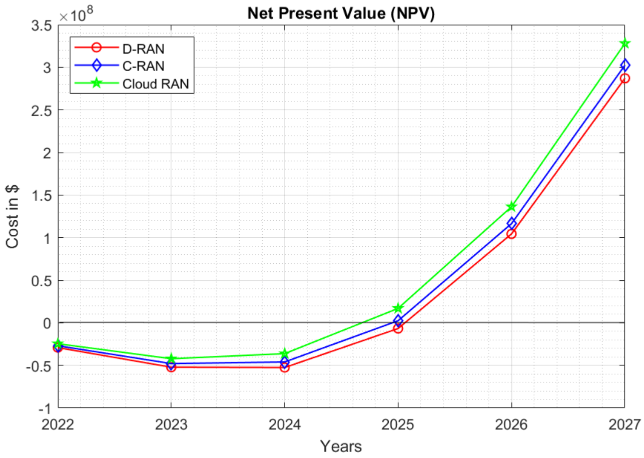


Fig. 27. NPV SC 2.

TCO in high traffic scenarios. Cloud RAN attains the lowest TCO than D-RAN with 16.2% lower TCO. C-RAN also attain lower total cost than D-RAN with 5.8% lower TCO.

Figure 27 shows the result of the NPV analysis for all the architectures based on the yearly cost evaluation considering the 10% discount rate and revenue projection. The NPV value was negative until year 3.5 of deployment for Cloud RAN and around 4 years for the other architectures, whereas after year 4 all the architectures show positive NPV values with $234.80, $251.09, and $285.78 for D-RAN, C-RAN and Cloud RAN respectively. The recorded positive NPV values show that each architecture is economically feasible within the study period. The Cloud RAN deployment has the lowest TCO among all the architectures and a higher positive NPV value showing that Cloud RAN deployment has the highest profitability in high traffic scenarios. This is because of the cost-saving attained due to better scalability in cloud hardware and improved performance in Cloud RAN.

Table III summarizes all the economic indicators used for decision-making. Based on the results in the summary table, positive NPV values, higher IRR values than the defined discount rate, and payback period for all architectures are depicted. When comparing comparable projects with payback periods, those with larger cash inflows in the earlier periods generally ranked higher. In addition, several studies suggest that investments with a payback time of between 3 and 4 years ($\leq$ 3.5 years) over a period of six years are profitable and feasible. Therefore, Cloud RAN attained better value with all economic indicators and it is economically viable within the study period. This shows that the time required to return the investment for Cloud RAN deployment for high traffic growth scenario in Addis Ababa is 3.5 years.

TABLE III
SUMMARY OF TEA FOR SC 2

Architectures	**NPV ($Mil)**	**IRR (%)**	**Payback Period (Years)**
D-RAN	$234.80	41.5%	4.16
C-RAN	$251.09	44%	3.95
Cloud RAN	$285.78	50.4%	3.5

VI. CONCLUSION

The explosion in mobile data traffic coupled with continuous demands for higher data rates, and low-latency connectivity are putting strain on network capacity, while also requiring the development of cost-efficient and energy-efficient solutions. This necessitates a deep rethink and revolution on mobile network design, and more specifically on the RAN architecture. In light of its superior performance and lower cost, Cloud RAN is a fundamental component of next-generation mobile networks (such as 5G). Nevertheless, to make Cloud RAN technically and economically viable option, a techno-economic study should be conducted, which is rare in the context of Addis Ababa, Ethiopia, primarily because of vendor-driven network deployment practices. In this paper, we have formulated potential Cloud RAN deployment scenarios for Addis Ababa, Ethiopia using scenario planning method. A detailed techno-economic analysis has been performed based on modified TERA model for the selected scenarios assuming a 6 year study period and a 10% discount rate. The analysis is implemented in MS Excel and MATLAB.

Achieved results indicate that traffic growth forecasts have a significant impact on Cloud RAN economic benefits. For low traffic growth forecast, Cloud RAN cost benefit is in doubt however, for small scale deployment with high traffic forecast Cloud RAN achieved better cost benefits with all economic metrics with a payback period of 3.5 years. The result of the TEA model reveals that moving to a cloud-based RAN architecture has a clear cost-benefit when traffic is expected to increase by a significant amount.

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