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

Techno-Economic Analysis of Hybrid Infrastructure Deployment for Mission-Critical Communications: A Case Study of Addis Ababa-Adama Toll Road Emergency Network

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Declaration

I, the undersigned, certify that the thesis below is my original work and has not been previously presented to receive any degree at this institution or any other university. I also attest that the references to the external sources and materials, which have been used in this work, have been referenced appropriately and fully.

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Abstract

An absence of efficient, modernized emergency-response and mission-critical communication technology will degrade the service and safety performance of the Addis Ababa Adama toll road. Accordingly, implementing a specific mission-dedicated communication system will be mandatory. However, technology upgrading decisions made without a detailed technical and economic feasibility assessment of emerging mission-critical communication options cannot deliver the expected performance and financial benefits of the intended investment.

In this thesis, an audit of the existing AATR communication infrastructure was carried out. Based on its capabilities, deployment scenarios were analyzed and formulated using scenario planning. Four scenarios were developed, either using the existing STM-4/MSTP infrastructure or upgrading Ethio-telecom assets to LTE/5G. The scenarios were evaluated along the Addis Ababa–Adama toll road, using data from Ethiopian Toll Road Enterprise documents and site surveys.

The techno-economic analysis of the deployment scenarios used a modified TEA framework for a 10-year period. Network dimensioning determined coverage and capacity for each option. Evaluation included net present value, payback period, benefit-to-cost ratio, and sensitivity analysis, considering currency fluctuation, inflation, operational expenditure, and discount rate uncertainty. An 8% discount rate was applied for all analyses.

As the analysis results show, the PBP (in years) and BCR (in decimal) of the scenarios, respectively, are 20.1 and 0.259 for Sc1, 5.29 and 1.224 for Sc2, 6.93 and 0.987 for Sc3, and finally 5.53 and 1.145 for Sc4. According to the above techno-economic analysis results, Scenario 2 (STM-4 Optimized Hybrid Deployment) is technically and economically feasible for the Addis Ababa–Adama Toll Road.

Keywords— *Mission-Critical Communications, Techno-Economic Analysis, LTE/5G, Hybrid Infrastructure, Toll Road Safety.*

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

3GPP	Third Generation Partnership Project
5G	Fifth-Generation
AI	Artificial Intelligence
AATR	Addis Ababa-Adama Toll Road
CAPEX	Capital Expenditure
DMR	Digital Mobile Radio
ETB	Ethiopian Birr
ETSI	European Telecommunications Standards Institute
ETRE	Ethiopian Toll Roads Enterprise
EPC	Evolved Packet Core
eNodeB	Evolved Node B
eMBB	enhanced mobile broadband
GIS	Geographic Information Systems
HSS	Home Subscriber Server
IoT	Internet of Things
ITU	International Telecommunication Union
MCC	Mission-Critical Communication
MHz	Mega Hertz
MATLAB	Matrix Laboratory
MCData	Mission-Critical Data
MCPTT	Mission-Critical Push-to-Talk
MCVideo	Mission-Critical Video
MME	Mobility Management Entity
mMTC	massive machine-type communication
NFV	Network Function Virtualization
OPEX	Operational Expenditure
QoS	Quality of Service
LTE	Long-Term Evolution
IMS	IP Multimedia Subsystem
PMR	Private Mobile Radio
P25	Project 25
PSMB	Public Safety Mobile Broadband
PGW	Packet Data Network Gateway
RRM	Radio resource management
RF	radio frequency
SGW	Serving Gateway
TCO	Total Cost of Ownership
TEA	Techno-economic Analysis
TETRA	Terrestrial Trunked Radio
TIA	Telecommunications Industry Association
UHF	Ultra High Frequency
UE	user equipment
URLLC	ultra-reliable low-latency communication
V2X	vehicle-to-everything

Chapter 1

Introduction

1.1 Background and Context

Formerly, the Addis Ababa–Adama Toll Road (AATR), which measures 78.5 km in length with six lanes, connects the capital of Ethiopia to its import–export gateway [1]. It is one of the key highways, supporting upwards of 40,000 vehicles daily. Among its significance as a trading route are several factors. In the economy of the region as a whole, the toll road suffers from operational problems due to the unavailability of a high-availability Mission-Critical Communication (MCC) system. Currently, emergency response and operational activities rely on various non-integrated communication systems, such as overloaded commercial cellular networks, while the existing STM-4 optical infrastructure, being legacy, fails to serve user mobility, broadband, and traffic prioritization for emergency users [2]. The stated communication limitations led to Addis Ababa-Adama toll road emergency work ineffective.Traffic control and road users safety monitoring, augmented hazards, and financial losses [3].

Going worldwide, mission-critical communications are increasingly being switched from narrowband Land Mobile Radio (LMR) systems, such as TETRA and P25, to broadband LTE- and 5G-based communications, which are together called Mission-Critical Services (MCX) [4]. These technologies enable reliable voice services (MCPTT), low-latency data transmission, and real-time high-definition video. ALso they significantly enhancing situational awareness and emergency response efficiency [5]. While adoption is expanding worldwide, the deployment of mission-critical communication networks involves significant capital investment, particularly in developing economies [6]. In the case of the Addis Ababa–Adama Toll Road, the availability of existing STM-4 fiber infrastructure and Ethio Telecom's network assets presents a strategic advantage for a hybrid network deployment plan [7]. By integrating an existing AATR infrastructure with the leased

Ethiotelecom network resources, redundant investment is minimized, and offers a cost-effective pathway for implementing broadband mission-critical communications at Addis Ababa Adama toll road [8].

The hybrid deployment model, which significantly solves the most difficult problem of financing modern MCC systems. BY reusing the existing AATR's fiber network for backhaul and renting tower space and power infrastructure from Ethio Telecom, the project will be able to save 60, 70 percent of the civil works and structural costs that are normally associated with a greenfield deployment [9]. The consequent impact of such a plan greatly lowers the initial capital expenditure (CAPEX) and extends the deployment timelines from a new-build project estimated 36 months to less than 18 months hence making the critical AATR safety services available at a faster rate [10].

Hence, this study locates itself at the crossroad of a very important local operational area a necessity, a worldwide technological shift, and a unique infrastructural opportunity within Ethiopia. It contains a thorough, empirically grounded techno-economic analysis to the AATR corridor that can be considered as the practical realisation of the hybrid MCC architectures potential. The primary goal is to devise a strategy for the deployment that is not only technically, economically, and strategically sound but also a blueprint that can be duplicated in the case of other infrastructure corridors in Ethiopia and similar environments.

1.2 Problem Statement

One of the key transport and economic corridors in Ethiopia is the capital city of Addis Ababa, and Adama which is connected by the toll road (also referred to as the AATR). However, the currently available corridor does not have a wide-band high-capacity, Mission-Critical Communication (MCC) network in place, which is a prerequisite of the MCC communications that need to be undertaken throughout any large roadway. The current communication system is using only the outdated STM -4 optical networks and commercially provided cellular systems, which are far below the modern-day communication standards of emergency and operational services [11]. Therefore, the safety standard on the road has worsened, performance efficiency has been compromised and the economic operations along the line is continually haunted by the threat of any disturbances.

This central issue may be outlined in four general areas. Second, the lack of unified and reliable communication system poses a crucial problem to emergency services with respect to their inability to respond in a coordinated fashion [12]. The telecommunication of ambulances, police, and rescue teams usually has to rely on cellular (or simple radio) communication which at times becomes saturated and stops halfway through the mission. As a result, there is a delay in incident clearance, traffic congestion, and the medical response becomes longer, which endangers the lives of the injured persons, and thus threatening lives of the injured people on the road [13]. Second, the traffic management systems that are used currently on the AATR do not have the capability to display real-time alerts or dynamically coordinate diversion routes in cases of emergency or overload situations [3]. The inability to provide low-latency, group based type of communication is an effective barrier to effective interaction between the toll stations, maintenance teams, and the traffic control centers leading to unnecessary delay, increased congestion, and low overall capacity of the road way. Third, the literature states that the inaccessibility of operational visibility and proactive monitoring is one of the core problems, where the currently deployed infrastructure is unable to meet the demands of the high-bandwidth surveillance and the integration of IoT-based sensors into it [14]. This constraint compels to use the only method of implementing live HD video and sensor data on the most visited points in the corridor, which consequently undermines the significance of preventing incidents by using real-time maintenance planning. Lastly, the inefficiency that impacts the functionality and safety of the toll roads is reflected in the significant economic consequence of the situation [15]. Long-term shutdowns caused by poor incident management cripple the traffic system, impact logistics, negatively impacting on the quality of life of people using the roads, and in the case of toll road operators, leads to a loss in revenue, high operating expenses and a lack of confidence in the system by the population, as the upkeep of the old systems perpetually consumes resources and leads to poor performance.

Finally, this study answers the following questions:

1. What are the technical and service demands for the AATR mission-critical network?
2. How well can the existing AATR communication infrastructure be functionally interoperable with the existing Ethio Telecom network system?
3. What scenarios of mission-critical network deployment take a high share of the network cost in each deployment scenario?
4. Which network deployment scenario is most feasible by balancing risk, technical, and economic viability?
5. How can the formulated network deployment scenarios be dimensioned to meet the required demands?

1.3 Objective

1.3.1 General Objective

The general objective of this thesis is to develop and analyze an optimal mission-critical network infrastructure deployment solution for Addis Ababa-Adama Toll Road.

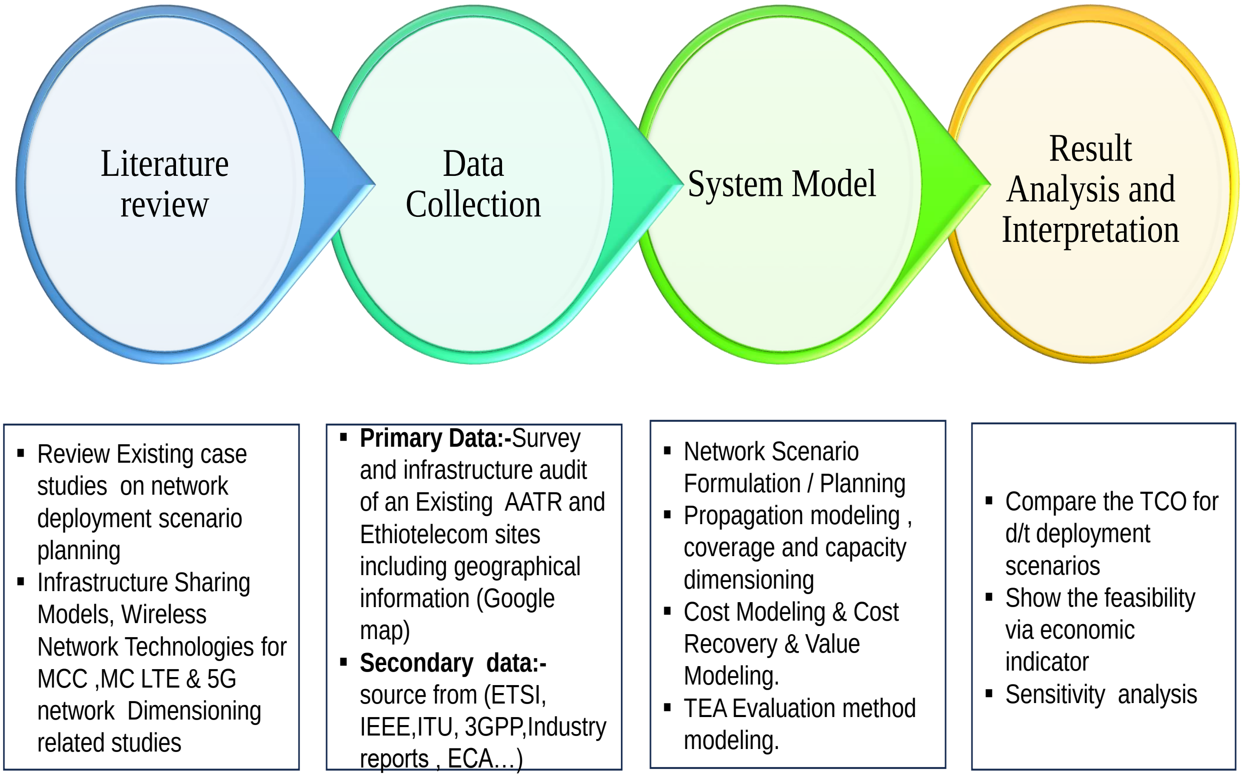
1.3.2 Specific Objectives

- To evaluate a comprehensive system audit and gap analysis for the existing AATR and Ethio Telecom network assets.
- To perform network dimensioning for the formulated MCC deployment scenarios based on the technical requirements.
- To evaluate CAPEX, OPEX and TCO for all network scenarios
- To conduct a cost-benefit analysis to determine economic soundness
- To analyze financial viability about the deployment from the cost-benefit ratio analysis perspective
- To Evaluate each scenario's technical, economic, and operational risks.
- To recommend an optimal and feasible deployment strategy for AATR.

Note: *In this thesis paper, the focus is on the technical and financial evaluation of LTE/5G deployment. The transition from legacy LMR involves operational staff and human adaptation problems; these aspects are acknowledged but are not included in the quantitative analysis.*

1.4 Methodology

Mixed-methods case study integrates qualitative audits with quantitative modeling to evaluate techno-economic feasibility of mission-critical networks along AATR. The methodology and procedures followed in the thesis presented in Figure 1.1 below.



- Review Existing case studies on network deployment scenario planning
- Infrastructure Sharing Models, Wireless Network Technologies for MCC ,MC LTE & 5G network Dimensioning related studies

- **Primary Data:-**Survey and infrastructure audit of an Existing AATR and Ethiotelecom sites including geographical information (Google map)
- **Secondary data:-** source from (ETSI, IEEE,ITU, 3GPP,Industry reports , ECA...)

- Network Scenario Formulation / Planning
- Propagation modeling , coverage and capacity dimensioning
- Cost Modeling & Cost Recovery & Value Modeling.
- TEA Evaluation method modeling.

- Compare the TCO for d/t deployment scenarios
- Show the feasibility via economic indicator
- Sensitivity analysis

Figure 1.1: Methodology Used for the Thesis

1.5 Scope and Limitation

1.5.1 Scope of the Study

Geographically, this research will only cover the 78 kilometers rural area of the Addis AbabaAdama Toll Road.

Regarding service provision, the study focuses on the implementation of core Mission-Critical Services (MCX), including Mission-Critical Push-To-Talk (MCPTT) voice, data, and real-time video services to specific emergency response teams, such as police departments, ambulance services, crane work, and road safety teams.

The technological view focuses on terrestrial LTE and 5G architectural solutions of mission-critical communications. Network dimensioning focuses on radio coverage and capacity, using low- and medium-band spectrum to guarantee reliable propagation, and satellite-based solutions are not in the scope.

1.5.2 Limitations of the Study

This paper also attempts a thorough analysis, but it is limited in a number of ways.

Its results depend on the quality and the completeness of the data provided by AATR and Ethio Telecom, and thus, any errors in the information about infrastructure can invalidate the analysis.

The economic model is founded on the market prices and exchange rates that are prone to fluctuations caused due to inflation pressures, currency fluctuations, supply chain and leasing circumstances. Even though a sensitivity analysis has been included, a completely dynamic cost model was not used.

In addition, the Ethiopian telecom regulatory framework affects the study, especially regarding the scenario of the Shared RAN, where regulatory approval, spectrum allocation, and strong third-party deals are required. Changes in regulatory or licensing can change the performance and feasibility.

The comparison will be limited to the existing standardized LTE and 5G technologies. New substitutes like LEO satellite backhaul had not been evaluated and may influence subsequent applicability.

Lastly, the recommendations are scenario-based and do not provide project-specific validation or human-operational concerns, such as the training needs and workflow modification.

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1.6 Literature Review

Comparative techno-economic performance of Private LTE and 5G systems in private mission-critical networks has been recently studied [16]. For emergency communications, Private LTE is usually preferred because of its cost-effectiveness and reliability. On the other hand, Private 5G can allow more users, provides ultra-low latency, and offers higher bandwidth [17]. Researchers point out that there are challenges in switching from legacy systems such as CAPEX, OPEX, and deployment complexity. They also suggest that network architectures must be specifically adapted to the targeted environment and usage contexts, such as transport corridors [18]. The example of the U.S. FirstNet program and RailNet Europe case shows that privately operated networks enable better crisis management systems, promote stable coverage even in the most remote areas, support the integration with the current infrastructure, and provide service even during the crisis peaks.

The techno-economic analysis is a methodological framework that combines the technical elements of network performance, which are coverage , capacity, and latency, with financial values that include capital expenses, operational expenses, and product lifecycle expenses. This method has become standard practice for assessing communication network rollout scenarios [19]. In this vein, the 5G NORMA project sets out a blueprint for utilizing TEA in steering cost-efficiency and performance compromise decisions, while the research works of Bohlin et al. (2017) and Katsianis et al. (2018) shed light on aspects such as cost factors, revenue models, and green credentials, among others. Certainly, the reliability and efficiency of mission-critical networks call for extra consideration in the context of sustainability [20]. In addition to TEA, the processes of network dimensioning and propagation modeling are fundamental elements of the design of private mission-critical communication systems. This is validated by case studies in Australia and Japan, which highlight the necessity of precise coverage prediction by the utilization of sophisticated models such as Longley-Rice and meticulous capacity planning to the point of satisfying very high-density and emergency service needs [21]. Summing up, the combination of these three methodologies clearly points to an accurate technical and economic planning as the cornerstone of an effective and sustainable communication network.

1.7 Significance and Contributions of the Study

The study adds to the theoretical background and practice by discussing the dire need of a robust mission-critical communication (MCC) system along the Addis Ababa-Adama Toll Road. The study contributes to the existing gap in the literature on the topic of MCC implementation in resource-limited environments by creating a hybrid framework that combines traditional infrastructure and modern wireless technologies [22]. By means of an evidence-based case study, this paper identifies the areas of infrastructure economics, public-private partnerships, and technology migration strategies in emerging contexts [23]. In fact AATR and Ethiopian transport authorities are provided with a decision-support framework that covers four deployment situations detailed with CAPEX/OPEX analysis, risk assessment, and guidance for a phased rollout to making a wise investment, risk reduction of the project, and ensuring better emergency coordination and road safety management, and thus, enabling.

The study reveals that if a mission-critical communication (MCC) system is installed along the Addis Ababa, Adama Toll Road, it can greatly improve public safety, operational efficiency, and economic benefits. [24]. Closing the communication gaps that exist, the system can make emergency responses faster and more coordinated and efficiently reduce the time needed to clear the incidents, thus it lowers the extent of injuries. [**?**]. From an economic point of view, it facilitates effective traffic management, lessens the consequences of road closures, and helps to raise the level of regional productivity. Using the existing telecom assets, the method provides a cheap and easily repeatable model for transport corridors, industrial parks, and urban areas in Ethiopia, thus guiding the formulation of policies that foster infrastructure sharing, public-private partnerships, and the best use of national resources, all while enhancing the resilience of the society and ensuring the continuity of operations. [25].

1.8 Thesis Layout

There are Eight Chapters in this thesis. The first Chapter explains the introduction, problem statement, objective, methodology, scope, limitations, literature reviews, and contributions of the thesis. The second Chapter deals with a general overview of Mission-Critical Communications (MCC) Systems, Wireless Network Technologies for MCC, Infrastructure Sharing Models, and Research Gap Identification. Chapter three discusses techno-economic modeling and evaluation methods, cost modeling, Cost Recovery & Value modeling, and investment decision-making tools within their mathematical approach.

In Chapter four, the general principles and methods for network scenario based coverage and capacity network dimensioning basic approaches are introduced. Chapter five discusses the analysis of existing infrastructure and Deployment scenarios. The implemented TEA framework, network dimensioning, Coverage site Maps for each network scenarios , Data-driven cost assumptions ,CAPEX and OPEX Estimation, Cost Recovery and Value Modeling are all explained in Chapter six. Chapter seven clarifies the obtained results from techno-economic modeling and interpretation for each scenario's feasibility. Finally, conclusion and future works are explained in Chapter Eight.

Chapter 2

Literature Review

2.1 Mission-Critical Communications (MCC) Systems

Evolution of MCC Technologies:

Mission-Critical Communications (MCC) have evolved from traditional, closed, voice-centric networks through open, broadband-enabled systems capable of supporting various data and multimedia services. The development of the MCC has been through different technological generations, which at each stage have introduced major changes in the architecture that have allowed for more capacity better interoperability, and richer services for critical operations [11].

1. Analog Land Mobile Radio (LMR) Systems:The Foundation

Mission-Critical Communications (MCC) have a genealogical line extending to the analog Land Mobile Radio (LMR) systems, which were the first wireless communication platforms primarily aimed at public safety and industrial coordination [4]. Working mainly in the VHF and UHF frequency bands, these systems employed quite simple trunked architectures such as MPT-1327, where a central controller would manage the shared Push-to-Talk (PTT) channels in a centralized manner [26]. Early LMR systems, though, which were primarily aimed at basic voice coordination, had several shortcomings limited coverage, being prone to interference, low capacity, no data services, and poor interoperability between agencies [27].

2. Digital Mobile Radio (DMR) First-Generation Digital Standards

Up until the shift to digital technology, professional mobile radio might be considered as having been slowly evolving from the perspective of voice quality, spectral efficiency, and the introduction of basic data services. Nowadays, professional mobile radio uses enhanced voice quality, higher spectral efficiency, and the availability of basic data services even to the remotest areas [28]. From an architectural point of view, the systems were largely trunked but adopted digital modulation and increasingly supported IP-based backhaul, thus allowing the interconnection of multiple sites and the extension of the coverage area [29]. Technologically, the DMR standardized by ETSI (Tier II III) was the most popular technology for cost-effective deployment, it also offered text messaging and basic status reporting even though the operations were still narrowband.

3. TETRA and P25: The Gold Standard for Professional Critical Voice

In the late 1990s and early 2000s, digital mission-critical communication (MCC) technologies based on dedicated standards, such as TETRA in Europe and P25 in North America, first became available [30]. These systems were designed using a cellular-style architecture with a zone controller responsible for call setup, mobility, and network resource management. This architecture features wide-area coverage as well as device-to-device communication via Direct Mode Operation when the network is unavailable. Besides that, the systems were capable of secure, encrypted voice, fast group call setup, and small data services like up to 28.8 kbps for TETRA Data. With a focus on P25 in particular, interoperability featured multi-vendor equipment compatibility [31].

4. The Broadband Revolution: 3GPP LTE 5G for MCC

3GPP was first to integrate mission-critical communication (MCC) requirements into LTE and 5G standards from Releases 12 and 13 onwards due to the increasing need for data in MCC environments and the inability of narrowband systems to meet those needs [32]. The changes included MC (Mission-Critical) services (MCPTT, MCVideo, MCData), priority QoS, local resilience with IOPS, direct communication via ProSe, and 5G network slicing for dedicated performance guarantees, all in an IP-based architecture [33].

5. Evolution From Voice to Data-Services

This evolution brings an important change in the operational capability:

Modern Mission-Critical Communications (MCC) have gone a long way from being isolated radio systems. They are now multi-functional broadband IP platforms that can

Era	**Primary Service**	**Key Enabler**	**Architecture**
Analog/Digital LMR	Voice and Basic PTT	Radio Channels	Closed, Trunked
TETRA/P25	Secure Voice and Low-speed Data	Digital Standards	Cellular, Vendor-Interoperable
LTE/5G-MC	HD Voice, Video, Real-Time Data, IoT	Broadband IP	Open, All-IP, Cloud-Native

Table 2.1: The Paradigm Shift of Services

support a real-time video, MCData, location tracking, and AI-enabled analytics [30]. This unification which is 3GPP standards-driven, fits perfectly into improving situational awareness and operational efficiency while at the same time it can get the most stringent security, reliability and latency requirements of emergency services up effectively, which is also evident in the AATR case study [34].

A. Fundamental MCC Requirements

Mission-Critical Communication (MCC) networks aim to provide highly reliable, secure, and low-latency communication channels for emergency services. They achieve latency of less than one millisecond from end to end, the handling of priority traffic, and a system availability of five-nines through the use of redundancies and the implementation of features such as IOPS. Security is twofold: encryption and authentication. Besides, group communication functionalities help in the coordination of operations; 5G further enhances these capabilities [35].

B. 3GPP Mission-Critical Services (MCX) Standards

3GPP has defined mission-critical services (MCX) over LTE and 5G with IMS-core integration since its Release 13 to enable modern emergency communications [30]. Among these MCX services, MCPTT offers prioritized broadband voice together with off-network operation and emergency alerts. MCVideo allows real-time video streaming and group video services. MCData caters for critical messaging, file transfer, and short data services such as location, status, and sensor information. The set of MCX standards mutually constitutes a solid and interoperable base for private mission-critical network projects such as the AATR deployment.

Global MCC Deployment Trends

The adoption of public safety broadband networks (PSBN) is a major global trend characterized by the shift from the use of legacy LMR systems to broadband MCC in public safety organizations. Various international implementations (FirstNet in the USA, ESN in the UK, and Safe-Net in South Korea) represent different governance and deployment planning models [36].

The Addis Ababa, Adama Toll Road (AATR) can take a few lessons from the above case studies, among them: the importance of spectrum as a resource to be addressed at the highest level, governance modes suited to local contexts, using existing STM-4 fiber to get strong coverage, and having architectures in place that can scale up to live and IoT services.

The success of MCC essentially depends on the availability of advanced 3GPP technology, the sustainability of financing, effective governance, and operational reliability.

2.2 Wireless Network Technologies for MCC

LTE-MC and 5G-MC Features

The mission-critical communications (MCC) evolution within the 3GPP framework has seen a transition from simply having connectivity to getting guaranteed delivery of services even under very harsh conditions [32]. LTE-MC and its follow-up, 5G-MC, have incorporated features that allow them to take a commercial cellular network and turn it into a highly reliable public safety and emergency response network platform that provides dependable, low-latency services and continuity of services even when the network is disrupted [37].

A. LTE-MC: Foundational Broadband Capabilities for MCC

LTE-MC was a major step in providing broadband capabilities that were resilient enough to support mission-critical communications [38]. Key features of the LTE-MC include IOPS, which is a feature that allows eNodeB clusters to continue the operation of their services like MCPTT without any interruption even during a core network outage, and ProSe, which allows direct device-to-device communication for low-latency, on-scene coordination, traffic offloading, and extended coverage in places where there is weak signal such as tunnels or lonely sections of the highway.

B. 5G-MC: Advancing towards Ultimate Performance and Flexibility

Without losing sight of the strengths of LTE-MC, 5G-MC pushes the boundaries of mission-critical performance by achieving Ultra-Reliable Low-Latency Communication (URLLC) that allow it to have a sub-millisecond latency and high reliability which are perfect for real-time operations like giving the autonomous emergency vehicle the right of way on the Addis Ababa, Adama Toll Road (AATR). Network slicing guarantees the provision of dedicated QoS and security even in a situation where the infrastructure is shared, and Mobile Edge Computing (MEC) is used to reduce the latency as well as to continue the services. Taken together, LTE-MC and 5G-MC are the two solid pillars of a scalable and resilient framework that can provide a broad range of advanced, data-driven emergency services along the AATR.

2.2.1 Available Frequency Bands for Mission-Critical Communications

LTE-MC Frequency Bands (3GPP Release 13-15)

Band	Frequency Range	Duplex	Bandwidth
Band 3	1800 MHz (1710-1785 UL / 1805-1880 DL)	FDD	2×20 MHz
Band 1	2100 MHz (1920-1980 UL / 2110-2170 DL)	FDD	2×20 MHz
Band 7	2600 MHz (2500-2570 UL / 2620-2690 DL)	FDD	2×20 MHz
Band 20	800 MHz (832-862 UL / 791-821 DL)	FDD	2×10 MHz
Band 28	700 MHz (703-748 UL / 758-803 DL)	FDD	2×10-20 MHz

Table 2.2: LTE-MC Frequency Bands for AATR Deployment

5G-MC Frequency Bands (3GPP Release 16-17)

Band	Frequency Range	Duplex	Bandwidth
n78	3300-3800 MHz	TDD	50-100 MHz
n1	2100 MHz (1920-1980 UL / 2110-2170 DL)	FDD	2×20 MHz
n3	1800 MHz (1710-1785 UL / 1805-1880 DL)	FDD	2×20 MHz
n28	700 MHz (703-748 UL / 758-803 DL)	FDD	2×10-20 MHz
n41	2496-2690 MHz	TDD	40-100 MHz

Table 2.3: 5G-MC Frequency Bands for AATR Deployment

Challenges with Private mission-critical LTE and 5G Deployments

Private Mission-Critical LTE deployment challenges

Aspect	Pros	Cons/Challenges
Coverage	- Wider coverage range per cell - Better suited for rural areas with sparse populations	- Limited bandwidth for high data rates - May struggle with ultra-low latency requirements
Technology Maturity	- Proven and stable technology - Broad device ecosystem	- Less future-proof as 5G adoption increases
Cost	- Lower deployment and equipment costs compared to 5G	- Scalability for advanced applications (e.g., IoT, AR/VR) is limited
Latency	- Adequate for basic mission-critical use cases (e.g., voice, push-to-talk)	- Not ideal for ultra-reliable low-latency applications
Spectrum	- Easier to acquire licensed spectrum for LTE in rural areas	- Spectrum availability may be less optimal for high-bandwidth requirements

Table 2.4: Private Mission-Critical LTE Deployment Challenges

Private Mission-Critical 5G deployment challenges

Aspect	Pros	Cons/Challenges
Coverage	- Enhanced capacity with mmWave - Supports dense device connectivity	- Limited coverage per cell in FR2 - More base stations needed for rural areas, increasing costs
Technology Maturity	- Future-proof with advanced features (e.g., slicing, URLLC, eMBB)	- Still maturing, with higher complexity in deployment and integration
Cost	- Long-term cost benefits for advanced applications	- Higher initial investment in infrastructure and devices
Latency	- Ultra-reliable low-latency communication (URLLC) capabilities	- Requires advanced network planning to achieve low-latency goals in rural areas
Spectrum	- Availability of private spectrum bands in many regions	- High-frequency bands (FR2) are less effective for rural coverage due to propagation limitations

Table 2.5: Private Mission-Critical 5G Deployment Challenges

2.2.2 Network Slicing for Mission-Critical Services

Network slicing in 5G allows us to have virtual networks on the same infrastructure. This means Network slicing in 5G gives us reliable and secure performance for important communications. We do not need networks for this. This is very important for things like AATR where commercial infrastructure is shared. Network slicing in 5G is useful, for these kinds of deployments because it uses shared infrastructure [39].

A. Conceptual Foundation of Network Slicing

A. Conceptual Foundation of Network Slicing

A network slice is a network that is just for a specific service. This network slice has its computing and storage and networking resources. The Network Slice Template defines what a network slice is. It makes sure the network slice works by using something called Service Level Agreements. The network slice is also secure because it is separate, from networks and has its own rules. Each network slice can be. Managed on its own, which is called operation and management of the network slice.

B. Key Characteristics of a Mission-Critical Slice

A mission-critical communication slice is very important for networks. It makes sure that the network has the resources it needs the quality of service is high and everything is secure from one end to the other. The network uses its radio and other resources like the spectrum, backhaul and core functions, to make sure that things happen quickly and reliably. This helps a lot with applications, like the ones that need high priority and special treatment because they have to work all the time. The network also keeps everything secure so only the right people can get in which is what public safety needs to work properly. The mission-critical communication slice does this by using mechanisms, like high priority and taking control when necessary and it keeps the private network safe, with its own security functions.

C. Relevance to the AATR Hybrid Deployment Model

For the AATR case study the AATR case study uses network slicing to make mission-critical communications more affordable. This is done by renting a MCC slice" from Ethio Telecom. The AATR case study shares the existing infrastructure with Ethio Telecom.. The AATR case study still makes sure that the MCC slice is separate and secure.

The AATR case study has agreements in place to make sure that critical applications are always available and work quickly. The MCC slice can also be easily scaled up during emergencies. When new services are added.

The AATR case study uses network slicing to separate the quality of the service from who owns the infrastructure. This helps to create MCC networks and partnerships between the public and private sectors, along the Addis Ababa–Adama Toll Road.

2.2.3 Quality of Service (QoS) Requirements for Mission-Critical Communications

Mission Critical Communications over LTE and 5G use rules to make sure that emergency traffic gets priority and is very reliable. This means that emergency messages get through quickly and do not get lost. LTE uses something called QCIs which're like special codes to make sure that emergency voice, data and video messages get through. These codes are like a key that opens up a path for the emergency messages.

5G is even better at this because it uses something called 5QIs which're like super special codes and it can also control things dynamically. This means that 5G can make sure that time sensitive applications, like emergency messages get through quickly and reliably. The special rules that make sure emergency traffic gets priority work all the way from the device to the core of the network. This is important because it means that emergency messages can get through when the network is being used by a lot of people like in a big emergency situation where many people are trying to call for help at the same time. Mission Critical Communications get priority on shared networks, which's very important for things, like hybrid AATR deployments. The QCI/5QI framework is really important for police, ambulance and toll operations to work well. It plays a role in how networks are designed and how people make financial plans for technology. The QCI/5QI framework is something that affects these operations a lot so it is used to make decisions about networks and money, for technology.

2.3 Infrastructure Sharing Models

Infrastructure sharing is a way to save money and get communication networks up and running quickly. This is especially helpful in places like the Addis Ababa–Adama Toll Road where money's tight. Using what is already there is an option than starting from scratch. It helps keep things working smoothly and efficiently. Infrastructure sharing of communication networks is very useful, in situations.

2.3.1 Tower Sharing Economics

Tower sharing on Ethio Telecoms eight existing towers really helps cut down the costs of building a network for AATR MCC. It also makes it faster to get everything up and running. By using towers that're already there Ethio Telecom does not have to spend a lot of money to build new sites. They also save money on maintenance and power because they are sharing these costs.

This means they can get the network running in 3 to 6 months instead of 12 to 18 months. This is a deal because it helps Ethio Telecom get the network working quickly and safely. Tower sharing is a way for Ethio Telecom to build a new network without spending too much money or taking too much time. It is a way to make sure the network is working well and is safe to use. Tower sharing is important, for Ethio Telecom because it helps them build a network quickly and at a low cost.

2.3.2 RAN Sharing

RAN sharing is a way for multiple phone companies to share the parts of their network that connect to cell towers. This helps lower the costs of building and running the network. There are a ways to do this. One way is called MOCN. With MOCN multiple phone companies can use the cell towers to connect to their own main systems. Another way is called MORAN. With MORAN the phone companies share the cell tower sites and the connections to those sites but they each have their own equipment.

MOCN is good for expanding the area where people can get service. MORAN is good for phone companies that want to be in control of how data and service they can provide to their customers. For important systems like AATR using a MOCN-style sharing system with Ethio Telecom could be a good idea. This would allow them to provide service to an area while still keeping control over the critical parts of their system and the data that is being sent. RAN sharing and MOCN can help phone companies, like Ethio Telecom work together to provide service to their customers.

2.3.3 Network as a Service (NaaS) and Core Network Sharing

Network as a Service lets people like AATR use the internet and communicate from one end to the other for important things without having to own all the equipment and systems. This means they do not have to pay a lot of money upfront. Instead they pay a money each month which is easier to budget for.

A good way to do this is to use a mix of shared equipment and private systems. This helps people like AATR get internet coverage without spending too much money. At the time they get to control their own data and security and make sure their internet service is good quality. This way Network as a Service can meet the needs of people like AATR who need good and reliable internet for important things. Network as a Service has to be reliable and secure and it has to work so people, like AATR can use it for their important communication.

2.3.4 Public-Private Partnership (PPP) Frameworks

Public Private Partnerships can help get communication systems by using money and knowledge from private companies. For the Addis Ababa–Adama Toll Road Public Private Partnerships help with the cost of building something while making sure the service is good. There are ways to do Public Private Partnerships, like DBFOM, BOOT and BOO and they are different, in how they share risks and who owns what. DBFOM is a way when people cannot pay directly for something because it uses something called availability payments.

For Public Private Partnerships to work we need to know what we want to achieve share the risks fairly watch how things are going and use technology. Public Private Partnerships can deliver communication systems like the ones needed for the Addis Ababa–Adama Toll Road by using private investment and expertise. A DBFOM-based PPP for AATR is a way to get things done because it uses the good things about private companies and the oversight of the public. This is important for the economic analysis and the risks that are talked about in the chapters that come later. The DBFOM-based

PPP for AATR is a system that combines the best of both worlds, private efficiency and public oversight which's necessary for the techno-economic and risk analyses of the DBFOM-based PPP for AATR that are discussed in the later chapters of the DBFOM-based PPP, for AATR.

2.4 Research Gap Identification

When you look at what people have written about MCC, wireless technologies and sharing infrastructure you can see the things about LTE and 5G. You can also see that sharing infrastructure is a good idea from a money standpoint and that looking at the total cost of something and the return on investment is important.. There are still some things we do not know about how this works in countries that are not as rich and in areas where people and things move in a straight line. Most of the studies that have been done are about places where people have a lot of money to spend or where things are very simple so they do not really help us understand how to make choices when we do not have a lot of resources and things are complicated. MCC and wireless technologies are very important, in this context. We need to think about how to use them in the best way. This thesis addresses these gaps by developing a techno-economic framework applied to the Addis Ababa–Adama Toll Road, systematically evaluating multiple deployment scenarios for hybrid MCC networks.

Chapter 3

Techno-economic modeling and Evaluation Method

3.1 Techno-Economic Analysis (TEA) Framework for AATR MCC Deployment

In this thesis, an integrated techno-economic assessment (TEA) framework is developed that connects technical design, economic modeling and risk assessment in a loop. The framework allows technical solutions to be constrained by economic considerations, financial models to be reflective of technical realities, and risks to be systematically factored into feasibility analysis. With such a structured approach, the thesis offers a sound, evidence-based basis for the choice of optimal hybrid deployment strategy for the Addis Ababa-Adama Toll Road mission-critical communication network, obtaining a balance among how it performs, what it costs and the overall result.

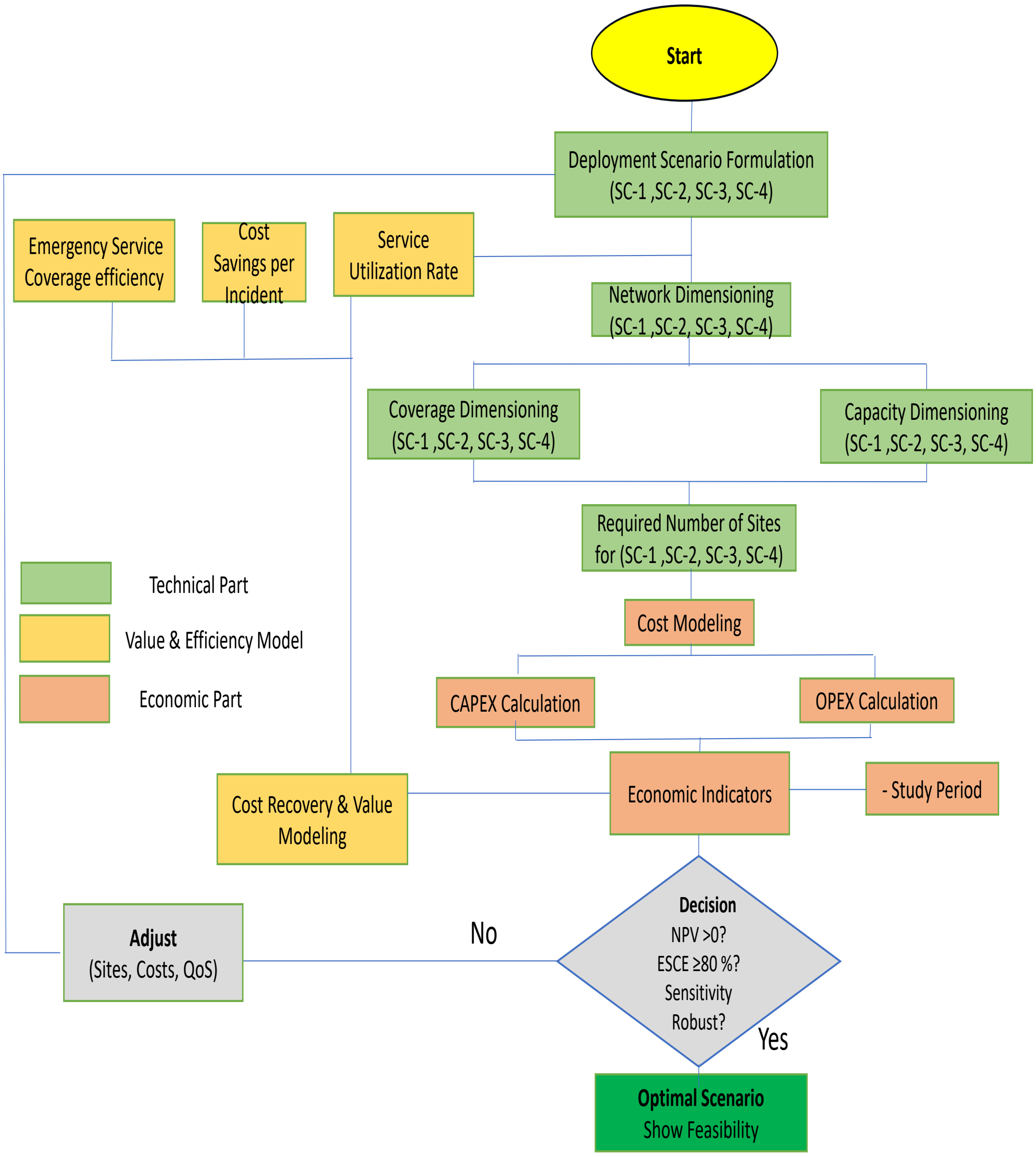


Figure 3.1: Modified (TEA) Framework for AATR MCC Deployment

3.2 Techno-Economic Analysis Methodologies

The techno-economic analysis (TEA) combines the technical performance and the economic feasibility to assess the feasibility of implementing the Mission-Critical Communication (MCC) networks along the Addis Ababa-Adama Toll Road. The method enables the evaluation of hybrid deployment situations to be balanced as engineering design is connected with financial sustainability. In the analysis, the most important methodologies such as cost modelling on network scenarios, total cost of ownership (TCO), cost-benefit analysis with different assumptions, and risk assessment are used to support decision-making regarding investment and guarantee efficiency in long-term operations.

3.3 Cost modeling

Techno-economic analysis is a formal approach to evaluation of the economic feasibility and performance of the deployment of private mission-critical LTE/5G networks. This analysis has incorporated technical and economic aspects by using the ACTS (TERA) Framework to optimize network deployment and operation.

The framework is designed in a manner that it gives an insight into cost modelling, including the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) and that the network meets the specifications of performance and reliability.

3.3.1 Capital Expenditure (CAPEX)

Capital expenditure (CAPEX) covers upfront network deployment costs, determined by dimensioning to meet coverage, capacity, and performance requirements.

$$\text{CAPEX} = \sum_{i=1}^{N} \left(C_{\text{gNB},i} + C_{\text{Core},i} + C_{\text{Backhaul},i} + C_{\text{Installation},i} \right) \tag{3.1}$$

where:

- CAPEX refers to the total capital expenditure on the private LTE/5G network,
- N is the number of network components or sites included in the deployment,
- $C_{\text{gNB},i}$ denotes the cost of the i-th gNodeB (base station), which includes costs of hardware, software licensing, and site preparation.
- $C_{\text{Core},i}$ is the cost of the i-th core network element, such as AMF, SMF, UPF, and supporting servers,

- $C_{\text{Backhaul},i}$ is the cost of the i-th backhaul infrastructure, including fiber, microwave links, or satellite connections, and
- $C_{\text{Installation},i}$ is the installation and commissioning cost for the i-th network component, including labor and system setup.

3.3.2 Operational Expenditure (OPEX)

The operational expenditure (OPEX) for private LTE/5G networks is modeled as the sum of maintenance, site rental, infrastructure leasing, and energy consumption costs:

Total OPEX Formulation

$$\text{OPEX}_{\text{total}} = C_{\text{maint}} + C_{\text{site}} + C_{\text{infra}} + C_{\text{energy}} \tag{3.2}$$

Maintenance and Operational Costs

$$C_{\text{maint}} = \sum_{i=1}^{N} \left(C_{\text{maint},i} \times (1 + r_{\text{infl}})^{t} \right) \tag{3.3}$$

where:

- N is the number of network elements,
- $C_{\text{maint},i}$ is the annual maintenance cost of network element i,
- r_{infl} is the annual inflation rate, and
- t is time in years.

Site Rental Costs

$$C_{\text{site}} = \sum_{j=1}^{M} \left(C_{\text{rent},j} \times (1 + r_{\text{infl}})^{t} \right) \tag{3.4}$$

where:

- M is the number of sites, and
- $C_{\text{rent},j}$ is the annual rental cost per site j.

Infrastructure Leasing Costs

$$C_{\text{infra}} = \sum_{k=1}^{L} \left(C_{\text{lease},k} \times (1 + r_{\text{infl}})^t \right) \tag{3.5}$$

where:

- L is the number of leased infrastructure components, and
- $C_{\text{lease},k}$ is the annual leasing cost per component k.

Energy Consumption Costs

$$C_{\text{energy}} = \sum_{m=1}^{P} \left(P_m \times C_{\text{energy/unit}} \times H_m \times (1 + r_{\text{infl}})^t \right) \tag{3.6}$$

where:

- P_m is the power consumption of network element m (in kW),
- $C_{\text{energy/unit}}$ is the cost per unit of energy (e.g., USD/kWh),
- H_m is the annual operating hours of network element m, and
- P is the total number of energy-consuming network elements.

3.3.3 Total Cost of Ownership (TCO)

The **Total Cost of Ownership (TCO)** is calculated as the sum of the initial capital expenditure and the discounted recurring operational costs over the network lifetime:

$$\text{TCO}_{\text{total}} = \text{CAPEX} + \sum_{t=1}^{T} \frac{(\text{OPEX}_t + \text{Maintenance}_t + \text{Upgrade}_t)}{(1+r)^t} \tag{3.7}$$

where:

- $\text{TCO}_{\text{total}}$ is the total cost of ownership over the study period,
- CAPEX is the initial capital expenditure, including network equipment, civil works, installation, and system integration,
- OPEX_t is the operational expenditure in year t, including energy, staffing, site lease, and licensing costs,
- Maintenance_t represents annual maintenance and repair costs in year t,
- Upgrade_t denotes periodic upgrade or capacity expansion costs in year t,
- T is the total network lifetime in years, and
- r is the discount rate accounting for the time value of money.

3.4 Cost Recovery & Value Modeling

Cost Recovery and Value Modeling in this thesis provides a structured approach to evaluate the economic return of deploying private mission-critical LTE/5G networks along the Addis Ababa–Adama Toll Road. By analyzing the annual cost saving per emergency event, the rate of service utilization and the efficiency of infrastructure coverage, the model will be useful in evaluating the time behavior related to the investment recovery and delivery of the value of public safety in the context of different deployment situations.

The societal and economic value of each of the scenarios is considered through a costrecovery and value modeling framework that incorporates quantitative and qualitative gains of improved emergency response systems.

It supports decision-makers by quantifying both financial viability and societal impact over a 10-year horizon.

3.4.1 Emergency Service Coverage Efficiency (ESCE)

Emergency Service Coverage Efficiency (ESCE) specifies the percentage of the toll road corridor and critical emergency points (e.g., stations, tunnels, and accident hotspots) effectively covered by the private LTE/5G network for mission-critical communications.

$$\text{ESCE} = \frac{\text{Area Covered by Network}}{\text{Total Target Area}} \times 100 \tag{3.8}$$

where:

- ESCE is the Emergency Service Coverage Efficiency expressed as a percentage,
- Area Covered by Network represents the physical or functional area where mission-critical communication services are available, and
- Total Target Area is the total area of the toll road corridor and all key emergency locations that require coverage.

Modeling Approach:

- Use GIS-based coverage maps and cell planning outputs from the Radio Link Budget (RLB) to determine total km^2 or percentage of road covered.
- Assign a coverage efficiency score for each scenario (e.g., Scenario 4 = 95 percentage, Scenario 1 = 60 percentage).
- Factor this into value modeling as a coverage multiplier (higher coverage → higher service value).

3.4.2 Service Utilization Rate (SUR)

The **Service Utilization Rate (SUR)** represents the percentage of system capacity actively used by authorized mission-critical personnel or applications (e.g., video feeds, push-to-talk, telemetry, IoT sensors).

$$\text{SUR} = \frac{\text{Used Network Capacity (per day or month)}}{\text{Total Available Capacity}} \times 100 \tag{3.9}$$

where:

- Used Network Capacity is the actual bandwidth or resource consumed by authorized users,
- Total Available Capacity is the maximum network capacity available for mission-critical services,
- SUR is expressed as a percentage (%).

Modeling Approach:

- Use traffic modeling data from the capacity planning section.
- Define the potential user base (e.g., number of patrol vehicles, control center agents).

- Estimate daily or monthly average utilization as a percentage of network capacity (DL/UL Mbps used vs. total capacity).

3.4.3 Effective Per-Incident Cost Reduction ($\mathbf{p_{eff}}$)

The total economic benefit depends not only on the intrinsic capability of LTE/5G technologies to reduce incident management costs, but also on the actual share of the expressway that is covered and the fraction of services actively utilized. Therefore, the effective incident cost reduction is computed as a multiplicative combination of three factors:

The effective reduction rate is:

$$p_{\text{eff}} = p_{\text{tech}} \times ESCE \times SUR \tag{3.10}$$

where:

- **p tech** :Technical reduction capability (fractional), representing the maximum possible cost reduction per incident if the system is perfectly deployed and fully used (e.g., 0.50 = 50%).
- **ESCE:** Emergency Service Coverage Efficiency, representing the proportion of the corridor or incident areas reliably served (e.g., 0.85 = 85%).
- **SUR:** Service Utilization Rate, representing the proportion of mission-critical users who actually utilize the system for operational tasks (e.g., 0.60 = 60%).

Interpretation:

Even if the technology is capable of reducing incident response costs by a large margin, the realized savings along the Addis Ababa–Adama Expressway depend on how much of the corridor is covered by LTE/5G (ESCE) and how consistently emergency and operational teams use the network's mission-critical services (SUR).

3.4.4 Annual Savings from Incident Reduction

Let C_{annual} denote the current annual cost associated with traffic incidents, delays, fuel losses, response logistics, and related operational inefficiencies. The implementation of the private LTE/5G network yields economic savings proportional to the effective reduction rate p_{eff}.

$$\text{Annual Savings} = C_{\text{annual}} \times p_{\text{eff}} \tag{3.11}$$

where:

- C_{annual} is the total annual cost of incidents and inefficiencies,
- p_{eff} is the effective reduction rate, as defined in Section 3.4.3

Interpretation:

This expresses the monetary value of efficiency gains due to improved situational awareness, real-time video, faster dispatch coordination, and reduced incident duration.

3.4.5 Annual OPEX (Derived from 10-Year Totals)

OPEX estimates for the deployment scenarios are provided as cumulative values over a 10-year period. To evaluate annual financial performance under Techno-Economic Analysis (TEA), the annualized operating cost is calculated as:

$$\text{annual\_OPEX} = \frac{\text{OPEX}_{10\text{y}}}{10} \tag{3.12}$$

where:

- $\text{OPEX}_{10\text{y}}$ is the total operational expenditure over the 10-year study period,
- annual_OPEX is the average annual operating cost.

Interpretation:

This ensures comparability across scenarios and aligns with the assumption of steady yearly operations (maintenance, fiber lease, power consumption, monitoring, etc.).

3.4.6 Annual Net Economic Benefit (AnnualNet)

The annual net economic benefit represents the difference between annualized savings from incident reduction and the annual operating costs:

$$\text{AnnualNet} = \text{Annual Savings} - \text{annual\_OPEX} \tag{3.13}$$

where:

- Annual Savings is the annual cost reduction achieved through the deployment of the mission-critical LTE/5G network (see Section 3.4.4)
- annual_OPEX is the average annual operational expenditure (see Section 3.4.5),
- AnnualNet represents the net annual financial benefit to the toll road authority from the system deployment.

Interpretation:

This directly represents the yearly value generation attributable to the mission-critical communication system, before discounting and before CAPEX recovery.

3.5 TEA Evaluation Method

The TEA combines the above parameters to evaluate the financial viability and societal return of each deployment scenario.The approach integrates cost models, discounted valuation, and investment metrics consistent with network infrastructure TEA frameworks.

3.5.1 Net Present Value (NPV)

The cash-flow structure for the mission-critical LTE/5G deployment is as follows:

- Year 0: $-\text{CAPEX}$
- Years 1 to 10: AnnualNet

The present value factor for a constant annual benefit stream over T years at discount rate r is given by:

$$PV_{\text{factor}} = \frac{1-(1+r)^{-T}}{r} \tag{3.14}$$

where $T = 10$ years.

Therefore, the total project Net Present Value (NPV) is calculated as:

$$\text{NPV} = -\text{CAPEX} + \text{AnnualNet} \times PV_{\text{factor}} \tag{3.15}$$

where:

- CAPEX is the total capital expenditure for network deployment (see Section 3.3.1),
- AnnualNet is the net annual economic benefit (see Section 3.4.6),
- r is the discount rate, and

- PV_{factor} accounts for the present value of a constant 10-year benefit stream.

Interpretation

NPV measures the true discounted economic return of each LTE/5G scenario, accounting for initial investment and recurrent benefits.

3.5.2 Discounted Benefit–Cost Ratio (BCR)

The discounted benefits and costs are calculated as follows:

Discounted Benefits

$$\text{Discounted Benefits} = \text{Annual Savings} \times PV_{\text{factor}} \tag{3.16}$$

Discounted Costs

$$\text{Discounted Costs} = \text{CAPEX} + \text{annual\_OPEX} \times PV_{\text{factor}} \tag{3.17}$$

Benefit–Cost Ratio (BCR)

$$\text{BCR} = \frac{\text{Discounted Benefits}}{\text{Discounted Costs}} \tag{3.18}$$

where:

- Annual Savings is the annual economic benefit from incident reduction (see Section 3.4.4),
- annual_OPEX is the annual operating expenditure (see Section 3.4.5),
- CAPEX is the total capital expenditure (see Section 3.3.1),
- PV_{factor} is the present value factor for a 10-year constant benefit stream (see Section 3.5.1),

- BCR represents the ratio of discounted benefits to discounted costs.

Interpretation

A BCR > 1 indicates that the economic benefits exceed the discounted total costs, justifying the deployment.

3.5.3 Payback Period

For deployment scenarios with a positive annual net economic benefit, the payback period is defined as the time required for cumulative net benefits to recover the initial capital investment.

$$\text{Payback Years} = \frac{\text{CAPEX}}{\text{AnnualNet}} \tag{3.19}$$

where:

- CAPEX is the total initial capital expenditure,
- AnnualNet is the annual net economic benefit,
- Payback Years represents the number of years required to recover the initial investment.

Interpretation

This indicates how many years are required to recover the initial investment through economic gains. It is useful for infrastructure prioritization and risk assessment.

3.5.4 Sensitivity Analysis

1. **To test the robustness of results, sensitivity analysis was performed by varying key parameters:**
    - $CSP_i \pm 20\%$ (benefit uncertainty)
    - OPEX growth rate ±10%
    - Discount rate (6–12%)
2. **Adjustment for Currency Fluctuation and Inflation**

Given Ethiopia's volatile exchange rate environment and high inflation, the original techno-economic analysis based on a fixed exchange rate (1 USD = 153.53 ETB) may underestimate financial risk. To improve realism, both CAPEX and OPEX values are adjusted using a range of plausible exchange-rate variations (±10%) and an annual inflation factor consistent with historical trends.

The adjusted cost in Ethiopian Birr (ETB) for year t is calculated as:

$$\text{Adjusted Cost}_{\text{ETB},t} = \text{Base Cost}_{\text{USD}} \times \text{ExchangeRate}_t \times (1+i)^t \tag{3.20}$$

where:

- $\text{Base Cost}_{\text{USD}}$ is the baseline cost expressed in USD,
- ExchangeRate_t is the USD–ETB exchange rate in year t, incorporating a fluctuation range of ±10% (i.e., FX factor = 0.9–1.1),
- $i = 0.07$ is the assumed annual inflation rate,
- t is the time index in years ($t = 0$–1 for the 18-month implementation period).

This adjustment enables a more robust assessment of cost uncertainty and financial exposure under Ethiopia's macroeconomic conditions while preserving consistency across deployment scenarios.

Chapter 4

Network Dimensioning

Network dimensioning is a critical preliminary stage of a larger process of network planning, which seeks to establish the density and structure of the sites that are required to meet the coverage and capacity needs of a given geographic region. In this step, the calculation of key parameters such as cell range, sector throughput, and the projected amount of network equipment are calculated. The results of such calculations are the necessary inputs of Technical and Economic Assessment (TEA) stage, which also measures the resources and expenditures involved in the network deployment.

The need to balance coverage and capacity imperatives leads dimensioning activities. The coverage dimensioning takes the priority to make sure that the network has adequate geographic coverage and most of these factors are mainly determined by factors like the characteristics of propagation, the transmission power, and environmental conditions. On the other hand, capacity dimensioning is guided by the need to ensure that the network is able to support the expected traffic loads considering the following variables: user density, typologies of services, and peak usage conditions.

At this stage, two important values are obtained, one of the coverage dimensioning and the second one of the capacity dimensioning. Based on the set dimensioning guidelines, whichever of these two values is larger is adopted as the final output hence guaranteeing that neither coverage nor capacity requirements are compromised. This methodological approach ensures that the network design is such that it is capable of supporting the most challenging needs be it geographic coverage needs or traffic capacity needs. The outputs of the resulting network dimensioning are the foundation of the next stage planning and deployment processes that will ensure the network is efficient and cost effective and mission critical goals are achieved.

4.1 Coverage Dimensioning Approach

The section outlines the coverage dimensioning approach used in the implementation of a private Mission Critical Communication (MCC) network along the Addis Ababa-Adama Toll Road (AATR). The main objective would be to ensure sustained, dependable radio coverage to meet high availability and reliability standards of emergency and safety-critical services. These approaches include radio link budget analysis, choice of a suitable propagation model and geometric coverage planning, which are all modified to suit a rural highway environment.

The step of coverage dimensioning starts with a radio link budget (RLB) of the downlink (DL) and uplink (UL) directions. The RLB is used to define the maximum allowed path loss between the user equipment (UE) and the serving base station (eNB/gNB) and maintain the desired quality-of-service level. This analysis brings in transmitter power, antenna gains, receiver sensitivity, noise figure, interference margins, and shadow-fading margins and as a result, makes sure that targets of mission-critical performance are achieved.

Maximum coverage radius is independently calculated in case of DL and UL, depending on the propagation model chosen and the link budgets calculated. In order to ensure the bidirectional connectivity, the effective cell radius is the smaller of the DL and UL coverage radii. A covering margin is then added to provide continuity of coverage and handover strength along the expressway line.

General Assumptions

The coverage dimensioning analysis is based on the following assumptions:

- **Corridor length**: $L = 78.5$ km
- **Road morphology**: Rural highway toll road environment
- **Sectorization**: Two sectors per site

- **Coverage overlap factor**: $O = 10\%$
- **Effective cell radius**: $R_{\text{eff}} = \min(R_{\text{DL}}, R_{\text{UL}})$
- **Coverage reliability**: 95% location probability
- **Service availability**: 99.9% for mission-critical services

These assumptions serve as a consistent and conservative framework for calculating the number of locations necessary to attain dependable coverage along the AATR while also meeting the needs of mission-critical communication.

4.1.1 Propagation Model Selection for Rural Mission-Critical Networks

Choosing the right propagation model for a private mission-critical LTE or 5G network is a very important step of network design because it has a direct influence on coverage prediction, capacity planning, and resource allocation. Rural highway environments have few buildings, mainly open land, and very little vegetation, so the models that will be used need to be able to reflect large-cell propagation behavior over very long distances.

The COST-231 Hata model is chosen in this paper as the main propagation model for LTE deployments below 2 GHz. The model is extensively tested and validated for rural and suburban macrocells situations and gives a good estimation of the path loss at 1500, 2000 MHz which is the frequency range of choice for mission-critical LTE-based services along the AATR.

The COST-231 Hata urban path loss formulation is given by:

$$PL_{\text{urban}} = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_b) - a(h_m) + [44.9 - 6.55\log_{10}(h_b)]\log_{10}(d) + C_m \tag{4.1}$$

where:

- f is the carrier frequency in MHz,
- h_b is the base station antenna height in meters,
- h_m is the mobile station antenna height in meters,
- d is the transmitter–receiver separation distance in kilometers,
- C_m is the environment correction factor.

The mobile antenna height correction factor is defined as:

$$a(h_m) = (1.1\log_{10}(f) - 0.7)h_m - (1.56\log_{10}(f) - 0.8) \tag{4.2}$$

To adapt the model to the rural highway environment of the AATR corridor, the following rural correction is applied:

$$PL_{\text{rural}} = PL_{\text{urban}} - 4.78[\log_{10}(f)]^2 + 18.33\log_{10}(f) - 40.94 \tag{4.3}$$

For 5G deployments operating above 2 GHz, the empirical Hata-based models are no longer valid. Therefore, the **3GPP TR 38.901 Rural Macrocell (RMa) model** is used for 5G coverage analysis, as it supports frequencies up to 100 GHz and incorporates terrain- specific parameters relevant to modern broadband systems.

The corresponding path loss expression for the 3GPP TR 38.901 RMa scenario is:

$$\text{PL} = 28 + 22\log_{10}(d) + 20\log_{10}(f_c) \tag{4.4}$$

where:

- PL is the path loss in decibels (dB),
- d is the distance between transmitter and receiver in meters,
- f_c is the carrier frequency in gigahertz (GHz).

By combining the COST-231 Hata model for LTE frequencies and the 3GPP TR 38.901 model for 5G frequencies, this study ensures accurate and standards-compliant propagation modeling across all deployment scenarios considered for the AATR mission-critical communication network.

4.1.2 Operating Frequency and Bandwidth

Choosing the operating frequency, bandwidth, and duplexing mode is the most critical aspect of the design of the LTE and 5G networks of the private mission when it comes to achieving the best coverage, capacity, and the overall network performance. Frequency bands are selected based on 3GPP Mission Critical Specifications, regulatory availability and unique deployment environment necessities. Poor propagation characteristics of higher frequencies, e.g. 700 -850 MHz, give wide coverage in rural or challenging environments, and higher capacity and throughput of lower frequency ranges such as 3.5 GHz.

Traffic asymmetry and spectrum availability determine the duplexing mode to be used, which can either be Time Division Duplex (TDD) or Frequency Division Duplex (FDD). TDD gives the flexibility of dynamically assigning the uplink and downlink resources, but FDD ensures a consistent performance due to separate channels in each direction of transmission.

Network performance requires enough bandwidth per channel. It is generally suggested that at least 20MHz per channel should be allocated to allow high data rates, many simultaneous users, and decent cell edge performance.

In general, a multi-band approach consisting of low- and mid-frequency frequencies along with the choice of the most suitable duplexing mode and providing the required bandwidth in the channel allows achieving the necessary cost-effective and high-performance communication depending on the specific needs of the mission-critical LTE and 5G services.

Table 4.1. The frequency bands, propagation situations, models, bandwidths, and duplexing modes used in four mission-critical communication deployment situations are

summarized.

Scenario	**MC Technology**	**Propagation Scenario**	**Frequency Band (GHz)**	**Propagation Model**	**Bandwidth**	**Mode**
Scenario 1	LTE-MC	Rural Highway	0.7	COST-231 Hata	10 MHz	FDD
Scenario 2	LTE-Advanced	Mixed Highway	1.8 + 0.7	COST-231 Hata	20 MHz	FDD
Scenario 3	LTE-MC	Rural Highway	1.8	COST-231 Hata	20 MHz	FDD
Scenario 4	5G-NR	Advanced Highway	3.5	3GPP TR 38.901	100 MHz	TDD

Table 4.1: Frequency Band and Propagation Model Summary

Frequency Band Rationale:

- **1800 MHz Band:** Scenario 1-3 Primarily used in scenarios giving a good compromise between coverage and capacity.
- **700 MHz Band:** This is the coverage-extension band in Scenario 4, which has better propagation properties.
- **3500 MHz Band:** Primary 5G band in Scenario, which is chosen to provide high-capacity services.

To achieve the objective of guiding the network planning towards the optimal performance, the mapping of mission-critical communication (MCC) services into the bandwidth that it needs, frequency bands that it prefers, and the latency limits is summarised in the following table 4.2.

4.1.3 Radio Link Budget parameter modeling

This section details the radio link budget parameters used for network dimensioning across the four deployment scenarios. The parameters are optimized for mission-critical communications in the rural highway environment of the Addis Ababa-Adama Toll Road.

Service	**Required BW**	**Preferred Band**	**Latency**
MCPTT Voice	64 kbps	700/1800 MHz	Less than 100 ms
MCData	256 kbps	1800/2100 MHz	Less than 150 ms
MCVideo	2-8 Mbps	1800/2600/3500 MHz	Less than 100 ms
IoT Sensors	10-100 kbps	700/1800 MHz	Less than 1 s
HD Video Analytics	10-20 Mbps	2600/3500 MHz	Less than 50 ms

Table 4.2: Service-Band Mapping for MCC

1. **eNodeB and gNodeB Transmitter Power:**

    - Higher power may be used to extend coverage in rural areas.

      Downlink (DL):

    - Scenario 1-3 (LTE): 46 dBm (40 W) per carrier
    - Scenario 4 (5G): 46 dBm for sub-6 GHz, 42 dBm for mmWave
    - Rationale: Maximum allowable power for coverage optimization in rural areas

    Uplink (UL):

    - UE power considered at device side
    - Base station receiver sensitivity optimized for -95 dBm

2. **eNodeB and gNodeB Antenna Gain :**

    The gain provided by the base station antenna, which enhances signal strength.

    - Typical value: 18–24 dBi
    - High-gain antennas are preferred in rural areas to maximize coverage.

      Macro Sites:

    - Scenario 1-3: 17 dBi (65° azimuth, 7° elevation)
    - Scenario 4: 21 dBi (advanced massive MIMO)
    - Small Cells: 5 dBi (omni-directional where deployed)

3. **UE Maximum Total Transmitter Power:**

    The maximum power transmitted by the user equipment (UE).

- Typical value: 23–26 dBm (200–400 mW).
- Limited by device hardware and regulatory constraints.

  Vehicle-mounted Terminals:

- LTE Devices: 23 dBm (200 mW)
- 5G Devices: 26 dBm (400 mW)
- Handheld Devices: 23 dBm

4. **Loss:**
   - Losses due to cables, connectors, and other components in the transmission path.
   - Typical Value: 2–3 dB.
   - Body Loss: 0 dB (vehicle-mounted equipment)
5. **Effective Isotropic Radiated Power (EIRP):**
   - The total power being radiated by the eNodeB/gNodeB in all the directions, is the combination of transmitter power and antenna gain, less the losses.

     Typical Values:

   - Scenario 1-3 DL: 46 + 17 - 3.5 = 59.5 dBm
   - Scenario 4 DL: 46 + 21 - 2.0 = 65 dBm

$$\text{EIRP} = P_{\text{TX}} + G_{\text{ANT}} - L_{\text{LOSS}}$$

Where:

- P_{TX}: Transmitter Power (dBm)
- G_{ANT}: Antenna Gain (dBi)
- L_{LOSS}: Loss (dB)

6. **Cell Edge User Throughput :**
   - The minimum achievable throughput for users at the edge of the cell.

- Typical Value: depending on bandwidth and modulation schemes.

  Minimum Requirements:

- MCPTT Voice: 64 kbps (UL/DL)
- Emergency Video: 2 Mbps DL, 512 kbps UL
- Data Services: 1 Mbps DL, 256 kbps UL

7. **Thermal Noise :**

   Calculation:

$$N = 10\log_{10}(kTB) + 30$$

Where:

$$\begin{aligned} k &= 1.38 \times 10^{-23}\,\mathrm{J/K} \\ T &= 290\,\mathrm{K} \\ B &= \text{bandwidth in Hz} \end{aligned}$$

Typical Values:

- 20 MHz LTE: -101 dBm
- 100 MHz 5G: -94 dBm

8. **Noise Figure :**

   Represents the degradation of the signal-to-noise ratio (SNR) caused by the receiver.

- Typical value: 3–7 dB for egNodeB/ggNodeB/ receivers.

  Receiver Components:

- Base Station: 3 dB (eNodeB/gNodeB)
- UE Device: 7 dB (commercial grade)
- Mission-critical UE: 5 dB (enhanced hardware)

9. **Signal-to-Interference-Noise Ratio (SINR):** This is the proportion of the power of a signal and the total power of the interference and noise, a very important factor for the determination of the quality of a link.

    - Typical value: -5 dB to 20 dB, depending on environmental conditions and interference levels.

      Target Values:

    - Voice Services: -3 dB minimum
    - Data Services: 0 dB to 20 dB (QPSK to 256QAM)
    - Mission-critical: +3 dB margin over commercial

10. **Receiver Sensitivity :**

$$S_{\text{RX}} = kT + NF + 10\log_{10}(B) + \text{SINR}_{\text{min}}$$

    Where:

    - kT: Thermal noise power density ($-174\,\text{dBm/Hz}$)
    - NF: Noise Figure (dB)
    - B: Bandwidth (Hz)
    - SINR_{min}: Minimum Signal-to-Interference-Noise Ratio (SINR) (dB)

    Typical Values:

    - Base Station UL: -95 dBm (MCPTT voice)
    - UE DL: -95 dBm
    - Enhanced: -98 dBm (Scenario 4)

11. **Slow/Shadow Fading Margin :** A margin to account for signal variations due to obstacles and terrain.

    - Typical value: 8–10 dB in rural areas.

      Clutter-based Penetration Losses:

    - Open Rural: 8 dB (95 Percentage coverage probability)

Parameter	**Scenario 1-3 (LTE)**	**Scenario 4 (5G)**	**Units**
eNodeB/gNodeB TX Power	46	46	dBm
Base Station Antenna Gain	17	21	dBi
UE TX Power	23	26	dBm
Total Losses	3.5	2.0	dB
EIRP (DL)	59.5	65.0	dBm
Cell Edge Throughput	1-2	2-10	Mbps
Thermal Noise (20/100 MHz)	-101/-94	-101/-94	dBm
Noise Figure (BS/UE)	3/7	2/5	dB
Target SINR	-3 to 20	0 to 25	dB
Receiver Sensitivity	-95	-98	dBm
Shadow Fading Margin	8-15	6-12	dB
Maximum Path Loss	137-144	150-154	dB

Table 4.3: Parameter Summary Table

- Vegetated Areas: 12 dB
- Tunnel Entries: 15 dB
- Vehicle Penetration: 6 dB

12. **Maximum Allowable Path Loss (MAPL) :**

$$\text{MAPL} = \text{EIRP} - S_{\text{RX}} + \text{Fading Margin}$$

Where:

- EIRP: Effective Isotropic Radiated Power (dBm)
- S_{RX}: Receiver Sensitivity (dBm)
- Fading Margin: Slow/Shadow Fading Margin (dB)

Typical Ranges:

- Scenario 1-3: 137-144 dB
- Scenario 4: 150-154 dB (advanced features)

4.1.4 Cell Area and Site Count

Cell Radius Calculation:

The effective cell radius R_{eff} is determined as:

$$R_{eff} = \min(R_{DL}, R_{UL}) \tag{4.5}$$

The inter-site distance (ISD) is calculated as:

$$ISD = \frac{2 \times R_{eff}}{\sqrt{1+O}} \tag{4.6}$$

Where the overlap factor $O = 10\%$ ensures seamless handover and coverage continuity essential for mission-critical communications.

Site Count Calculation

The number of sites required for coverage is calculated as:

$$N_{sites} = \frac{L}{ISD \times (1-O)} \tag{4.7}$$

This coverage dimensioning approach technically enable reliable mission-critical communications on the 78.5 AATR corridor and thus allow for an economical analysis of each deployment scenario.

1. **Path Loss Calculation**

   Model Used: The COST-231 Hata model is employed to calculate path loss for determining the cell radius. This model is widely used in rural, suburban, and urban environments due to its reliability in predicting signal attenuation over distances.

2. **Site Coverage and Configuration**

   Hexagonal Site Model:

- The hexagonal model is a standard approach in network planning to maximize coverage and minimize overlap between adjacent cells. It assumes that each site provides uniform coverage.

Site Configurations:

- Omni-directional: A single antenna covers 360 degrees, typically used in areas requiring simple coverage.
- Bi-sector: Two antennas split coverage into two sectors, often used to enhance coverage in specific directions.
- Tri-sector: Three antennas divide coverage into three 120-degree sectors, commonly used for high-capacity and high-density areas.

Next Steps Cell Radius Determination: After calculating the MAPL (Maximum Allowable Path Loss) for both uplink (UL) and downlink (DL), the radius is derived. This is critical for determining the number of sites required. Site Count Estimation: Based on the calculated cell radius and the total area to be covered, the number of required sites can be estimated.

4.2 Network Capacity Dimensioning

The Beginning of the Emergency Mission Critical LTE and 5G Capacity Dimensioning Process is Estimating Demand for Traffic by Determining the Amount of Emergency Users and What their Data Demand will be. The next Step in the Process is Selecting the Bandwidth Selection and Modulation Scheme Based On SINRs to Determine Cell Throughput/Efficiency/Capacity (Throughput is determined using Bandwidth and Spectral Efficiency) with Consideration for Overhead Considerations with the Network. The Number of Required Sites is then Calculated by Dividing Total Traffic Demand by Cell Capacity. The Entire Process meets Required QoS and Throughput Standards which leads to Finalizing a Site or Coverage Plan where Connectivity will be Reliable and the last Stage in the Process will Result in a Completed Design Readied for Implementation.

Capacity Dimensioning Process

1. **Traffic Demand Estimation**

   Identify the number of emergency users and their data plan requirements. Calculate the total traffic demand (T_{total}) using:

   $$T_{\text{total}} = N \cdot D \tag{4.8}$$

   where:

   - N: Number of users
   - D: Average data requirement per user

2. **Bandwidth and Modulation Scheme**

   - Determine the available bandwidth.
   - Select the modulation and coding scheme (MCS) based on the Signal-to-Interference-plus-Noise Ratio (SINR) levels.

3. **Throughput Calculation**

   Calculate the spectral efficiency (S) based on the MCS. Compute the cell throughput (T_{cell}) using:

   $$T_{\text{cell}} = B \cdot S \tag{4.9}$$

   where:

   - B: Bandwidth
   - S: Spectral efficiency

4. **Cell Capacity**

   Estimate the maximum supported traffic per cell:

   $$C_{\text{cell}} = \frac{T_{\text{cell}}}{(1 + O)} \tag{4.10}$$

   where:

   - O: Overhead factor (e.g., signaling, control traffic)

5. **Site Count**

   Determine the number of cells/sites required to handle the total traffic demand:

$$N_{\text{sites}} = \frac{T_{\text{total}}}{C_{\text{cell}}} \tag{4.11}$$

6. **Quality of Service (QoS) Assurance**

   Ensure that the blocking probability and throughput requirements meet the mission-critical service levels.

4.2.1 Aggregate Throughput or Data Rate Modeling

Network operators establish capacity requirements using traffic predictions and required cell throughput to determine capacity-based site counts. For Mission-Critical LTE and 5G networks, aggregate throughput is modeled according to 3GPP standards.

The maximum data transfer rate for downlink (DL) and uplink (UL) can be calculated using the following formula:

$$R_{\max} = N_{\text{RB}} \cdot BW_{\text{RB}} \cdot \eta \cdot (1 - O) \tag{4.12}$$

Where:
$R_{\max}$: Maximum data transfer rate (DL or UL),
N_{RB}: Number of Resource Blocks (RBs) available,
BW_{RB}: Bandwidth per Resource Block (e.g., 180 kHz for LTE),
η: Spectral efficiency based on the modulation and coding scheme (MCS),
O: Overhead factor (e.g., signaling, control, etc.)

4.2.2 Traffic modelling

To calculate the average total throughput per emergency user during the High Emergency Hour (HEH) for a private mission-critical LTE network, we can use the following formula:

$$T_{\text{avg, HEH}} = \frac{T_{\text{total, HEH}}}{N_{\text{HEH}}}$$

Where:

- $T_{\text{avg, HEH}}$: Average throughput per emergency user during HEH (in Mbps or kbps).
- $T_{\text{total, HEH}}$: Total throughput required during HEH (in Mbps or kbps).
- N_{HEH}: Number of active emergency users during HEH.

4.2.3 Capacity Based Site Counts

The capacity-based site count for an Emergency mission-critical LTE or 5G network can be calculated using the following formula:

$$\text{Max. no. of subscribers per e/gNodeB (DL, UL)} = \frac{C_{\text{e/gNodeB}}}{T_{\text{avg, sub}}}$$

Capacity-Based Site Count:

$$N_{\text{sites}} = \frac{T_{\text{total}}}{C_{\text{e/gNodeB}}}$$

Where:

- $C_{\text{e/gNodeB}}$: Total capacity of the e/gNodeB (in Mbps or kbps), considering both downlink (DL) and uplink (UL).
- $T_{\text{avg, sub}}$: Average throughput required per subscriber (in Mbps or kbps).
- T_{total}: Total traffic demand for the entire area (in Mbps or kbps).
- N_{sites}: Total number of sites required.

Chapter 5

Existing Infrastructure and Deployment Scenarios Analysis

5.1 Study Area: Addis Ababa-Adama Toll Road

5.1.1 Geographic and Demographic Context

The Addis AbabaAdama Toll Road (AATR) is a transport route that is strategically important and is located in the central highlands of Ethiopia. The corridor is about 78.5km long and links the capital city of Addis Ababa (elevation 2,355m) and the industrial centre of Adama (elevation 1,712m). The resultant difference in elevation of approximately 643 metres puts certain unique pressure on radio-frequency propagation and by extension on network design. The landscape of the path includes mountainous peaks, cut valleys and vast plains; all the geomorphological units vary in the coverage of signals and determine the best positioning of network infrastructure. The changing climatic conditions and seasonal precipitation also vary the behaviour of wireless signals further, which means that adaptive coverage strategies are required. The corridor is characterized by the gradual urban-rural transformation, which is reflected by the corresponding decrease in population density and communication demand further away one is to Addis Ababa. The AATR functionally acts as the main economic route in Ethiopia connecting the largest population centre in the country to the key industrial hubs and offering a key inland connection point to the Port of Djibouti.

5.1.2 Traffic Patterns and Emergency Service Requirements

Traffic analysis shows that the AATR manages an average daily traffic of about 40,000 vehicles annually and the growth is expected to be between 6 0 and 8 0. The composition of vehicles is as follows: 35% heavy commercial trucks, 45% private cars, 15% public transport vehicles and about 5% emergency and service vehicles. This allocation is indicative of the dual nature of the corridor in providing economic logistics and at the same time ease of movement of people. Within the framework of high-speed travel and high commercial flow, the need to have a stable communication system is the most relevant aspect of managing the traffic and responding to an incident and coordinating the emergency activities. The quantification of emergency service communication requirements was conducted using stakeholder consultations and incident data analyses, as well as critical requirements were identified to provide real-time voice, video, and data connectivity to enhance real-time response timelines and operational safety at the corridor.

5.2 Existing AATR Communication Infrastructure

5.2.1 General

The Addis Ababa-Adama Toll Road from Addis Ababa to Adama is 78.5 KM long with 2 mainline toll stations, 4 interchange toll stations, 1 service area. The Monitor Toll center is in mainline beginning point. Please see the numbers of stakes in table 5.1.

No.	**Station name**	**Number of stake**
1	Tulu Dimitu Mainline beginning point toll station	K2+690
2	Debre Zeit North Interchange Toll station	K16+930
3	The Service Area	K28+950
4	Debre Zeit South Interchange Toll station	K33+810
5	Modjo Interchange Toll station	K52+380
6	Adama West Interchange Toll station	K60+530
7	Adama mainline toll station	K64+900

Table 5.1: AATR Stations & Locations

The existing AATR communication system consists of optical transmission system, program-controlled switch, communication power, optical cable.

5.2.2 Communication system components

1. **Optical transmission system :**

   The existing AATR communication system applied the method of MSTP system and access network. The transmission section of access network will be applied built-in STM-4 equipments which jump every two stations and form a ring network. Management subcenter will be applied to manage network.

   Integrated service access network optical line terminal (OLT) equipments will be installed at the section of mainline beginning point. Optical integrated Service Access Network Optical Network Unit (0NU) equipments will be installed at service areas andtoll plazas to realize communication between the stations under subcenter's jurisdiction.

   All communication stations in this section will form one complete self-healing ring network. Optical integrated services access network transmission level is designed to be STM-4 so that adequate transmission services needed by monitoring tolling-maintenanceoperation will be provided in toll plazas, service areas.

2. **Stored-Program Control exchange system**

   One program-controlled switch will be installed in mainline beginning point. Program-controlled switchs are charge of tel-communication and relay switching operation. Communication system provides transmission link. Other stations will provide user interface by access equipments and also provide voice service. V5 interface will be applied to connect program-controlled switches and user terminal equipment OLT. Based on installation scale of operation, service and maintenance equipments and the investigation, switch user allocation is shown in the following table 5.2.

   Program-controlled switches charging: calls within the network will not be charged, calls between different networks will be charged. Compounded charging system will be applied in switch charging system. Numbering plan: uniform numbers will be made according to Ethiopia Motorway Bureau requirements. Interface signaling modal: V5 signaling will be applied between program-controlled switch and OLT, user's signaling will be applied in user signal. Distribution cabinet equipment: capacity of main distribution frame in mainline beginning point communication

No.	Unit name	number
1	Mainline beginning point toll station	100
2	Debre Zeit North Interchange Toll station	20
3	The Service Area	50
4	Debre Zeit South Interchange Toll station	20
5	Modjo Interchange Toll station	20
6	Adama West Interchange Toll station	20
7	Adama mainline toll station	50
8	Wonji Interchange	2
9	Asela Interchange	2
10	Endpoint of Mainline	2
	Total	**286**

Table 5.2: Switch User Allocation Table

center is 256 loops. Unit assembling can be applied. Capacity of audio distribution frame in other stations will be 64 loops installed in ONU cabinet. The number of security equipments will be half of that of 256 loops or 64 loops.

3. **Communication power supply**

To guarantee the realiable operation of communication equipments, UPS is required. DC — 48V power supply will be used in optical communication equipments and program-controlled switches. AC power supply: AC power needed by high frequency switches of communication system will be provided by UPS of monitoring system. DC power supply: float system will be applied by DC power supply. Remote measure, remote signal, remote control will be conducted in various communication stations along the motorway by communication power management system in the center of mainline beginning point, remote monitoring of communication power equipments will be realied by this way. One set of 60A high-frequency switch power supply and 2 sets of 200AH accumulator battery will be used in communication center of mainline beginning point. One set of 30A high-frequency switch power supply and 1 set of 200AH accumulator battery will be used in every other stations.

Communication power ground:

Grounding system

- Joint grounding of communication system will be conducted through housing construction grounding. Joint grouding resistance is **1**.

- DC power supply grounding will apply single-point grounding mode and be led from ground pool line next to it.

4. **Fiber optic Cable**

   Along the motorway one 24 core fiber optic cable will be trunk cable of trunk network, access network transmission and monitoring. Communication trunk fiber optic cable will be GYTA53-24B1 type. The fiber optic cable will be directly buried. Steel pipe will be layed near the equipment monitoring outfield along the motorway. Two89×4 galvanized steel pipes will be led to manhole at the side of the motorway. Near ramp of toll plaza branch will be layed. Three 114×4 galvanized steel pipes will be led to manhole at the side of the motorway.

5.2.3 STM-4/MSTP Network Architecture

The preexisting communication infrastructure of the Addis AbabaAdama Toll Road (AATR) is a Synchronous Transport Module-Level 4 (STM-4) Multi-Service Transport Platform (MSTP). This infrastructure is based on a self-healing ring topology, with a total transmission capacity of 155Mbps; therefore, it ensures high network availability and resilience to failure of links. The design uses Time division Multiplexing (TDM) technology and offers limited Ethernet-over-SDH capability, so it is not surprising that it is oriented towards legacy circuit-switched services. The network management is performed in the K2+690 main station, and a 24-core GYTA53-24B1 buried fibre optic cable is used as the main medium of transmission throughout the whole corridor. This will provide a reliable voice and data transport, and will use automatic rerouting to recover faults hence will not be affected by failure conditions of the system.

Operational Flow :- Voice/Data Transmission and fault recovery

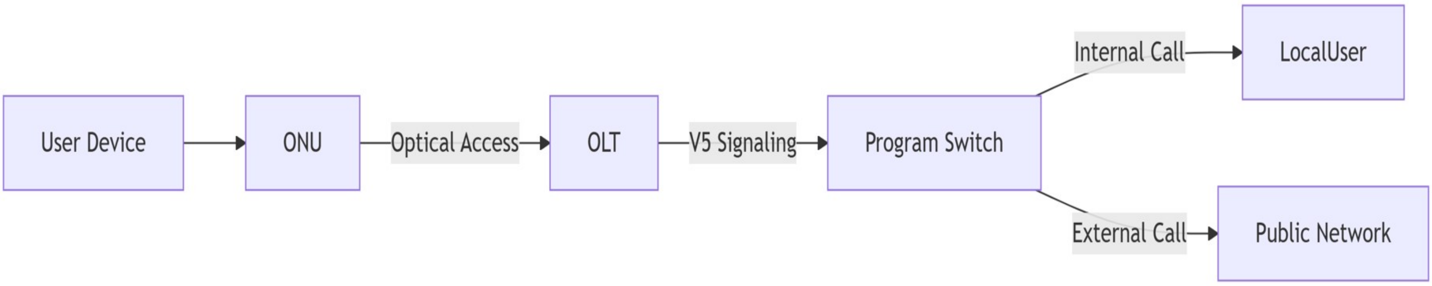


Figure 5.1: Voice and Data Transmission

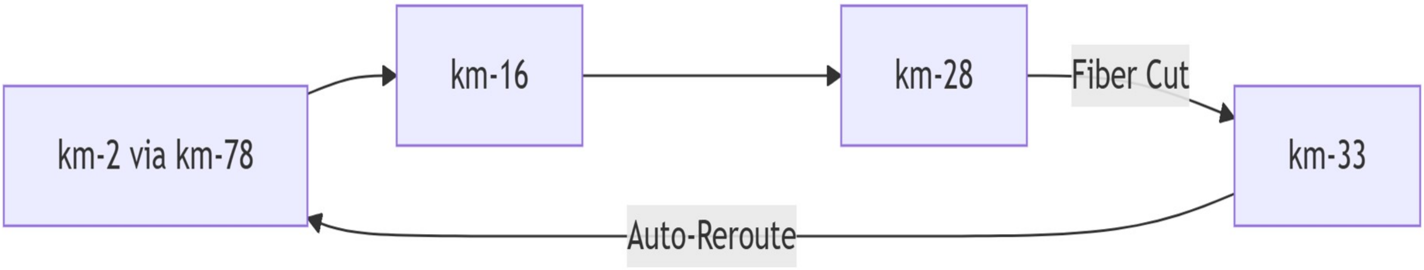


Figure 5.2: Fault Recovery

5.2.4 Current Capabilities and Limitations

The STM-4/MSTP has several operational strengths, the most prominent of which is its strong 24 core fiber backbone that has 16 unused fibers which can be used in future upgrading of the system. The system provides a very high availability rate of 99.99 percent which is supported by a self-healing ring protection system and has a proven history of operational stability as a mature technology. As it currently stands, the backbone has adequate backhaul capacity to support mission-critical communication (MCC). However, there are some important limitations to the system as a result of technological obsolescence; the time-division multiplexing (TDM) structure of the system limits its compatibility with modern IP-based services and limits the Ethernet bandwidth. In addition, the failure to have a radio access network (RAN) layer limits wireless communication of the system. Lastly, there is a problem of maintenance since old hardware is being used, and vendor support is dwindling.

5.2.5 Infrastructure Assessment

The physical infrastructure analysis shows that the AATR network provides a strong base on future communication deployments that are mission-critical. The power systems include 60 ampere high frequency power supply in the primary station and 30 ampere units in the peripheral locations with battery backups to offer 4-8 hours of independent operation at all sites. Moreover, enough rack space can be added to all the seven stations to fit new communication or server equipment. The grounding systems meet the required 1 ohm resistance requirement, and thus, guarantee safety and reliability of the electrical system and network. Combined, these features put the current infrastructure in place as a reliable base of modernization to IP-based LTE and 5G communications systems.

5.3 Ethio Telecom Infrastructure overview

This part provides an in-depth study of the currently existing infrastructure resources of Ethio Telecom along the Addis AbabaAdama toll-road. The evaluation will focus on determining the resources that can be leveraged to implement a mission-critical LTE network, with the view of minimizing the capital investment and shortening the implementation periods.

5.3.1 Geographic Distribution of Ethio Telecom Sites

Site Location Strategy

Ethio Telecom operates eight strategically located sites along the 78.5 km stretch that are geographically poised to give cellular coverage and network redundancy at their best:

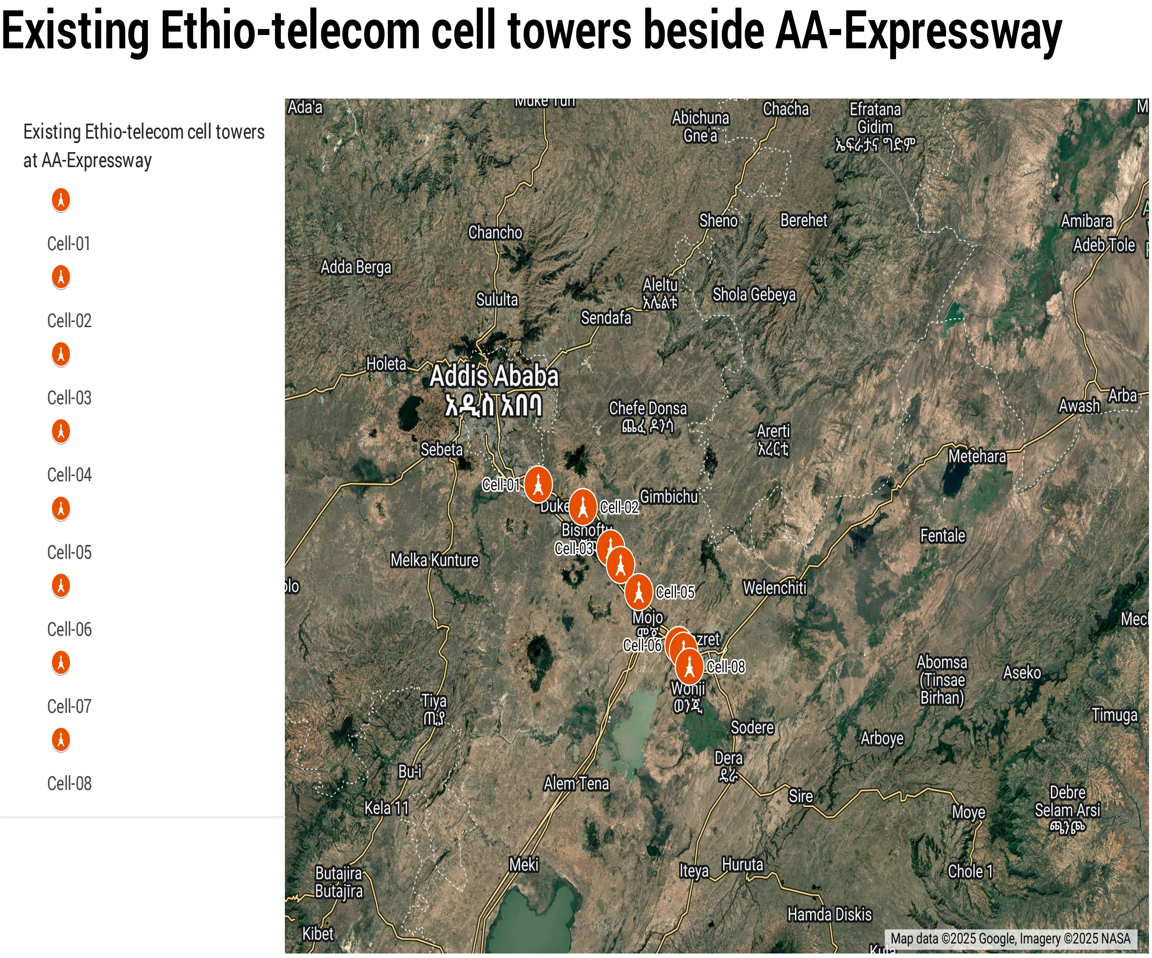


Figure 5.3: Existing Ethiotelecom Network Towers Along AATR

Site Location	Chain age Position	Primary Coverage Area	Adjacent Toll Station
km-4	Beginning of corridor	tuludimitu beginning point area	K2+690 (Adjacent)
km-17+400	17.4 km from start	Debre Zeit North area	K16+930 (1 km)
km-29+400	29.4 km from start	Service area coverage	K28+950 (0.5 km)
km-33+700	33.7 km from start	Debre Zeit South	K33+810 (0.1 km)
km-41+200	41.2 km from start	Modjo approach gap	K52+380 (11 km)
Km-59+100	59.1 km from start	Adama West approach	K60+530 (1.4 km)
Km-61	61 km from start	Adama metropolitan	K60+530 (1 km)
km-64+900	64.9 km from start	Adama terminal area	K64+900 (Co-located)

Table 5.3: Ethio Telecom Site Locations and Coverage Areas

5.3.2 Capacity and Capability Analysis

The evaluation of the Ethio Telecom infrastructure along the AATR corridor shows that it has a high capacity and ability to integrate network services and share infrastructure. Each of the extant towers has sufficient structural capacity to support additional loads on the antennas (200 300 kg) which is backed by a total spare power capacity of 115A and an average of 5.75 rack units of available space per site. The network enjoys the advantage of having a heterogeneous backhaul connectivity where four sites are connected through fibre optic and four through microwave transmission. When using a weighted tool based on technical readiness, strategic location, and operational viability, the analysis of the integration potential found that km-29+400, km-64+900 and km-4 were high-priority areas (score above 8.5/10) and that km-61 and km-41+200 were medium-priority. These results highlight the strong infrastructure baseline of Ethio Telecom that provides significant potential to facilitate hybrid and mission critical network implementation by the means of effective reuse of infrastructure and efficient allocation of resources.

5.4 Gap Analysis and Infrastructure Readiness

The gap analysis of the AATR communication system revealed the following critical deficiencies such as the lack of a dedicated MCC wireless RAN, the lack of a modern LTE/5G EPC core, the lack of support of mission-critical QoS, and the lack of a platform to support MCPTT, MCVideo or MCData services. Nevertheless, the available infrastructure has a great reuse potential: 24-core fiber optic cable can be reused, 90 per cent of power systems can be upgraded with minor modifications, all seven physical locations can be reused, and 95 per cent of supporting infrastructure, including conduits, grounding, and security, can be reused. In total, it is possible to reuse about 78% of the physical infrastructure, which will allow potential savings in CAPEX of more than USD 650,000 and will reduce deployment time by 6-10 months compared to greenfield projects. The implementation of a new wireless RAN is still required; however, the solid fiber backbone and power base is a cost-effective, low-risk base to the implementation of hybrid MCC.

5.5 Scenario Planning Methodology

We use an eight-step systematic scenario-planning approach in order to comprehensively examine and build plausible future conditions of the AATR Mission-Critical Communication (MCC) network deployment. The methodology will provide a thorough analysis of the external and internal environment which will lead to sound and strategic scenarios.

Step 1: Issue Identification and Scope Definition

- Issue: How to deploy a cost-effective and reliable MCC network at the AATR.
- Time Frame: a 10-year planning period (2025-2034).
- Scope: 78.5 km toll road Highway, analyzing the technical, economic, and operational behavior.
- Key Stakeholders: Ethiopian Toll Road Enterprise, Ethio Telecom service provider, emergency service units (police and ambulance),Addis Ababa-Adama Toll road maintenance teams, and regulatory bodies.

Step 2: Factor and Trend Analysis using STEEP Framework

A comprehensive environmental scanning was conducted using the STEEP (Social, Technological, Economic, Environmental, Political) framework:

Step 3: Uncertainty Analysis via Impact/Uncertainty Grid

Key uncertainties were plotted on an impact-uncertainty matrix to identify the two most critical axes for scenario development. The analysis revealed:

- **High Impact, High Uncertainty:** Infrastructure strategy, service demand level, regulatory changes
- **High Impact, Low Uncertainty:** Technology standards, fiber infrastructure availability

Domain	Key Factors	Impact Direction
Social	Increasing public safety expectations; Growing road usage	Increases demand for reliable emergency response
Technological	LTE/5G MCC standards maturity; Network slicing evolution	Enables advanced services but requires modern infrastructure
Economic	CAPEX constraints; OPEX optimization needs; Ethio Telecom lease costs	Favors solutions balancing initial and recurring costs
Environmental	Terrain challenges; Climate conditions	Affects coverage planning and infrastructure resilience
Political	Government digital transformation policy; Public-private partnership initiatives	Creates enabling environment for hybrid models

Table 5.4: Critical Factors Influencing MCC Deployment

- **Low Impact, High Uncertainty:** Specific vendor selection, exact timing of technology adoption
- **Low Impact, Low Uncertainty:** Basic communication needs, existing site locations

Step 4: Initial Scenario Theme Creation Four initial scenario themes were conceptualized based on the uncertainty axes:

- **Cost-Minimization Scenario (A1):** Focus on immediate basic needs with minimal investment
- **Performance-Optimization Scenario (A2):** Maximize capabilities through owned infrastructure
- **Partnership-Efficiency Scenario (B1):** Balance cost and coverage through strategic leasing
- **Future-Proofing Scenario (B2):** Comprehensive investment for long-term scalability

Step 5: Research Application and Validation

The developed scenarios provide the framework for subsequent techno-economic analysis in Chapters 6-8. Each scenarios evaluated against:

- Technical performance metrics (coverage, capacity, QoS)
- Economic indicators (TCO, ROI, NPV)
- Risk assessment (technical, operational, commercial risks)
- Stakeholder requirement alignment

5.6 Key Deployment Uncertainties

Based on the uncertainty analysis, two critical uncertainties were selected as scenario axes due to their high impact and uncertainty:

5.6.1 Axis 1: Uncertainty Infrastructure Utilisation Strategy.

- **Why Critical:** This axis is critical as it determines the balance between the capital expenditure (CAPEX) and the operating expenditure (OPEX), has a direct effect on the velocity of deployment, and dictates long-term control of network infrastructure.
- **How It Influences Outcomes:**
  - **A: STM-4 Upgrade Path:** The initial investment cost is high; but it provides better control over the network and will have lower long term costs due to ownership of assets. The STM-4 upgrade and extension plan focuses on upgrading and sole utilization of the available, owned assets of the Airborne Advanced Tactical Radio (AATR) in order to take maximum control and cost-effectiveness with time at a higher initial acquisition cost.
  - **B: Ethio Telecom Lease Path:**It lowers the CAPEX, but the use of leased solutions creates continuous leasing dependencies and possible Service Level Agreement (SLA) issues. The Ethio Telecom Asset Lease strategy focuses on leasing and sharing of the existing Ethio Telecom infrastructure with focus on minimal upfront capital expenditure and rapid deployment and at the same time creating dependency on third-party providers and recurring operational expenses.

- **Stakeholder Influence:** AATR management (budget control) and Ethio Telecom (commercial interests).

5.6.2 Uncertainty Axis 2: Level of Service Demand

- **Why Critical:** The level of service demand is a decisive factor that drives technical requirements, capacity planning, and the need for future-proofing of the communication ecosystem.
- **How It Influences Outcomes:**
  - **1: Basic Demand:** Voice-based operations with small bandwidth needs (50 kbps -4Mbps). This case involves the classic voice-based communication requirements like Mission-Critical Push-to-Talk (MCPTT), basic data, SMS alerts, and low-resolution imagery, which is an extension of the existing operational models.
  - **2: High Demand:** High capacity requirement and low latency (4-8Mbps) driven by data/video-centric operations. Including real-time high-definition video of incident points, sophisticated MCPTT with video, high-definition voice, analytics, and artificial-intelligence-powered situational awareness, this situation is an indication of a revolutionary change in the capabilities of operational forces.
- **Stakeholder Influence:** Emergency services (operational needs) and AATR operations (efficiency goals)

5.7 Detailed Scenario Specifications

1. **Scenario 1: Minimal Upgrade (Quadrant A1)** In Scenario 1, Minimal Upgrade (Quadrant A1), the company will upgrade its current system, but the upgrades will be minimal and do not enhance the system's functionality to the level of the new system in Scenario 2.

- Strategic Driver: The general goal is the reduction of cost to meet basic needs at the moment.
- Technical Architecture: We re-use the current AATR STM-4 backhaul, and use IP gateways in converting the protocol. LTE eNodeBs are only installed in the seven remaining toll stations and a small EPC core is used.
- The infrastructure requirements are as follows:
  - CAPEX Focus: LTE RAN equipment (seven eNodeBs), IP gateways, and core-network software.
  - Reused Assets: 100 percent of the AATR fibre, power supply and site infrastructure.
  - New Leases: None.
- Service Capabilities: The system offers the basic MCPTT voice, SMS text alerts, and low-resolution image sharing. There is a peak of 4Mbps of data throughput, and there may be coverage gaps between toll stations. These solutions are suitable to simple voice coordination but not suitable to modern data-driven emergency response requirements.
- Business Model: It has low CAPEX, intermediate OPEX and low scalability.
- Stakeholder Impact: It can only facilitate limited emergency coordination, which provides limited operational-efficiency benefits.
- Risk Profile: It has a high operational risk due to coverage gaps, and the probability of obsolescence due to technology is low.

2. **Scenario 2: Quadrant A2 STM 4 Optimised.**

   - Strategic Driver: This aims to optimise performance and control through modernisation of proprietary assets.
   - Technical Architecture: STM -4 backbone is enhanced to IP/MPLS packet-transport network. Macro eNodeBs are installed in toll stations with strategic LTE/5G small cells as fill-in. The nodes of edge-computing are deployed at strategic points, e.g. service areas.
   - The infrastructure requirements are as follows:

  - CAPEX Priority: Network upgrade (IP/MPLS), RAN densification (15 sites), edge-computing servers, and 5G-capable core.
  - Reused Assets: 100-percent of the upgraded AATR fibre, power (with upgrades) and sites.
  - New Leases: None.
- Service Capabilities: The facility offers HD voice, advanced MCPTT, real-time HD video streaming, and data analytics, which gives it great coverage and capacity capabilities of high-demands services. This will allow advanced operation models, including remote expert support and real-time video analytics.
- Business Model: The business model entails high CAPEX, optimised OPEX and high scalability.
- Stakeholder Impact: Change operational capabilities that are highly efficient.
- Risk Profile: The risk is high financial risk, low dependency risk, and medium technology risk.

3. **Scenario 3: Shared RAN (Quadrant B1): Ethio Telecom.**
   - With strategic partnership, the aim is to attain an accelerated cost-effective coverage.
   - Technical Architecture: Ethio Telecom rents out RAN space and power in all the eight locations. The AATR STM -4 is the main backhaul to privately owned and operated EPC core in the main toll station, which creates a hybrid RAN-shared model.
   - The infrastructure requirements are as follows:
     - CAPEX Focus: EPC core, RAN integration, and network-management system.
     - Reused Assets: AATR STM-4 of backhaul, core-site power and space.
     - New Leases: Eight Ethio Telecom tower locations (tower space, power, backhaul tower to AATR fibre)
   - Service Capabilities: The setup provides a cost-effective balance to serve basic to moderate-high demand services, which have an excellent geographical

coverage since Ethio Telecom places are strategically located. Ethio Telecom SLAs are dependent on performance, but mission-critical services and data are controlled by the private core.

- Business Model: Medium CAPEX, predictable OPEX and good scalability.
- Stakeholder Impact: Great improvement compared to the current and equal capacities.
- Risk Profile: Medium dependency risk, medium financial risk and high flexibility.

4. **The Full Hybrid Upgrade (Quadrant B2) scenario** is a scenario where both the engine and the battery are upgraded with a full hybrid system instead of hybrid features.

    - Strategic Driver: Future-proofing and maximisation of capability due to wholesome integration of all assets.Strategic Driver: Future-proofing and maximizing capability through a comprehensive integration of all assets.
    - Technical Architecture: The most comprehensive one is to combine the upgraded AATR fibre network (as in Scenario 2) with the densified RAN which makes use of the seven AATR locations as well as the eight leased Ethio Telecom locations (which makes 15 locations in total). It has a complete 5G-ready core that is able to support network-slicing.
    - The infrastructure requirements are as follows:
        - CAPEX Focus: Large, including STM-4 upgrade, RAN on 15 locations, 5G core, and sophisticated management system.
        - Reused Assets: The whole of the upgraded AATR infrastructure.
        - New Leases: Ethernet infrastructure of eight Ethio Telecom locations.
    - Service Capabilities: The most developed services (HD video, IoT, URLLC) will be supported and have the highest coverage, capacity, and reliability. The 5G-enabled core and dense RAN can offer a platform on which future scalable services, including autonomous vehicle corridors and dense IoT implementation can be available, thus delivering the greatest long-term strategic value.

- Business Model: Maximum scalability, efficient OPEX and highest CAPEX.
- Stakeholder Impact: Industry-leading capabilities, which develop an innovative platform.
- Risk Profile: This has the highest financial risk, low operational risk and low technology risk.

Chapter 6

Implemented TEA Model and Techno-economic Analysis

6.1 Deployment Scenario Evaluation and Decision Process

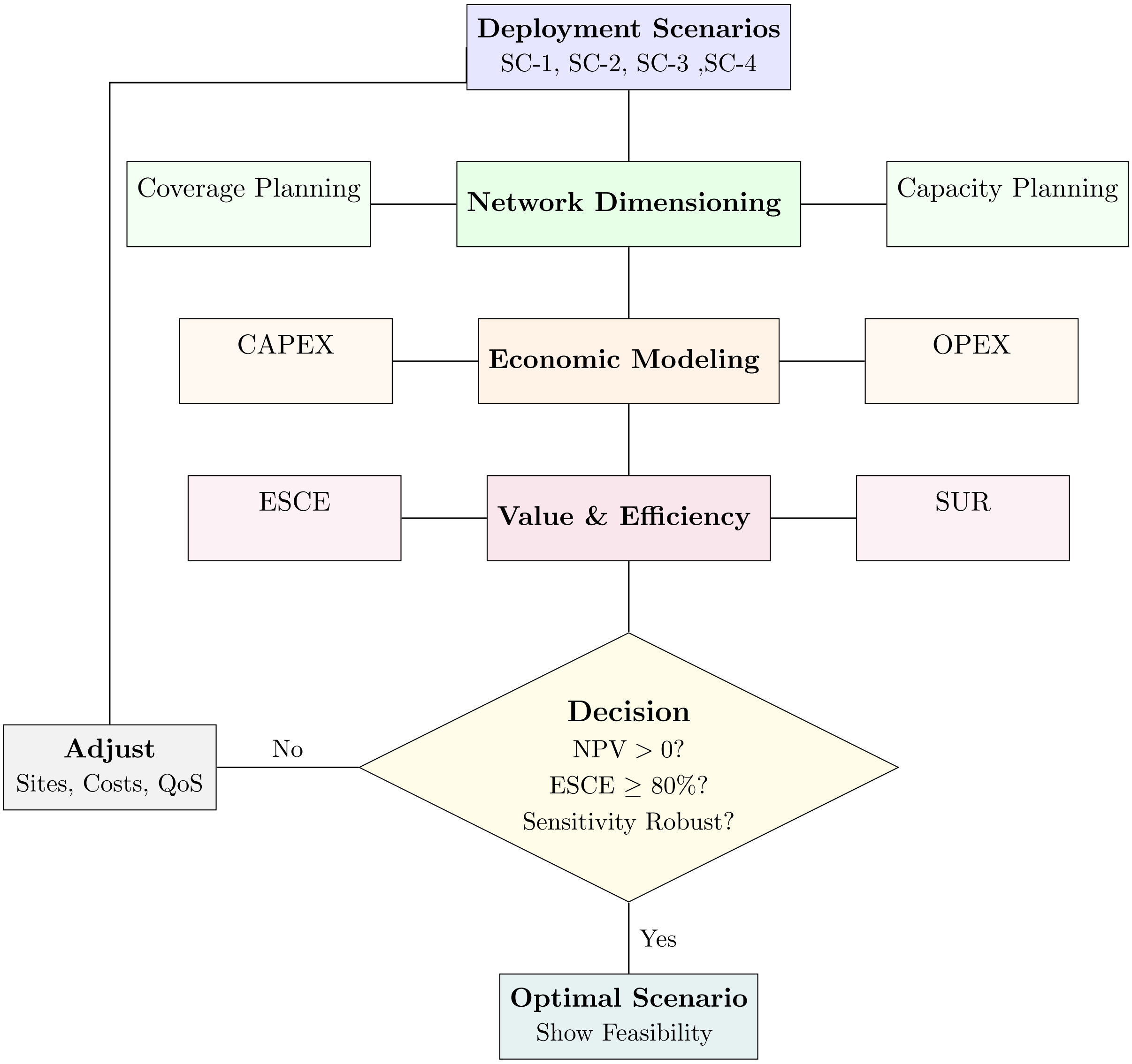


Figure 6.1: Flowchart of the Deployment Scenario Evaluation and Decision Process

6.2 Analysis of Deployment Scenarios

This study analyses and compares the four architecturally-based scenarios for the deployment of mission-critical emergency communication services along the 78 km-long Addis Ababa-Adama Toll Road.

1. **Scenario 1 - Minimal Upgrade**

   The Minimal Upgrade scenario focuses on minimising costs while dividing existing assets into as many components as possible by taking adva ntage of the available AATR STM fibre, power and site resources. An LTE eNodeB will be installed only at each toll booth on the toll road and an existing legacy system can be connected to the new LTE network using an IP gateway after being connected through the Evolved Packet Core. The only types of service that will be offered are MCPTT voice, SMS and low-resolution image sharing; with an expected throughput of approximately 4 Mbps and significant gaps in coverage across the entire toll road. Overall, the capital and operating costs of this scenario are both relatively low; therefore this type of system would be appropriate for coordinating emergency response in the short term, but would not provide a viable solution for modern data-oriented applications. While the operational risks associated with this scenario are relatively high, technological obsolescence is relatively low.

2. **Scenario-2: STM-4 Optimized**

   The STM-4 backbone will move to an IP/MPLS model, which provides improved transport efficiency and scalability; however, this upgrade will not change the ownership of AATR's physical assets. Approximately 15 sites consist of macro eNodeBs and LTE/5G small cells and edge-computing nodes, which will help them meet the very low-latency requirements. Providing an advanced network with MCPTT functionality, high-definition video streaming and data analysis will enable high-demand mission-critical services to be delivered at maximum efficiency. Although this solution incurs a high capital cost, it is expected to provide optimised operating cost and high scalability. The strategy is expected to provide transformational performance with a high level of financial risk and a medium level of technological risk.

3. **Scenario-3: Ethio Telecom Shared RAN**

   Shared RAN is a type of partnership with Ethio Telecom, enabling quick and cost-effective expansion of coverage. AATR rents space and power from Ethio Telecom at eight of their locations and has its own STM-4 backhaul and own EPC core. It is a basic to medium need model, compromising cost versus coverage effectiveness. It will have a medium CAPEX profile and a predictable OPEX, thus offering coverage of a large area and managing critical services. However, it will require the efforts of Ethio Telecom's Service Level Agreements (SLA), which represents a medium dependency and financial risk but is balanced by high flexibility.

   Note:*In Scenario-3, it is assumed that spectrum and RAN sharing are available within the national regulatory framework and that it has enforceable SLAs with Ethio Telecom, meeting mission-critical performance requirements.*

4. **Scenario-4: Full Hybrid Upgrade**

   The Full Hybrid Upgrade is the most advanced and future-proof option, which includes the updated AATR infrastructure and Ethio Telecom's RAN sites, which are leased to provide a 15-site LTE/5G solution. It includes a 5G-ready IP/MPLS core with network slices and advanced management. It includes support for high-definition video, Internet of Things (IoT), and Ultra-Reliable Low Latency Communications (URLLC), ensuring that the highest coverage, capacity, and reliability will be provided to next-generation applications like autonomous vehicle corridors and intelligent tolling. Although it carries the largest CAPEX and financial risk, it eliminates the operational risk and makes AATR a mission-critical communication leader.

6.3 Technical Analysis

6.3.1 Coverage Dimensioning

1. **Summary of Coverage Dimensioning and RLB**

   Coverage dimensioning and the radio link budget were crucial in the evaluation of the technical viability of the four mission-critical emergency network deployment options along the Addis Ababa–Adama Toll Road. The evaluation of the four options considered both the Downlink (DL) and Uplink (UL) link budget calculations, considering the rural highway morphology of the road while including the essential parameters of the transmission, reception, and propagation environment. Some of the parameters considered include the frequency bands of 700 MHz, 1800 MHz, and 3.5 GHz; the MIMO modes of 2×2 and 4×4; the duplex mode of FDD; the antenna gains; EIRP; and receiver sensitivity.

   The cell radii of the emergency networks were derived from the Maximum Allowable Path Loss (MAPL) calculations of the four options, considering the standardized models of COST-231 Hata and 3GPP TR 38.901 Rural Macro, thereby directly influencing site planning, total coverage, and CAPEX/OPEX of the networks.

Parameter	**Downlink**	**Uplink**
Morphology	Rural	Rural
Cell Edge Coverage Probability	95%	95%
User Environment	Outdoor	Outdoor
Data Channel Type	Shared	Shared
MIMO Scheme	2x2	2x2
Duplex Mode	FDD	FDD
Frequency Band (MHz)	700	700
Bandwidth (MHz)	10	10
eNB TX Power (dBm)	43	23
Antenna Gain (dBi)	15	0
Cable Loss (dB)	2	0
EIRP (dBm)	56	23
UE Noise Figure (dB)	7	7
Thermal Noise (dBm)	-104	-104
Receiver Sensitivity (dBm)	-100	-102
Path Loss Model	COST-231 Hata	COST-231 Hata
BS Antenna Height (m)	35	35
UE Antenna Height (m)	1.5	1.5
Shadowing Fading Loss (dB)	8	8
Interference Margin (dB)	3	3
Indoor Penetration Loss (dB)	15	15
Max Allowed Path Loss (dB)	142	135
Estimated Cell Radius (km)	**5.5**	**4.8**

Table 6.1: Scenario 1: DL and UL Radio Link Budget

Parameter	**Downlink**	**Uplink**
Morphology	Rural	Rural
Cell Edge Coverage Probability	95%	95%
User Environment	Outdoor	Outdoor
Data Channel Type	Dedicated	Dedicated
MIMO Scheme	2x2	2x2
Duplex Mode	FDD	FDD
Frequency Band (MHz)	700 &1800	700&1800
Bandwidth (MHz)	20	20
eNB TX Power (dBm)	46	23
Antenna Gain (dBi)	18	0
Cable Loss (dB)	2	0
EIRP (dBm)	62	23
UE Noise Figure (dB)	7	7
Thermal Noise (dBm)	-101	-101
Receiver Sensitivity (dBm)	-97	-99
Path Loss Model	COST-231 Hata	COST-231 Hata
BS Antenna Height (m)	35	35
UE Antenna Height (m)	1.5	1.5
Shadowing Fading Loss (dB)	8	8
Interference Margin (dB)	3	3
Indoor Penetration Loss (dB)	15	15
Max Allowed Path Loss (dB)	146	139
Estimated Cell Radius (km)	**3.6**	**2.9**

Table 6.2: Scenario 2: DL and UL Radio Link Budget

Parameter	**Downlink**	**Uplink**
Morphology	Rural	Rural
Cell Edge Coverage Probability	95%	95%
User Environment	Outdoor	Outdoor
Data Channel Type	Shared	Shared
MIMO Scheme	2x2	2x2
Duplex Mode	FDD	FDD
Frequency Band (MHz)	1800	1800
Bandwidth (MHz)	20	20
eNB TX Power (dBm)	49	23
Antenna Gain (dBi)	18	0
Cable Loss (dB)	2	0
EIRP (dBm)	65	23
UE Noise Figure (dB)	7	7
Thermal Noise (dBm)	-101	-101
Receiver Sensitivity (dBm)	-95	-97
Path Loss Model	COST-231 Hata	COST-231 Hata
BS Antenna Height (m)	30	30
UE Antenna Height (m)	1.5	1.5
Shadowing Fading Loss (dB)	8	8
Interference Margin (dB)	3	3
Indoor Penetration Loss (dB)	15	15
Max Allowed Path Loss (dB)	150	140
Estimated Cell Radius (km)	**5.2**	**4.6**

Table 6.3: Scenario 3: DL and UL Radio Link Budget

Parameter	**Downlink**	**Uplink**
Morphology	Rural	Rural
Cell Edge Coverage Probability	95%	95%
User Environment	Outdoor	Outdoor
Data Channel Type	Dedicated	Dedicated
MIMO Scheme	4x4	4x4
Duplex Mode	TDD	TDD
Frequency Band (MHz)	3500	3500
Bandwidth (MHz)	100	100
eNB TX Power (dBm)	49	23
Antenna Gain (dBi)	18	0
Cable Loss (dB)	2	0
EIRP (dBm)	65	23
UE Noise Figure (dB)	7	7
Thermal Noise (dBm)	-98	-98
Receiver Sensitivity (dBm)	-92	-94
Path Loss Model	3GPP TR 38.901 RMa	3GPP TR 38.901 RMa
BS Antenna Height (m)	30	30
UE Antenna Height (m)	1.5	1.5
Shadowing Fading Loss (dB)	8	8
Interference Margin (dB)	3	3
Indoor Penetration Loss (dB)	15	15
Max Allowed Path Loss (dB)	155	144
Estimated Cell Radius (km)	**2.2**	**1.8**

Table 6.4: Scenario 4: DL and UL Radio Link Budget

2. **Effective Radius Calculation and Coverage Based Site Count**

   General Assumptions Total corridor length: $L = 78\,\text{km}$, Overlap factor: $O = 10\%$, Sectoring: 2 sectors per site ,Effective radius: minimum of DL and UL radius , Effective Diameter: $D_{\text{eff}} = 2 \times R_{\text{eff}} \times (1 - O)$, Site Count: $N = \frac{L}{D_{\text{eff}}}$

   Scenario 1: Existing STM-4 Minimal Upgrade

$$R_{\text{DL}} = 5.5\,\text{km}, \quad R_{\text{UL}} = 4.8\,\text{km}$$

$$R_{\text{eff}} = 4.8\,\text{km}$$

$$D_{\text{eff}} = 2 \times 4.8 \times (1 - 0.1) = 8.64\,\text{km}$$

$$N = \frac{78}{8.64} \approx \mathbf{9\,sites}$$

Scenario 2: Existing STM-4 Optimized

$$R_{\text{DL}} = 3.6\,\text{km}, \quad R_{\text{UL}} = 2.9\,\text{km}$$

$$R_{\text{eff}} = 2.9\,\text{km}$$

$$D_{\text{eff}} = 2 \times 2.9 \times (1 - 0.1) = 5.2\,\text{km}$$

$$N = \frac{78}{5.2} \approx \mathbf{15\,sites}$$

Scenario 3: Ethio Telecom Shared RAN

$$R_{\text{DL}} = 5.2\,\text{km}, \quad R_{\text{UL}} = 4.6\,\text{km}$$

$$R_{\text{eff}} = 4.6\,\text{km}$$

$$D_{\text{eff}} = 2 \times 4.6 \times (1 - 0.1) = 8.28\,\text{km}$$

$$N = \frac{78}{8.28} \approx \mathbf{10\,sites}$$

Scenario 4: Full Hybrid (STM-4 and shared RAN) Upgrade

$$R_{\text{DL}} = 2.2\,\text{km}, \quad R_{\text{UL}} = 1.8\,\text{km}$$

$$R_{\text{eff}} = 1.8\,\text{km}$$

$$D_{\text{eff}} = 2 \times 1.8 \times (1 - 0.1) = 3.24\,\text{km}$$

$$N = \frac{78}{3.24} \approx \mathbf{25\,sites}$$

Scenario	RDL (km)	RUL (km)	Eff. Radius (km)	Eff. Diameter	Site Count
Scenario 1	5.5	4.8	4.8	8.64	**9**
Scenario 2	4.2	3.5	3.5	6.3	**13**
Scenario 3	5.2	4.6	4.6	8.28	**10**
Scenario 4	2.2	1.8	1.8	3.24	**25**

Table 6.5: Coverage Based Site Count Summary Table

3. **Site Count Calculation for Linear Corridor**

The number of sites required to cover a linear corridor such as a highway can be estimated using the following formula:

$$\text{Site Count} = \left\lceil \frac{L}{2 \times R_{\text{eff}} \times \text{Overlap Factor}} \right\rceil$$

Where:L: Total length of the corridor (km) , R_{eff}: Effective cell radius (km) Overlap Factor: A factor between 0.7 and 0.9 to ensure coverage overlap and handover $\lceil \cdot \rceil$: Ceiling function (rounds up to the nearest whole number)

6.3.2 Capacity Dimensioning

In addition to the fundamental parameters and mathematical approach described in Section 5.2, the input parameters used for the capacity dimensioning explained as follows:

1. **User Categorization and Monthly Data Demand**

User Category	Users	Daily Usage/User	Monthly Volume/User
Emergency Response Units	15	60 MB/day (VoIP, video)	∼1.8 GB
Patrolling Units	30	40 MB/day (PTT)	∼1.2 GB
Control Room Operators	10	100 MB/day (video feed)	∼3.0 GB
IoT / Surveillance Sensors	20	5 MB/day	∼150 MB
Other Operational Staff	10	20 MB/day	∼600 MB

Table 6.6: User Categorization and Monthly Data Demand

Total Monthly Data Volume per Station:

$$\text{Total}_{\text{Monthly}} = \sum_{i=1}^{n} \text{Users}_i \times \text{Monthly Volume}_i$$

2. **Mathematical Approach**

A. Average Throughput Calculation

Let: D_{monthly} = Total monthly data volume per cell (in GB) , T_{avg} = Average throughput required (Mbps) , t_{active} = Active time per day (hours) ,N_{days} = Number of days in a month (30)

$$T_{\text{avg}} = \frac{D_{\text{monthly}} \times 8 \times 1024}{N_{\text{days}} \times t_{\text{active}} \times 3600}$$

Input Parameters for Capacity Estimation

Parameter	Value / Range
Spectral Efficiency (DL/UL)	1.5–2.5 bps/Hz (LTE), up to 5 bps/Hz (5G)
Bandwidth	10 MHz (Scenario-1), 100 MHz (Scenario-4)
Available Capacity (per sector)	Depends on BW × spectral efficiency
Overhead Losses	∼30% (signaling, scheduling, guard bands)
Number of Sectors per Site	3 (typical)

Table 6.7: Input Parameters for Capacity Estimation

B. Net Capacity Estimation (DL)

$$\text{Net Capacity (Mbps)} = \text{BW} \times \text{SE} \times (1 - \text{Overhead})$$

Example: Scenario-2 with 20 MHz LTE, SE = 2 bps/Hz:

$$= 20 \times 2 \times 0.7 = 28 \text{ Mbps per sector} \Rightarrow 84 \text{ Mbps/site}$$

Final Output — Capacity Sufficiency Check

- Compare total monthly station demand with available monthly cell throughput.
- For mission-critical traffic, peak hour dimensioning also considered:

$$\text{Peak Capacity (Mbps)} \geq \text{Busy Hour Traffic (Erlang)} \times \text{Required kbps/call}$$

3. **Scenario Summary**

Scenario	BW	Demand/Month	Peak Load	Net Capacity/Site
Scenario-1	10 MHz LTE	540 GB	10 Mbps	∼28 Mbps
Scenario-2	20 MHz LTE	1.2 TB	30 Mbps	∼56 Mbps
Scenario-3	20 MHz 5G	1.2 TB	30 Mbps	∼70 Mbps
Scenario-4	100 MHz 5G	1.8 TB	50 Mbps	∼350 Mbps

Table 6.8: Monthly data Demand Scenario Summary

4. **Average Throughput Calculation for Mission-Critical Network Scenarios**

Formula

$$T_{\text{avg}} = \frac{D_{\text{monthly}} \times 8 \times 1024}{N_{\text{days}} \times t_{\text{active}} \times 3600}$$

Where: D_{monthly} = Monthly data volume (in GB) , t_{active} = Daily active period (in hours), $N_{\text{days}} = 30$

Assumptions

- Active period per day: 8 hours
- Number of communication stations: 6

Monthly Data Volume per Scenario:

- Scenario-1: 90 GB per station → 540 GB total
- Scenario-2: 200 GB per station → 1.2 TB = 1200 GB total
- Scenario-3: 180 GB per station → 1.08 TB = 1080 GB total
- Scenario-4: 300 GB per station → 1.8 TB = 1800 GB total

Throughput Calculations for each scenarios:

Scenario-1: Existing STM-4 Minimal Upgrade

$$T_{\text{avg}} = \frac{540 \times 8 \times 1024}{30 \times 8 \times 3600} = \frac{4423680}{864000} \approx 5.12 \text{ Mbps}$$

Scenario-2: Existing STM-4 Optimized

$$T_{\text{avg}} = \frac{1200 \times 8 \times 1024}{30 \times 8 \times 3600} = \frac{9830400}{864000} \approx 11.38 \text{ Mbps}$$

Scenario-3: Ethio Telecom Shared RAN

$$T_{\text{avg}} = \frac{1080 \times 8 \times 1024}{30 \times 8 \times 3600} = \frac{8859648}{864000} \approx 10.25 \text{ Mbps}$$

Scenario-4: Full Hybrid (STM-4 and shared RAN) Upgrade

$$T_{\text{avg}} = \frac{1800 \times 8 \times 1024}{30 \times 8 \times 3600} = \frac{14745600}{864000} \approx 17.07 \text{ Mbps}$$

Scenario	**Monthly Data Volume (Total)**	**Average Throughput (Mbps)**
Scenario-1	540 GB	5.12 Mbps
Scenario-2	1.2 TB (1200 GB)	11.38 Mbps
Scenario-3	1.08 TB (1080 GB)	10.25 Mbps
Scenario-4	1.8 TB (1800 GB)	17.07 Mbps

Table 6.9: Average Throughput per Scenario

5. **Capacity-Based Site Count Estimation:**

using capacity based site count formula in chapter 5 equation (),calculate the Estimated Usable Cell Capacity for each scenarios as follows:

Scenario	**Bandwidth**	**MIMO**	**Theoretical Max**	**Usable Capacity (C_{cell})**
Scenario-1	10 MHz LTE	2x2	$\sim$ 75 Mbps	50 Mbps
Scenario-2	20 MHz LTE	4x4	$\sim$ 300 Mbps	200 Mbps
Scenario-3	10 MHz LTE	2x2	$\sim$ 150 Mbps	100 Mbps
Scenario-4	100 MHz 5G	4x4	$\sim$ 1 Gbps	700 Mbps

Table 6.10: Usable Cell Capacity for Each Scenario

These are approximate values, assuming 30–40% protocol and control overhead.

4. Total Throughput Demand per Scenario

Scenario	**Total Avg. Throughput (T_{total}) (Mbps)**
Scenario-1	$5.12 \times 6 = 30.7$ Mbps
Scenario-2	$11.38 \times 6 = 68.3$ Mbps
Scenario-3	$10.25 \times 6 = 61.5$ Mbps
Scenario-4	$17.07 \times 6 = 102.4$ Mbps

Table 6.11: Total Throughput Across All 6 Stations

5. Capacity-Based Site Count Results

Scenario	T_{total} (Mbps)	C_{cell} (Mbps)	$N_{\text{sites}}^{\text{capacity}}$
Scenario-1	30.7	50	1
Scenario-2	68.3	100	1
Scenario-3	61.5	200	1
Scenario-4	102.4	700	1

Table 6.12: Calculated Capacity-Based Site Counts

6. Conclusion

For all four scenarios, the calculated throughput demand is well within the usable capacity of a single base station site. Hence:

- Capacity is **not** the limiting factor in network planning.
- The final site count is therefore determined by **coverage-based constraints**, not throughput.
- Thus, the **final number of sites = coverage-based site count** (as previously derived from radio link budget analysis).

6.3.3 Coverage Site Map of All Deployment Scenarios

Summary of Site relocation for Each Deployment Scenarios

To ensure uninterrupted and mission-critical service on the 78.5 km long Addis Ababa–Adama Toll Road, site relocation and densification strategies were developed for four deployment scenarios based on the current AATR site locations and possible new cell site locations. The four deployment scenarios are: Scenario 1 – Minimal Upgrade: Nine sites are used by reusing almost all of the current AATR locations, utilizing the existing infrastructure to keep the deployment cost minimal. Scenario 2 – STM-4 Optimized: Fifteen sites are deployed by keeping the seven cell sites of the AATR and adding eight sites at the gaps not yet covered by the AATR, ensuring evenly distributed sites along the corridor without the need to use Ethio Telecom sites. Scenario 3 – Hybrid Densification: Ten sites are deployed by combining the AATR sites with some additional sites to balance the need to improve the coverage with the need to keep the deployment cost low. Scenario 4 – Full 5G SA Densification: An intensive site densification strategy is implemented by utilizing twenty-five sites, combining the reused sites and additional sites to be added, to achieve almost continuous 5G coverage on the corridor, suitable for high-throughput and ultra-reliable communication services. The resulting coverage maps of the four deployment scenarios are presented to demonstrate the spatial distribution of the sites and the optimization of the site locations, ensuring the Effective Service Coverage Extent (ESCE) is maximized with minimal gaps in the coverage along the corridor.

NB:

- the **yellow** marked plot cell sites indicates the Existing/Available AATR sites.
- the **Red** marked plot cell sites indicates the Existing/Available Ethiotelecom 2G/3G/4G sites.
- the **Green** marked plot cell sites indicates the newly coverage based site numbers needed and with relocation made.

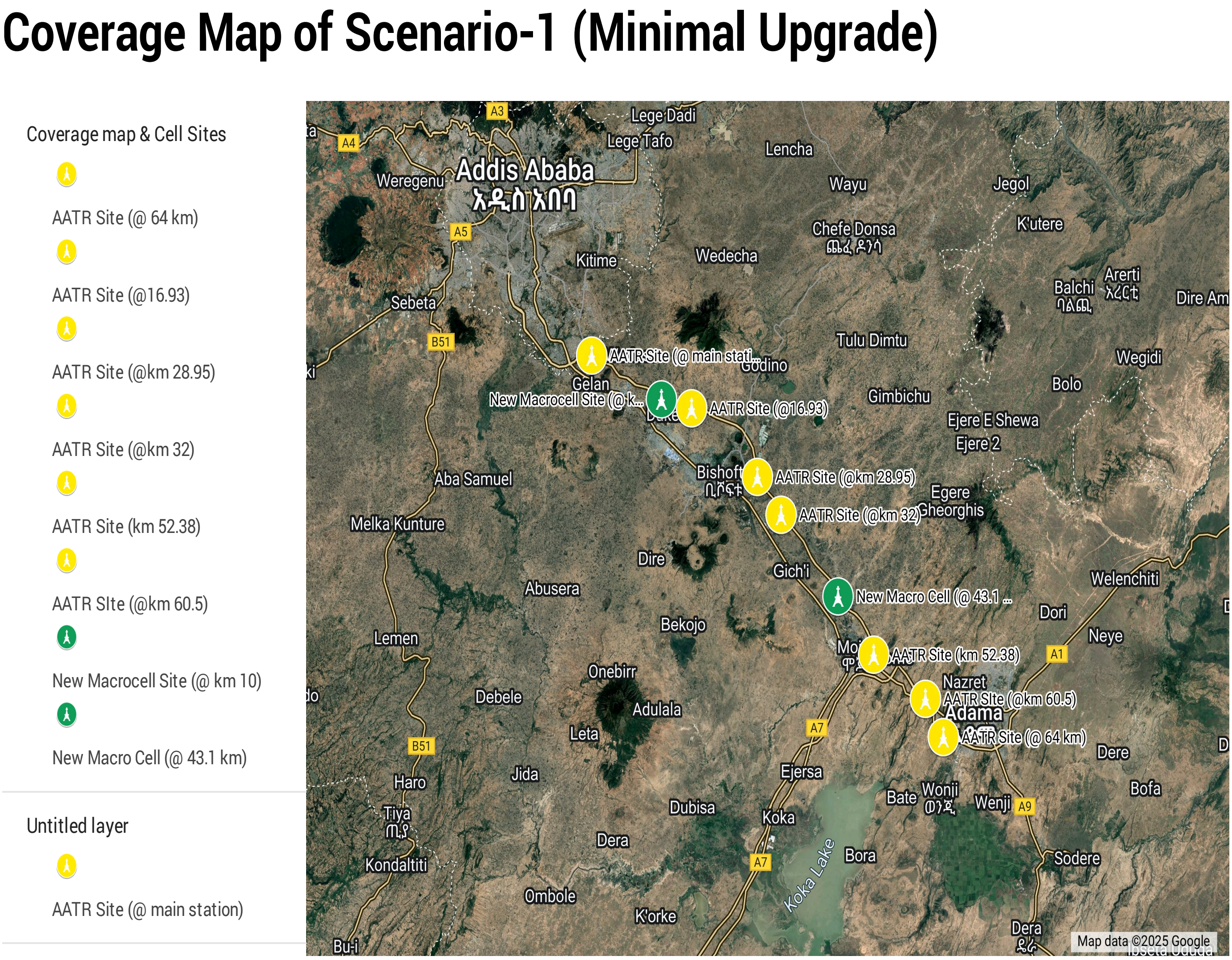


Figure 6.2: Scenario-1 Cell Relocation Site Map

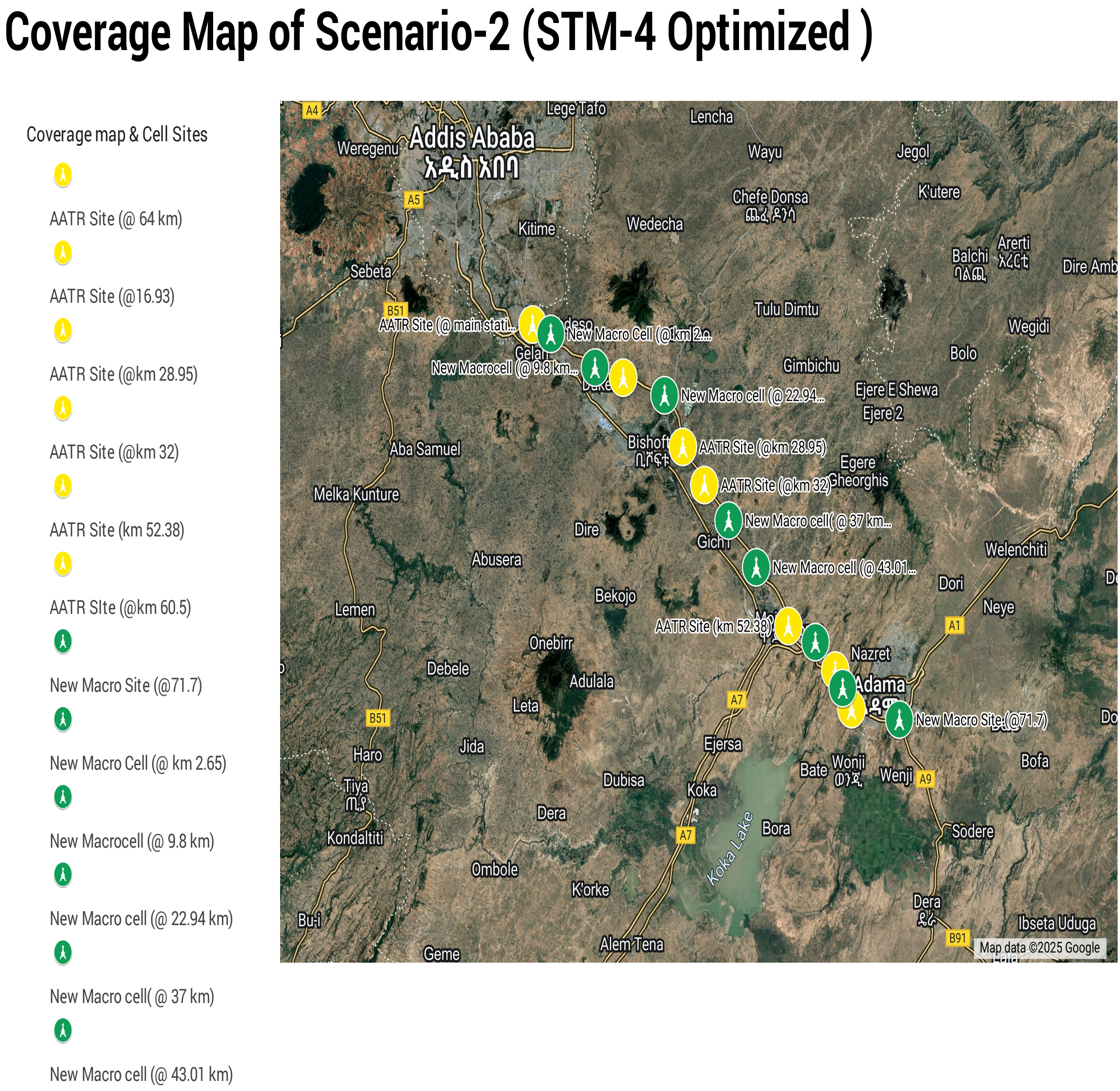
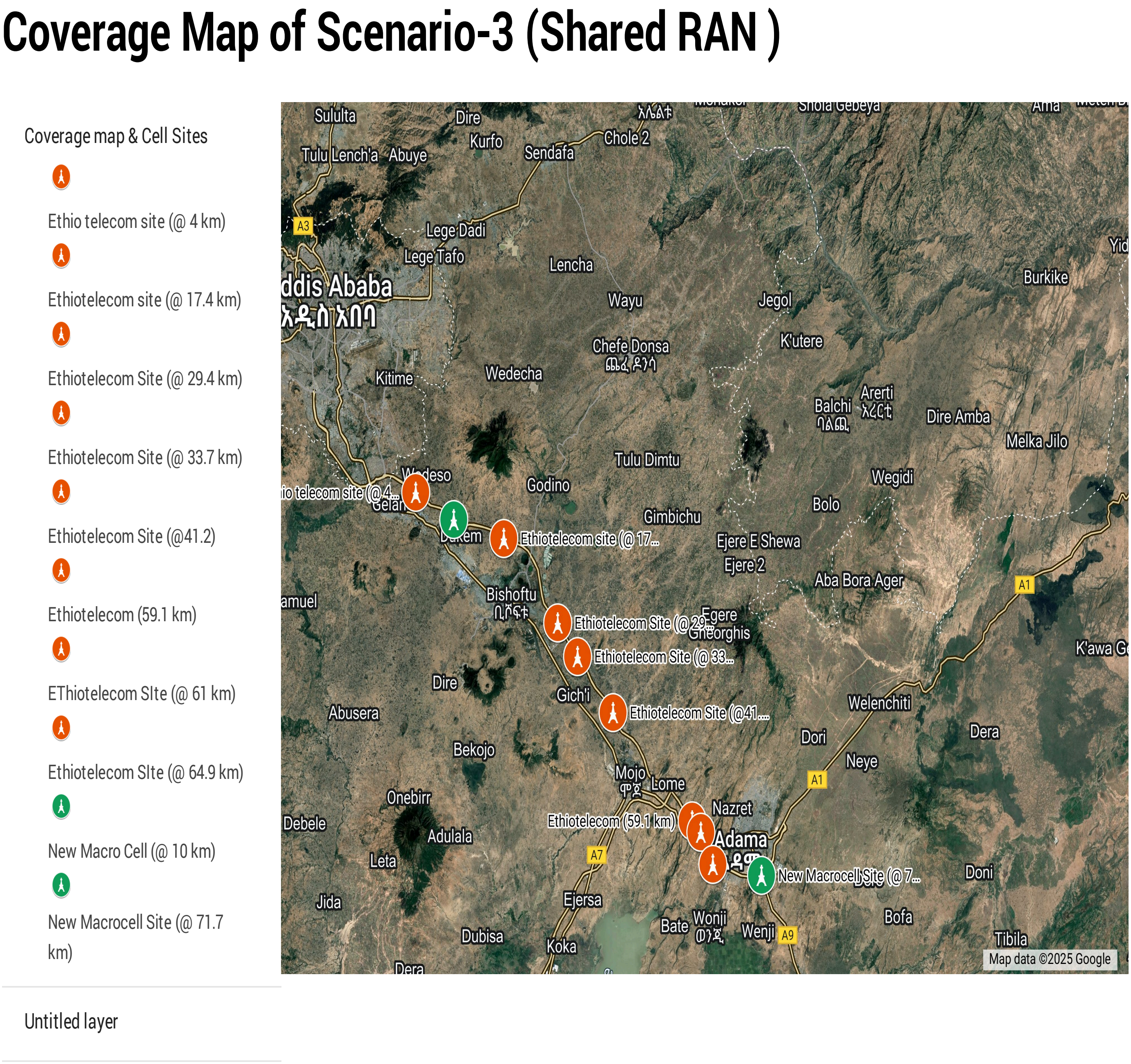


Figure 6.3: Scenario-2 Cell Relocation Site Map



Coverage Map of Scenario-3 (Shared RAN)

Coverage map & Cell Sites

- Ethio telecom site (@ 4 km)
- Ethiotelecom site (@ 17.4 km)
- Ethiotelecom Site (@ 29.4 km)
- Ethiotelecom Site (@ 33.7 km)
- Ethiotelecom Site (@41.2)
- Ethiotelecom (59.1 km)
- EThiotelecom SIte (@ 61 km)
- Ethiotelecom SIte (@ 64.9 km)
- New Macro Cell (@ 10 km)
- New Macrocell Site (@ 71.7 km)

Untitled layer

Figure 6.4: Scenario-3 Cell Relocation Site Map

Coverage Map of Scenario-4 (fully upgraded)

Coverage map & Cell Sites

- 🟠 Ethio telecom site (@ 4 km)
- 🟠 Ethiotelecom site (@ 17.4 km)
- 🟠 Ethiotelecom Site (@ 29.4 km)
- 🟠 Ethiotelecom Site (@ 33.7 km)
- 🟠 Ethiotelecom Site (@41.2)
- 🟠 Ethiotelecom (59.1 km)
- 🟠 EThiotelecom SIte (@ 61 km)
- 🟠 Ethiotelecom SIte (@ 64.9 km)
- 🟢 5G Macro Cell @ 8 km
- 🟢 New small cell @ 800 meter
- 🟢 LTE/5G macro cell (11.5 km)
- 🟡 AATR Site (@16.93)

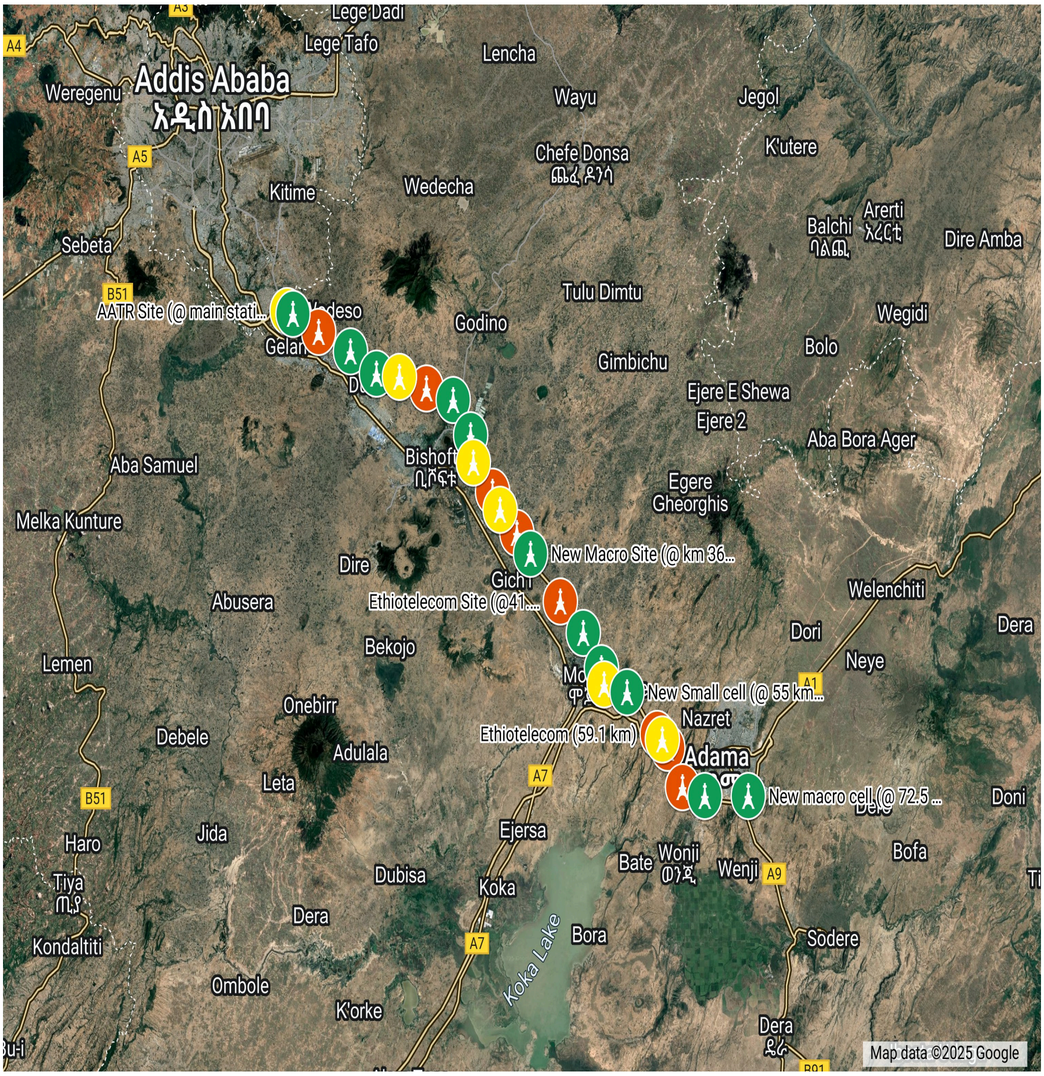


Figure 6.5: Scenario-4 Cell Relocation Site Map

6.4 Evidence-Based Incident Rates and Unit Cost Assumptions

Recent Ethiopian toll road and expressway safety data show that Addis- Adama expressway (78km) has had a reported 400 to 500 emergency incidents per year estimated or this amounts to 56 incidents in a long run which is approximately 5-6 incidents/ kilometre per year on average. This estimate does not contradict various empirical sources of information, such as the crash reports gathered during the period of 20152022 and short-term toll-road surveillance, by which the incident rate falls consistently within this range. To realize economic analysis, nationally summed reports on accidents-cost estimate accident-cost losses (annual loss) of Ethiopia to be about 3.3 -billion ETB, which incur in approximately 15,000 reported cases (according to exchange rates) of accident per year, with the current value economic cost basis of 220,000-240,000 ETB, per accident. The implication of these evidence-based values to the Addis-Adama corridor is that it will create a direct socio-economic load of about 100million +/-ETB annually that can be attributed to roadway accidents. Such parameters give realistic and context-relevant basis of techno-economic modelling, cost-benefit analysis and mission-critical communication system justification.

6.5 Economic Analysis

The economic analysis of the four deployment scenarios was mainly on the evaluation of the Total Cost of Ownership (TCO) at 10 years taking both the initial. Components of CAPEX and recurring OPEX. The study was conducted on the basis of the detailed analysis. cost breakdowns- equipment, civil works, power, site rentals, integration and by item licensing - in line with Ethiopian infrastructure preferences and global standards. The costs structure was affected by the specifics of infrastructure reuse, densification, and user demand as a scenario-specific assumption. The findings brought out the trade-offs among scalability, quality of services and long term financial sustainability, and offered an understanding of the most. enhanced deployment of mission critical services in the long term and cost efficient strategy. Addis Ababa–Adama Toll Road.

The economic study on every scenario that is conducted on the basis of the outcomes of the Monetized. benefit analysis and technical analysis. It is mostly concerned with cost and Emergency. monetized networks are beneficial in modeling of each situation. The key components of cost modeling are CAPEX estimation, OPEX estimation and TCO which are described in the. next sub section

Remark: *The costs are provided for an existing market price and an initial exchange rate. Sensitivity analysis considers inflation and fluctuations of currency instead. than by making the prices fixed in the long term.*

6.5.1 CAPEX and OPEX Estimation

All Deployment Scenarios CAPEX and OPEX Estimations

The capital expenditure (CAPEX) and the operating expenditure (OPEX) estimates of the four deployment scenarios were derived through a bottom-up costing approach that is distinctly cut to suit the Ethiopian telecommunications infrastructure scenario. The cost model of each scenario was based on the basis of an elaborate bill of quantities (BoQ) that synthesized counts of sites based on site count as a result of link-budget analysis, coverage analysis, availability of infrastructure to be reused, and the type of user demand, which is basic and high. The CAPEX items included base station equipment (eNodeB /gNodeB), antennas, towers, civil works, installation, power system, and integration with existing infrastructure whereas OPEX items included recurrent spending over a period of ten-year item, which consisted of site leasing, maintenance and power consumption, frequency licensing and staffing.

Realistic USD-priced price ranges were benchmarked on Ethiopian telecom projects (reference values to 20242025), Ethio Telecom modernization projects, internationally vendor average (Huawei, Nokia, Ericsson, ZTE) prices on similar deployments, offerings by other vendors and international reference datasets (GSMA Intelligence, ITU-T, and 3GPP cost-modelling literature) and tender bids of other similar projects in Africa were also used as the source of cost inputs. The cost of equipment was quoted in USD and then translated into the local currency using a base exchange rate, the impact of inflation and foreign-exchange variability on the relative cost value over the implementation period was also taken into consideration. Sensitivity analysis has been carried out to determine the strength of the cost estimates when there are reasonable price and exchange-rate changes.

Scenario 1 and Scenario 3, both of which were basic to moderate capacity demand service networks, had low capital costs due to broad based reuse and modernization of available infrastructure, whereas Scenario 2 adopted integration with leased assets of Ethio Telecom. On the contrary, Scenario 2 and 4, where the capacity demand was greater, were indicative of augmented cost related to network densification, installation of more capacity-incremental infrastructure and more integration with leased assets. This uncertainty-sensitive and structured estimation model allowed conducting a strict techno-economic analysis of the key LTE and 5G deployment policies along the line of Addis Ababa-Adama.

Below are detailed scenario-specific Bill of Quantity (BOQ) tables,

Item No	**Item Description**	**Unit**	**Estimated Cost ($)**	**10-Year OPEX (USD)**
1	LTE eNodeB (700 MHz, 2-sector, outdoor cabinet)	9 sites	270,000	77,000
2	Compact EPC Core (4 Mbps peak, voice/SMS)	1 set	85,000	25,000
3	IP Gateway / Protocol Converter (STM-4 to IP)	9 units	35,000	10,000
4	Network Management System (Basic NMS)	1 set	25,000	15,000
5	Installation & Commissioning (RAN + Core)	Lump sum	40,000	–
6	Site Civil/Power Retrofit (minor upgrade)	9 sites	21,000	–
7	Training and Documentation	Lump sum	10,000	–
Total			**486,000**	**167,000**

Table 6.13: Scenario 1 :BOQ with 10-Year OPEX (in ETB)

Item No	**Item Description**	**Unit**	**Estimated Cost (USD)**	**10-Year OPEX (USD)**
1	IP/MPLS Router Upgrade (STM-4 backbone)	6 links	120,000	30,000
2	LTE Macro eNodeB (at Toll Stations)	7 sites	210,000	60,000
3	LTE/5G Small Cell Sites (fill-in coverage)	8 sites	120,000	45,000
4	5G-Ready Core (EPC/5GC hybrid)	1 set	120,000	45,000
5	Edge Computing Server (MEC Node)	2 sites	40,000	15,000
6	Advanced NMS / OSS System	1 set	35,000	–
7	Installation & Integration (RAN + Core + IP/MPLS)	Lump sum	60,000	–
8	Training, Documentation, and Testing	Lump sum	15,000	–
9	Power Backup System Maintenance	15 sites	–	50,000
Total			**750,000**	**230,000**

Table 6.14: Scenario 2 : BOQ with 10-Year OPEX

Item No	**Item Description**	**Unit**	**Estimated Cost (USD)**	**10-Year OPEX (USD)**
1	Private EPC Core (Hosted at Main Toll Station)	1 set	90,000	50,000
3	LTE/5G Small Cell Sites (fill-in coverage)	2 sites	30,000	11,250
2	RAN Integration Equipment(Ethernet/IP interface)	10 sites	40,000	20,000
3	Network Management System / SLA Monitor	1 set	25,000	20,000
4	Network Leased Service (Tower, Power, Backhaul)	8 sites	40,000	400,000
5	Security Gateway & VPN Equipment	1 set	15,000	10,000
6	Installation, Integration & Testing	Lump sum	25,000	—
7	Training and Service Agreement Setup	Lump sum	10,000	5,000
Total			**275,000**	**511,250**

Table 6.15: Scenario 3 : BOQ with 10-Year OPEX

Item No	**Item Description**	**Unit**	**Estimated Cost (USD)**	**10-Year OPEX (USD)**
1	STM-4 to IP/MPLS Backbone Upgrade	6 links	120,000	40,000
2	LTE/5G RAN (Macro + Small Cell, 15 sites)	11 sites	330,000	100,000
3	Full 5G Core Network (Standalone + Slicing)	1 set	250,000	50,000
4	Network Management & Analytics Platform	1 set	60,000	25,000
5	Edge Computing / MEC Nodes	3 sites	75,000	20,000
6	Power System Upgrade (Solar + Battery Hybrid)	10 sites	100,000	–
7	Site Lease (Ethio Telecom Co-location)	8 sites	40,000	400,000
8	Power & Cooling System Maintenance	10 sites	–	90,000
9	Installation, Integration & Commissioning	Lump sum	80,000	–
10	Training, Documentation, and Testing	Lump sum	20,000	–
Total			**1,025,000**	**725,000**

Table 6.16: Scenario 4 : BOQ with 10-Year OPEX

6.5.2 TCO Estimation

The methodology of cost of ownership (TCO) estimation, as detailed in this thesis, integrates in a coherent manner the Initial Year Capital Expenditures (CAPEX) and Cumulative 10-Year Operational Expenditures (OPEX) of all the four deployment scenarios considered in this thesis. CAPEX includes base station and transmission equipment, site construction, power, and integration of existing (or newly acquired) assets. The recurrent expenses of OPEX include maintenance, energy usage, site rent, human expenses, and licensing expenses during the ten-year study period. A scenario-specific Bill of Quantities (BoQ) was devised to help in allocating costs accurately and all financial values were converted to a base exchange rate of 1 USD= 153.53 ETB. Although this framework provides a systematic and consistent framework of comparing long term cost efficiency and sustainability on the minimal upgrade, optimization, leasing/sharing, and full upgrade deployment options, it has been recognised that the actual costs can vary as a result of other factors such as inflation, currency volatility, global supply chain dynamics and negotiated commercial terms. Based on this, sensitivity analysis is conducted to be able to adapt to such variations and, therefore, make sure that the comparative scenario assessment is robust and reliable.

Scenario	**CAPEX in million (ETB)**	**OPEX in million (ETB)**	**TCO in million (ETB)**
Scenario 1	75	26	101
Scenario 2	115	35	150
Scenario 3	42	78	120
Scenario 4	157	111	268

Table 6.17: Initial Year CAPEX and OPEX over 10 Years for All Scenarios

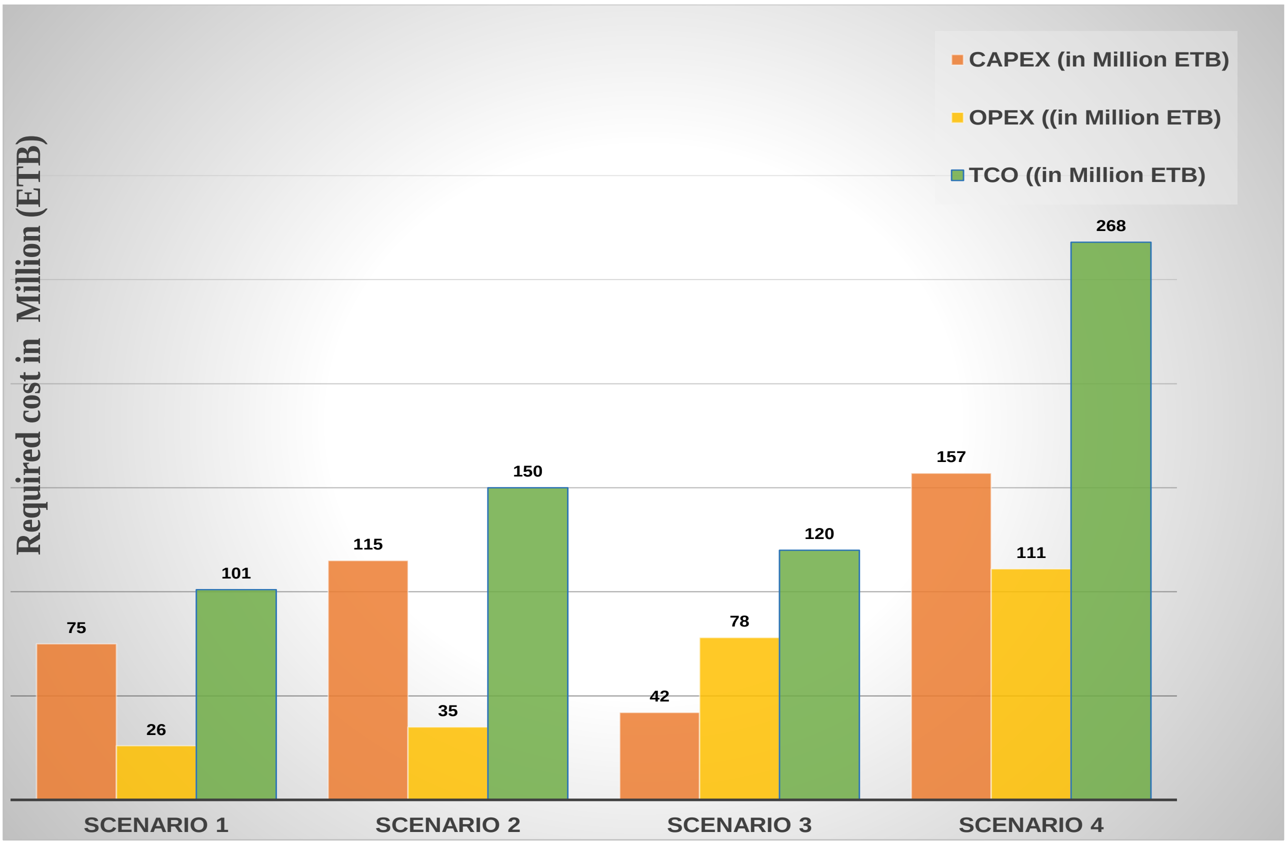


Figure 6.6: CAPEX,OPEX and TCO Estimation

6.5.3 Cost Recovery and Value Modeling

Cost Recovery Value Modeling Analysis for Addis Ababa – Adama Toll Road (AATR) Based on Four Deployment Scenarios

The thesis has assessed four deployment options of mission-critical network implementation along the Addis Ababa-Adama Toll Road. In Scenario 1, a low upgrade that uses existing infrastructure, about 60 percent of the area as well as nine locations is covered. It supports simple services like PTT and SMS, which would save costs per incident annually of 150 incidences, and the Service Utilization Rate (SUR) would be 60 percent. This situation provides high total cost of ownership (TCO) efficiency in terms of reuse and has a small amount of scalability. Scenario 2 is the densification of the current infrastructure to handle high demand, enhance coverage to 70 percent with 15 locations and enhanced services including live video. It has a SUR of 80 percent, which is a balance between performance and costs. Scenario 3 presents infrastructure additions to serve basic demand, and ten sites are deployed to serve 60 percent of the corridor. It offers committed LTE service at 25 percent SUR with increased capital expenditure (CAPEX), though at a higher quality and potential upgrading in the future. The most developed variant (Scenario 4) will implement completely new infrastructure and densification (25 sites) to provide 90 percent coverage, high user capacity, and new services including mobile edge computing (MEC) and analytics. It has a SUR exceeding 90 percent and the highest return on investment (ROI) on the society despite the high CAPEX, which makes it the best choice in a full-size mission-critical transformation.

Deployment scenarios based Cost Recovery and Value Modeling

Parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Coverage Efficiency (CEI)	60	85	80	95
Service Utilization Rate	40	60	50	70
TCO Efficiency	High	Medium	Medium	High
Scalability Potential	Low	Medium	Medium	Very High

Table 6.18: Scenario Based Cost Recovery and Value Modeling Comparison

The following shows the Cost Savings per Incident (CSPi) trend of each scenario of deployment within a decade, (2025 to 2034) with the assumption of a three per cent per year increase in value, efficiency and other operational improvements to the service.

Key Insights: CSPi is not a constant indicator but a changeable one, which also changes with the passage of time in terms of system maturation and higher efficiency. **Scenario 4** has the most CSPi due to the enhanced coverage and heightened operational impacts, which are related to the full presence of 5G infrastructure. There is a noteworthy annual saving in all the cases.

Chapter 7

Results and Analysis

7.1 Techno-Economic Analysis Model on Deployment Scenarios

There was a thorough techno-economic analysis of the viability of four alternative deployment scenarios of mission-critical broadband communications along the Addis Ababa-Adama Expressway.

The analysis uses a ten-year analytical horizon, discount rate of 8 per cent, and a measured baseline of the emergency incidents. The records show that there are about 450 incidences per year, with an average cost of 220,000ETB, which results in a baseline annual societal and operational cost of 99millionETB.

The economic benefits of each scenario were calculated based on the factors of incident response costs and were modeled using three technical impact factors, which included the potential technical effectiveness of the network (p tech), Effective Service Coverage Efficiency (ESCE) and the Service Utilization Rate (SUR). These factors as a whole measure the achieved decrease in per-incident losses in the scenarios.

Internal consistency was applied to all scenarios by distributing operating expenditures equally throughout the ten-year period and discounting to calculate present values and benefit-cost ratios (BCRs).

7.1.1 Infrastructure Expansion Over the Course of the Project's Duration

A detailed interpretation of the amounts investments throughout the study is provided in figure 7.1. The network operator will deploy the network in steps, according to the development and deployment pace of new MC LTE and 5G . The investment components, configurations as shown in Figure 7.1, illustrates the growth of each component and shows the trends, patterns, and amount of investment in different components over time with different deployment scenarios . The small cell network rollout's capacity planning infrastructure construction, and resource allocation may all be better understood and decided with the aid of this figure.

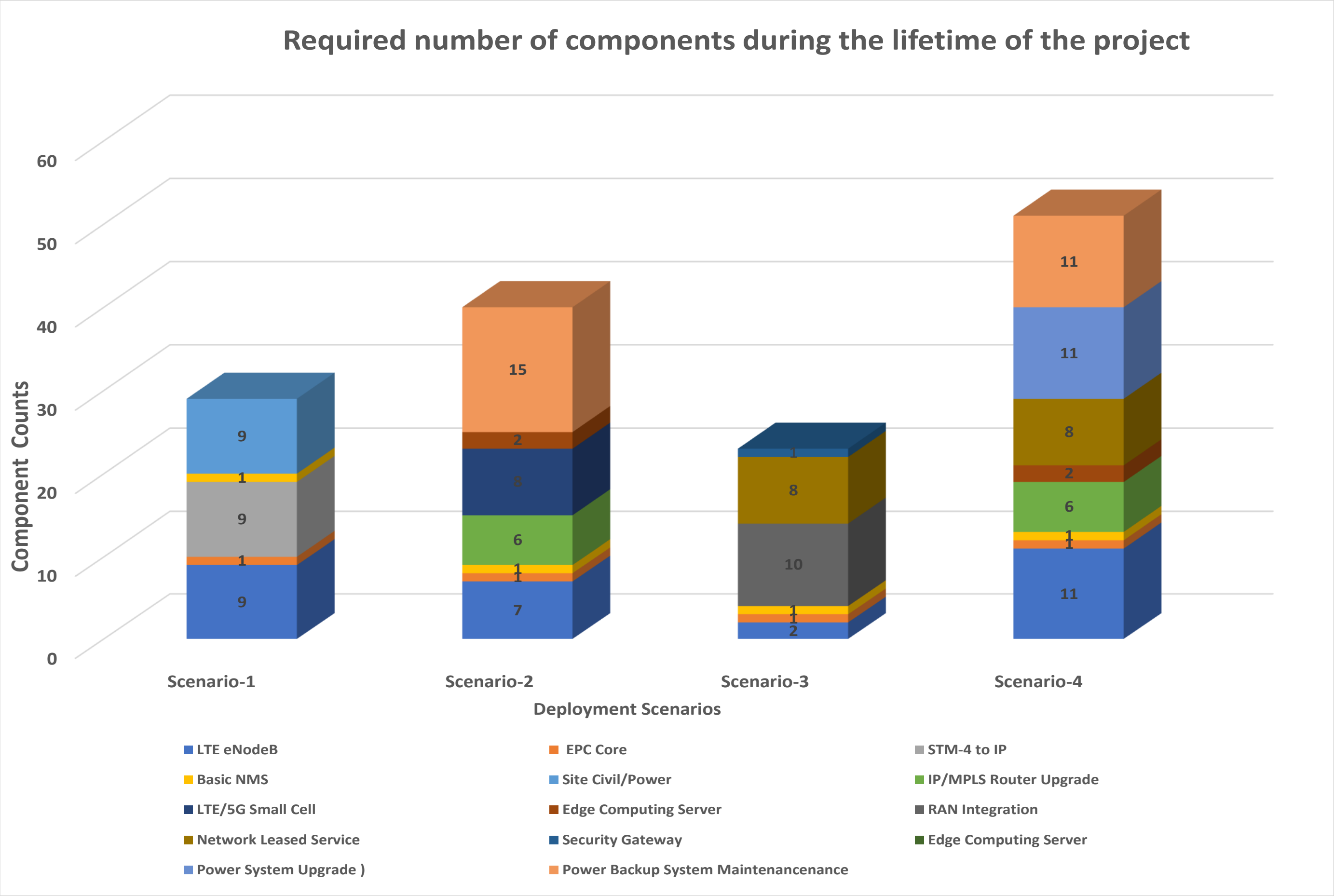


Figure 7.1: Required Number of Components During the Lifetime of the Project

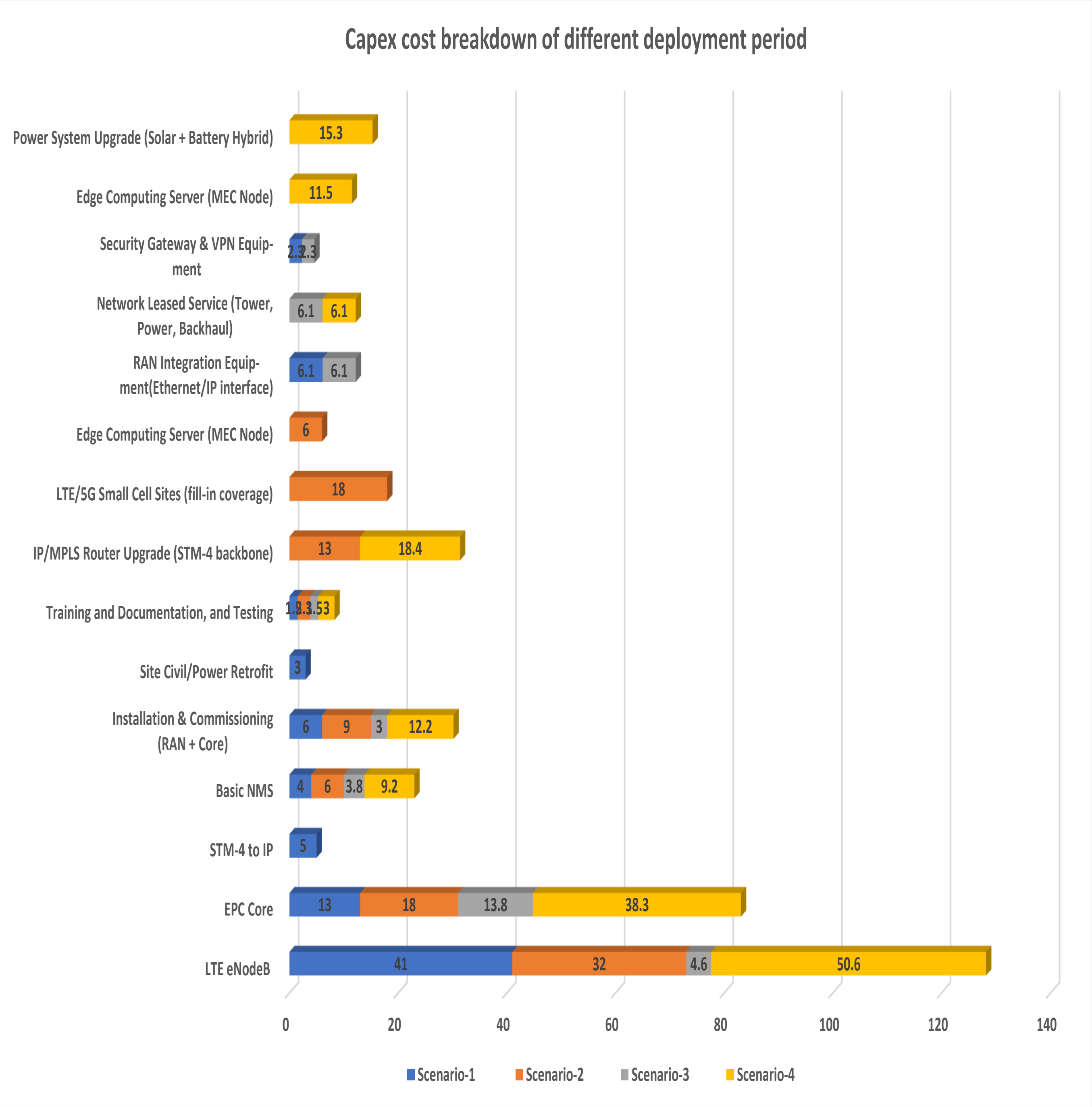


Figure 7.2: Capex cost breakdown of different deployment period

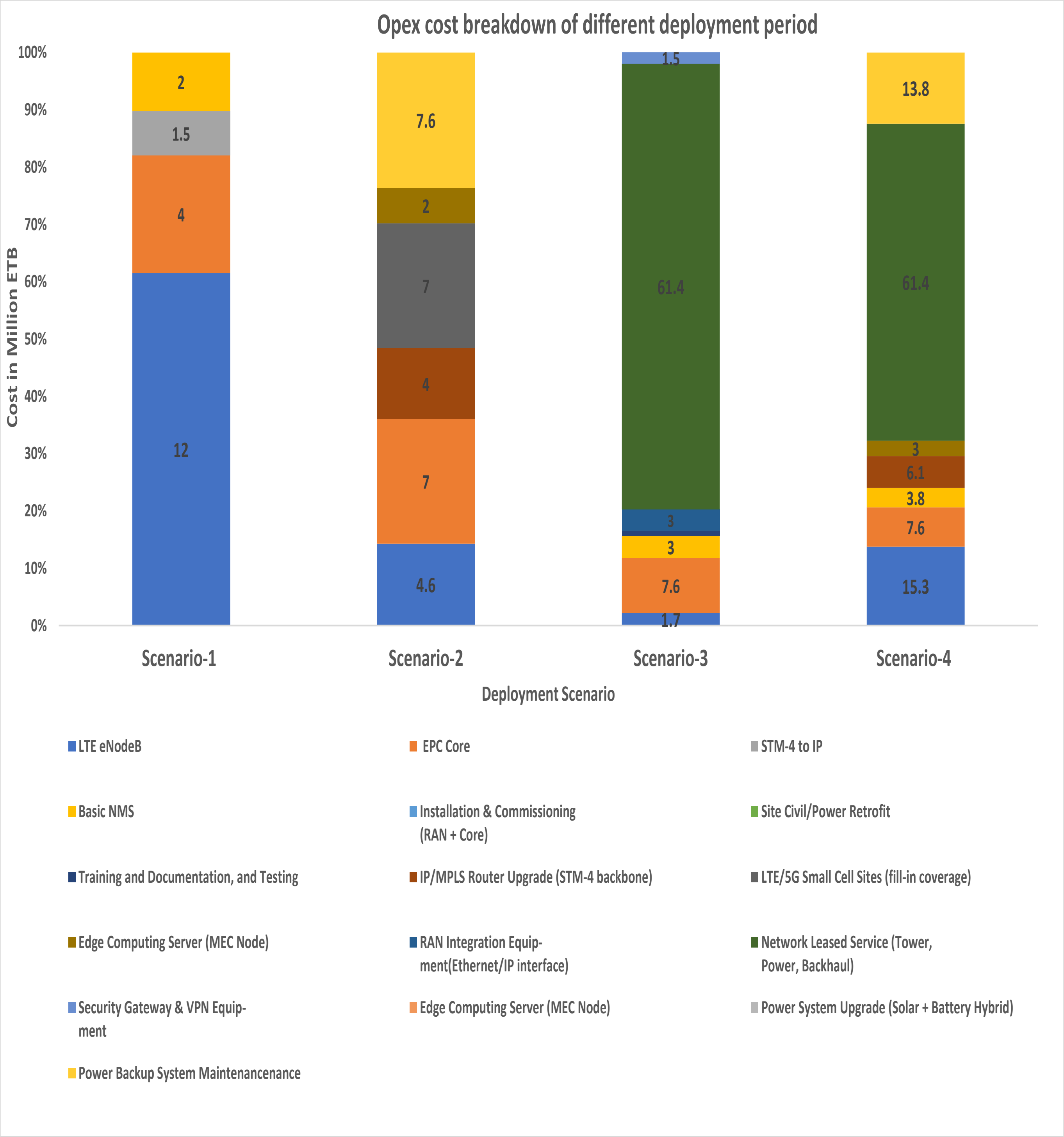


Figure 7.3: Opex cost breakdown of different deployment period

7.2 Economic Analysis

7.2.1 CAPEX and OPEX Estimations

The economic analysis of each scenario's CAPEX, OPEX, TCO, and revenue is covered in this section. As shown in Figure 6.1, the total estimated CAPEX costs of Sc-1, Sc-2, Sc-3 and Sc-4 are 75M ETB, 115M ETB, 42M ETB and 157M ETB respectively. Similarly, the total estimated OPEX for Sc-1, Sc-2, Sc-3, and Sc-4 during the study period is 26M ETB, 35M ETB, 78M ETB, and 111M ETB respectively.

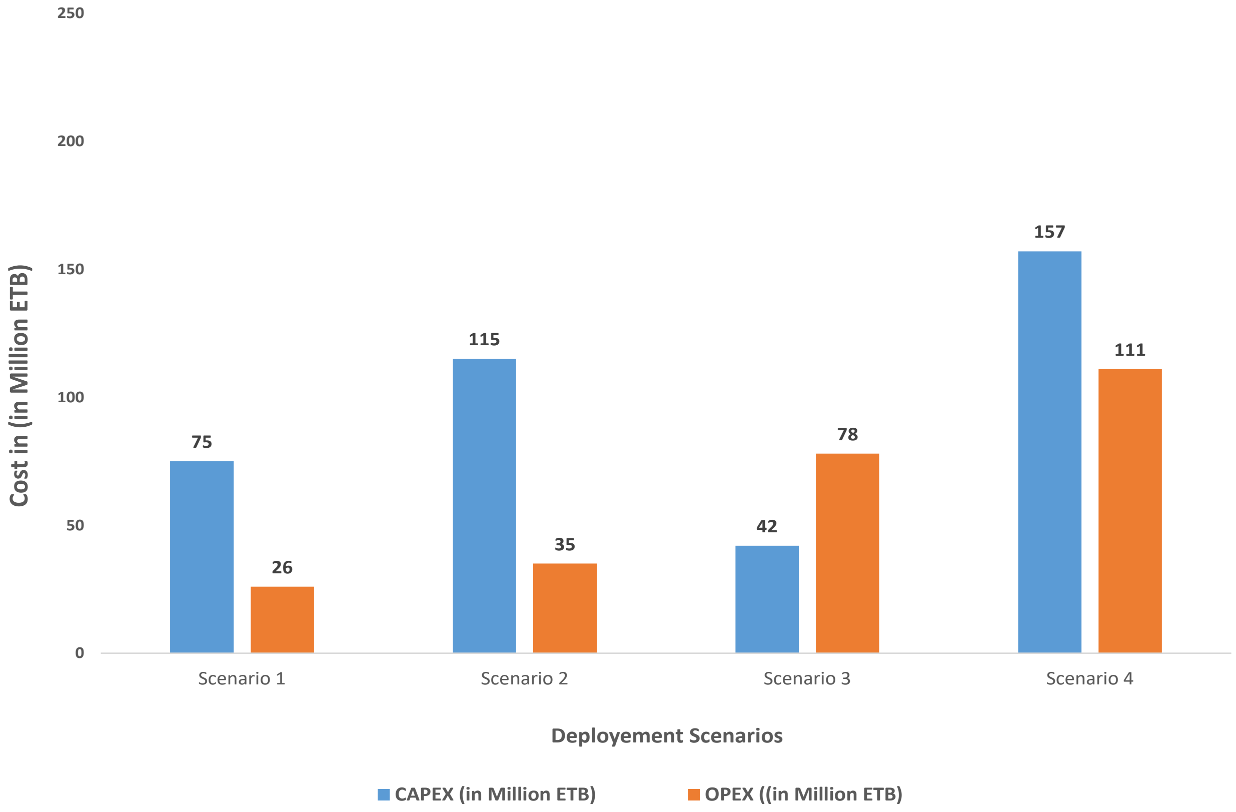


Figure 7.4: CAPEX and OPEX Estimation

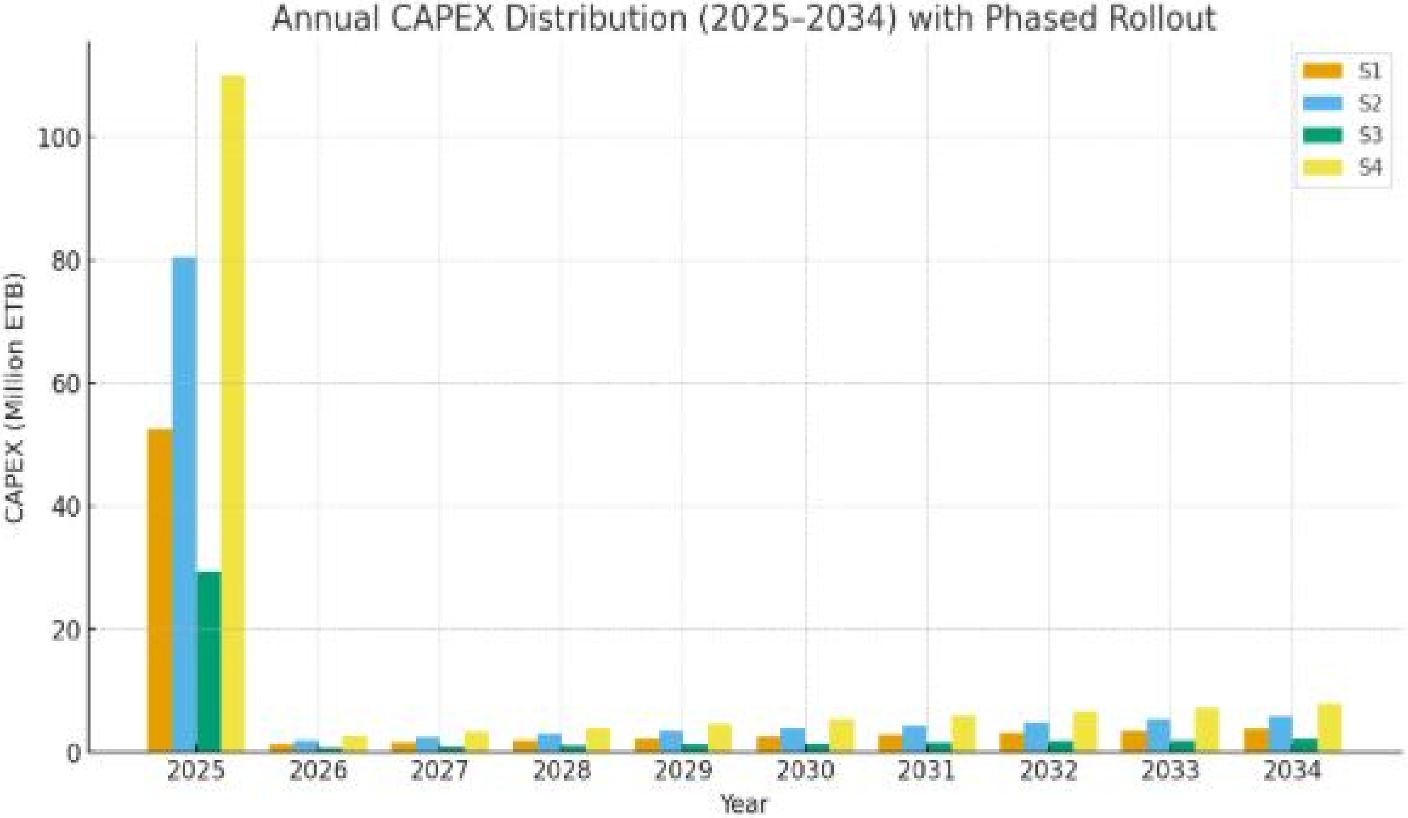


Figure 7.5: CAPEX cost trends for each scenarios

The four deployment scenarios as analyzed in the annual CAPEX with a phased rollout of 70^1 in the first year and 30^1 in 2025-2034, can be used to explain specific patterns of investments that can be applied to each strategic configuration.

Scenario-1 (Minimal Upgrade) will involve the total CAPEX of 75 million ETB, with 52.5 million ETB being spent during the first year and the remaining 22.5 million ETB being spent over the next nine years and hence indicates low-cost LTE upgrades and small incremental growth in services.

In Scenario-2, (STM-4 Optimised) the total CAPEX is 115millionETB and is front-loaded in the first year with 80.5millionETB to support the backbone infrastructure and edge infrastructure to support high-demand services with the rest of the 34.5millionETB spread across subsequent years to support incremental improvements.

Scenario-3 (Ethio Telecom Shared RAN) depicts an economical plan that has a total CAPEX of 42millionETB, whereby 29.4millionETB is initially invested and 12.6millionETB is spread over the nine years of operation (period), which is in accordance with a leased RAN implementation and a moderate upgrade of services.

The Full Hybrid Upgrade (Scenario-4) is the most capital-intensive scenario, with an overall CAPEX of 157million ETB, 109.9million ETB of which is spent in the first year, and the rest, 47.1million ETB is implemented over the years and hence represents a gradual introduction of the advanced LTE/5G services, high infrastructure resilience, and future proofing.

In general, the staged CAPEX graph reveals that there is a large initial investment in all the cases, and Scenario-4 and Scenario-2 focus on transformational capabilities, whereas Scenario-1 and Scenario-3 focus on cost efficiency and moderate service growth.

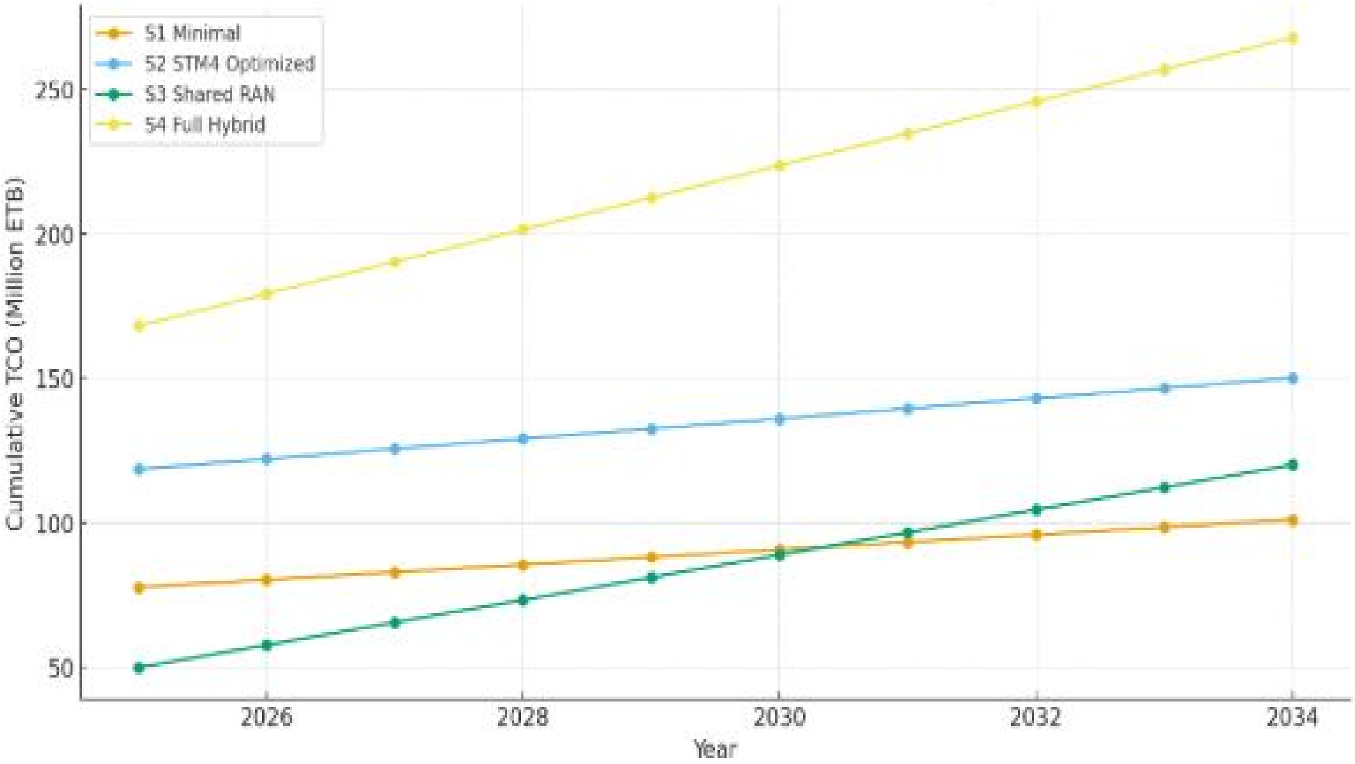


Figure 7.6: TCO trends (2025–2034)

The cumulative Total Cost of Ownership (TCO) has a progressive trend in all cases since annual OPEX is growing over the ten years horizon. Scenario-1 (Minimal Upgrade) is the only one that maintains the lowest TCO curve due to its relatively small CAPEX and limited operational needs, which results in the lowest cumulative cost at the period. Scenario-2 (Optimized STM-4 Reuse) starts with an average CAPEX but realizes a strong cost stability, giving a mid-range TCO curve that is significantly lower than the densification-heavy designs. Scenario-3 (Shared RAN) will start with an increased CAPEX and will grow faster, which represents increased infrastructure requirements, and OPEX pressures. Scenario-4 (Full Hybrid LTE/5G) is the steepest TCO curve that is influenced by the highest initial CAPEX and increased complexity in its operation, thus the most expensive long-term option. This leads to the following ranking of cumulative TCO (lowest to highest) during 2025-2034

$$\text{Scenario-1} < \text{Scenario-2} < \text{Scenario-3} < \text{Scenario-4},$$

.

indicating that Scenario-2 achieves a favorable balance between performance and lifecycle cost, while Scenario-1 offers the minimum-cost baseline.

7.2.2 Service Utilization Rate (SUR) and Coverage Efficiency.

All four deployment situations have non-homogeneous levels of service utilization rate (SUR) and coverage efficiency, which directly depend on the size of the infrastructure and the level of demand. In Scenario 1, which is characterized by the lack of upgrades and low demand, the utilization rate is 20 percent, and the coverage of the corridor is 60 percent. Scenario 2, which uses the existing infrastructure with densification, has a utilization popularity of 35 percent and coverage levels of 85 percent, thus striking a balance between the cost and service quality. Scenario 3, which implies the installation of new infrastructure to satisfy the modest demand, achieves a coverage rate of 75% and the utilization rate of 25% and thus provides more control and committed reliability. Scenario 4, which reflects the most sophisticated setup with complete densification and high demand, provides the highest coverage of 95 percent and a utilization rate of more than 45 percent, which facilitates strong service delivery of video, IoT, and real-time emergency response.

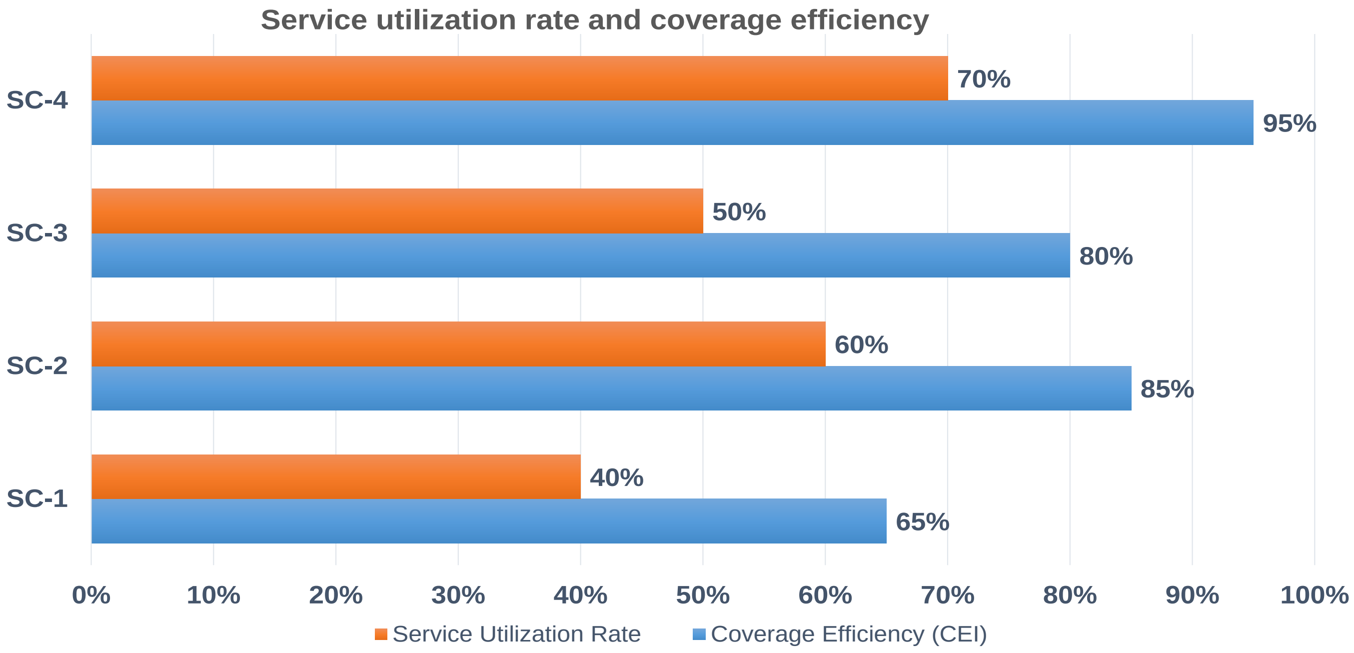


Figure 7.7: Service utilization rate and coverage efficiency of each deployment scenarios

7.3 Techno-economic Evaluation

7.3.1 Cross-Scenario Comparative Insight

Metric	Scenario-**1**	**Scenario-2**	**Scenario-3**	**Scenario-4**
Annual net Benefit	3.88 Million	21.745 Million	6.06 million	28.401 million
Discounted benefits	23.92 million	169.48 million	93.03 million	265.15 million
Discounted costs	92.446 million	138.485 million	94.339 million	231.582 million
TCO (M ETB)	101	150	120	268
Coverage Efficiency (ESCE %)	70	90	80	97
CAPEX Share of TCO (%)	74	77	35	59
OPEX Intensity (OPEX/TCO)	26%	23%	65%	41%
Risk Level	Low tech, high ops	Balanced	High dependency	High financial
Strategic Value	Low	High (Optimal)	Medium	Very High
Scalability	Limited	Strong	Moderate	Excellent

Table 7.1: Economic Indicators (Base Case Estimates Over 10 Years)

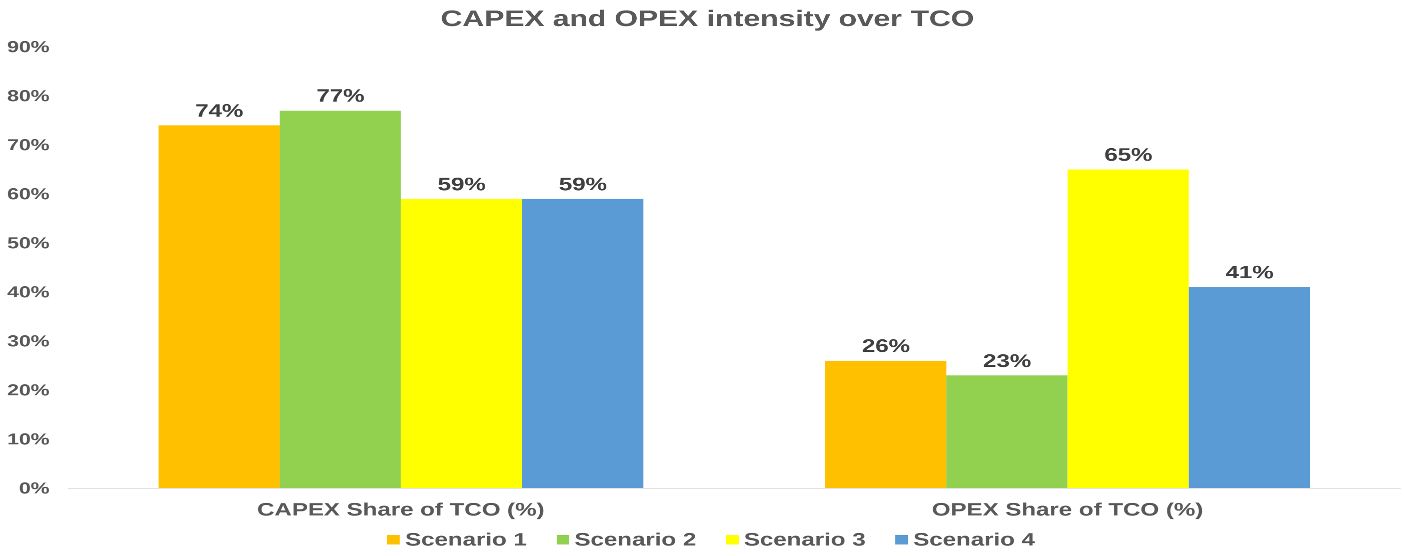


Figure 7.8: CAPEX and OPEX Intensity over TCO

In the Minimal Upgrade scenario (S1), the constraints of deployments with extremely low capital expenditure are highlighted. Though requiring a small initial outlay, only 75 million ETB it has a limited technical capacity (30 percent potential improvement), restricted coverage (60 percent) and use (40 percent) which results in a relatively small reduction of 3.6 percent in annual incident costs, resulting in comparatively small annual savings of 3.8 million ETB. Instead, the STM-4 Optimized scenario (S2) provides much better technical and operational performance. By implementing an enhanced level of analytics, improved utilization and a breadth of coverage of 85% it can achieve a successful decrease of 25.5% in incident-related costs and generate savings of 21.745 million ETB annually, which is a more efficient and effective solution.

The Shared-RAN scenario (S3) has the advantage of low capital expenditure requirements (42 million ETB) and potential of fast deployment but this is limited by the heavier commitments in operating costs and the performance constraints that rely on service level agreements. It provides an average of 14 percent of effective reduction and net savings of 6.06 million ETB annually and is susceptible to changes in wholesale leasing rates. In comparison, the Full Hybrid Upgrade scenario (S4) has the strongest technical results, which is backed by a high level of coverage (95%), high usage (70%), and a high possibility of improvement (60%). This scenario achieves the greatest effective reduced value 39.9 percent and savings of 28.401 million ETB annually, which indicates its focus on reliability, sophisticated video intelligence, and scalability over time. On the whole, S1 and S3 have incremental benefits at a limited budget whereas Scenario 2 and Scenario 4 are the most strategic and economical in terms of costs and operational impact on the mission-critical services, respectively.

Comment: ***Scenario 3*** *has economic benefits due to infrastructure and spectrum sharing, but it is not very applicable in mission-critical services because it is limited in the ability to control its operations, relies on service-level agreements (SLAs), and has regulatory uncertainties. These aspects reduce the resiliency of the networks as compared to fully owned deployments or dedicated deployments.*

7.3.2 Discounted Payback Period

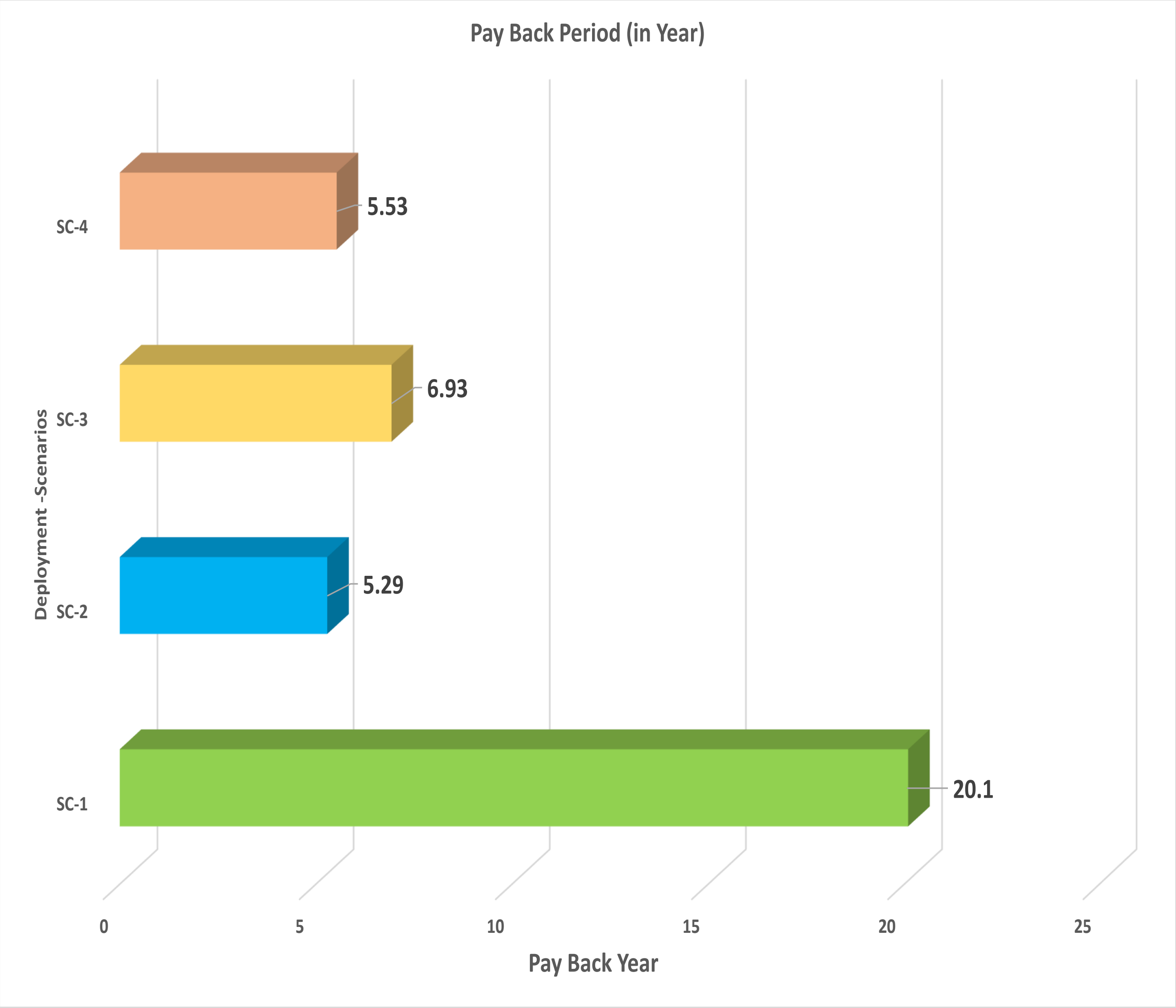


Figure 7.9: Payback Period in Years

The analysis of the payback period shows that there is a significant heterogeneity in the four deployment scenarios.

The Minimal Upgrade, referred to as S1, has the longest payback period, which is over twenty years, because of the marginal net savings, which can be attributed to the lack of technical capacity, utilization, and a rather small effect on the cost of incidents.

Scenario S2, or the STM-4 Optimised configuration, has the best financial performance in this metric with a payback period of 5.3 years. The results of this are supported by extensive coverage, increased service delivery, and an annual net saving of significant proportions.

S3 is the scenario that is related to the Shared model of the RAN and the intermediate payback period is 6.9 years, but the recurrent OPEX, even though initial capital investments are low, prevents financial payback.

The Full Hybrid Upgrade implementation in Scenario S4 is a competitive payback period of 5.5 years, as it is in Scenario S2, as it is highly effective and its annual cost savings are significant, despite the fact that CAPEX is high.

7.3.3 Net present value

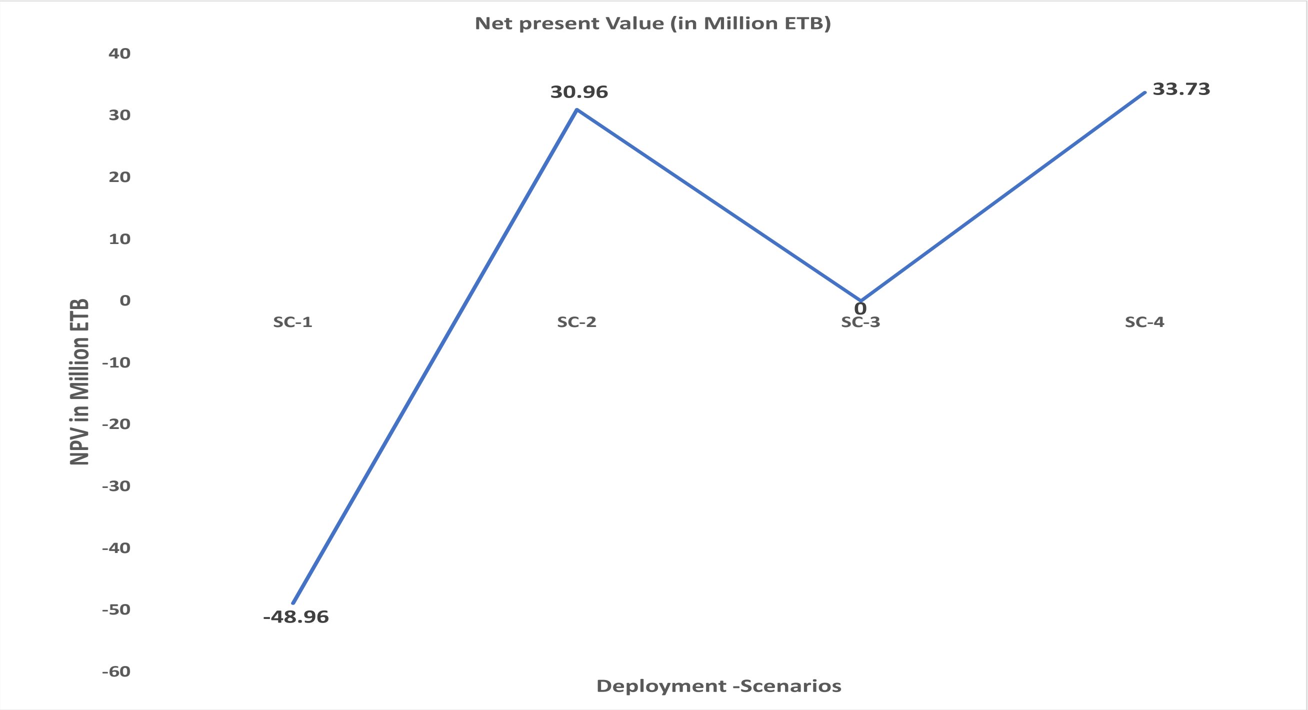


Figure 7.10: Net present value

The results of Net Present Value (NPV) clarify the financial feasibility of each of the suggested scenarios in the long term in the conditions of discounted cash-flow. In scenario 1 (S1), NPV is significantly negative, which is 48.96 million ETB, and it implies that minimal upgrades do not result in a high enough economic payoff during the period of study. The Scenario 2 (S2), however, gives a distinct positive NPV of +30.96 mill. ETB, thus offering a solid basis of justification to invest, especially considering less incident costs and evenly distributed operating expense (OPEX) profile. Scenario 3 (S3) has a negative NPV of 1.34million ETB, which places it at a point close to breakeven but in the end indicates poor financial returns since it has high leasing-based OPEX. The highest NPV is +33.73million ETB in scenario 4 (S4) that represents the economic value of its extensive coverage, excellent technical performance, and increased service use.

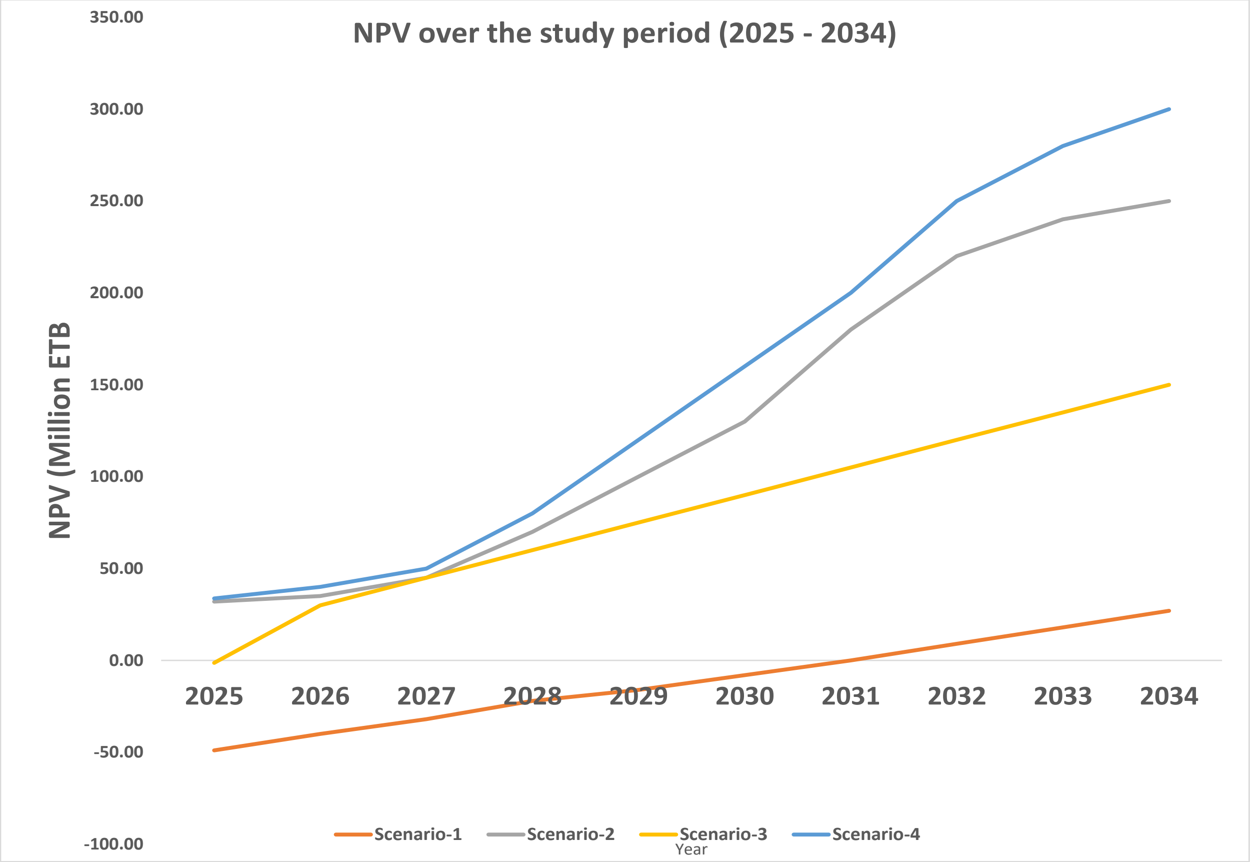


Figure 7.11: Cumulative NPV over the study period

The long-term economic trajectories for these alternative scenarios will significantly differ according to their cumulative net present value (NPV) data over the entire 10-year study period. Cumulative NPV for the alternative scenario S1 will remain consistently negative across the entire study period, as its annual net benefits are very small in amount and thus do not contribute to any recovery of the initial investment. In comparison, S2 has a large amount of cumulative net present value (NPV) growth which will not only cross into the positive arena early in the analysis, but that will also have high total cumulative return thereafter. Cumulative NPV growth for S3 was much less than S2 and continued to gradually increase until approximately reaching zero, giving rise to S3's cumulative NPV being very close to that of zero (or cost recovery) without providing any sustained positive cumulative NPV. Cumulative NPV growth for the last alternative scenario S4 was very similar to that of S2's growth; however, by the end of the 10-year cumulative NPV, S4 will have generated slightly higher cumulative value than S2 at that time due to S4 providing greater amounts of annual net savings than S2. Thus it has been demonstrated that the hybrid architecture produced the greatest amount of cumulative value after ten years of operation, although the hybrid does have the greatest initial cost to implement.

7.3.4 Discounted Benefit Cost Ratio (BCR)

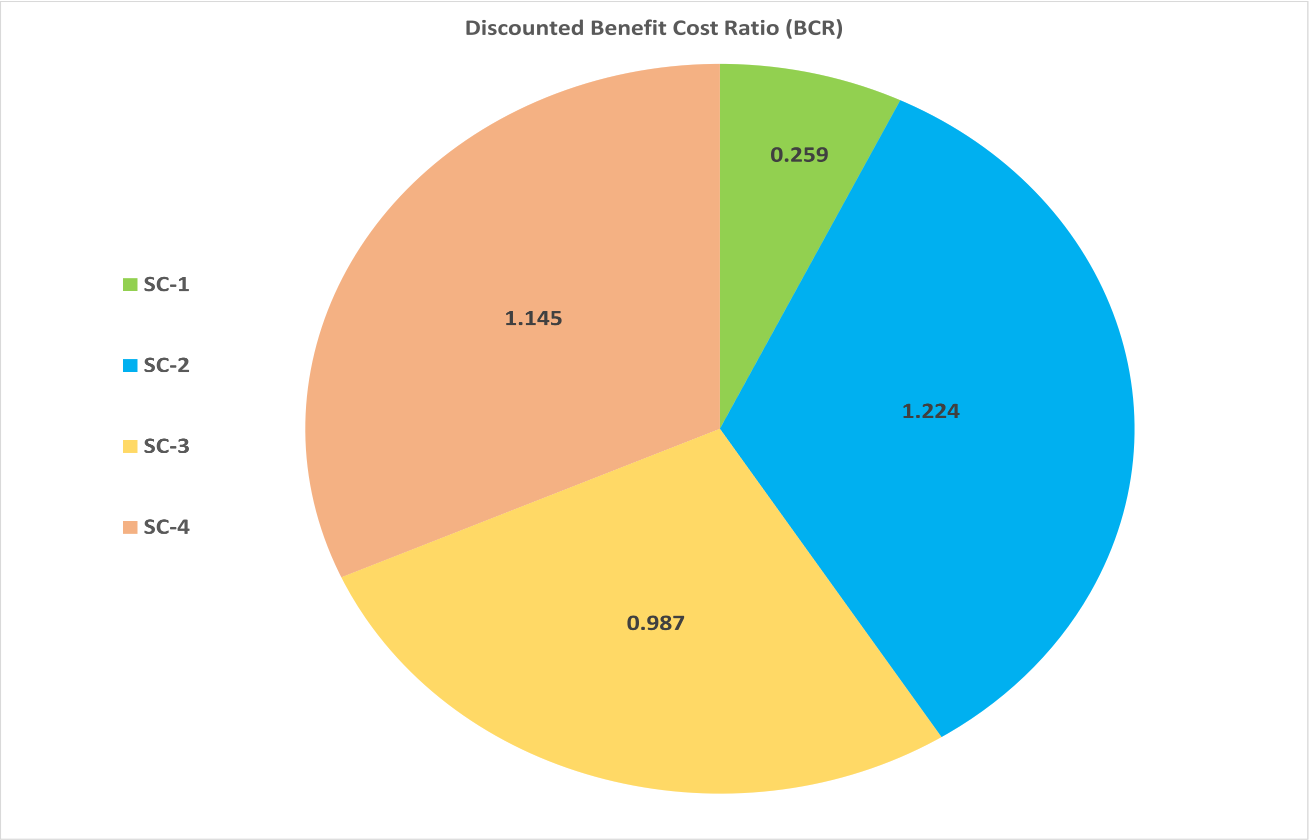


Figure 7.12: Discounted Benefit Cost Ratio (BCR)

The BCR for the different scenarios provides a relative measure of the attractiveness of the different economic scenarios. The BCR of Scenario 1 (S1) is 0.259 which shows that the discounted benefit is significantly lower than the total discounted costs. The BCR of Scenario 3 (S3) is better at 0.987, but yet again, represents a marginally insufficient amount to justify the economic viability of the scenario. However, Scenario 2 (S2) has the strongest BCR at 1.224; therefore, it provides 1.224 ETB of discounted benefit for every 1 ETB invested and thus, demonstrates that it is the most cost-efficient option. Scenario 4 (S4) BCR of 1.145 also indicates good economic justification for the scenario while illustrating the economic value of high coverage, high use, and 5G capable infrastructure in critical mission contexts.

7.3.5 Sensitivity Analysis

7.3.5.1. Sensitivity Impact of Currency Fluctuation and Inflation

Scenario	**Base TCO (ETB million)**	**TCO (FX + Inflation -10%) (ETB million)**	**TCO (FX + Inflation +10%) (ETB million)**
S1	101	92	111
S2	150	135	165
S3	120	108	132
S4	268	241	295

Table 7.2: Sensitivity Analysis for TCO (Million ETB)

7.3.5.2. Sensitivity Analysis of Key Economic Parameters

Scenario	**NPV (CSPi ±20%)**	**NPV (OPEX ±10%)**	**NPV (r: 6–12%)**	**Dominant Sensitivity**	**Overall Robustness**
Scenario-1	±34.5	±1.7	18 / +11	CSPi	High (stable but low value)
Scenario-2	±62.3	±2.3	28 / +19	CSPi	**Very High (best balance)**
Scenario-3	±53.1	±5.2	34 / +21	CSPi	Moderate –High
Scenario-4	±82.6	±7.4	49 / +31	CSPi & r	Low–Moderate (high risk)

Table 7.3: Sensitivity Impact on NPV (Million ETB)

The incorporation of the input adjustments into the sensitivity analysis indicates an increased total cost (CAPEX and OPEX) due to an increase in the exchange rate (±10%) and an increase in the annual inflation rate (7%). However, the relative order of deployment scenarios (S1-S4) remains the same, indicating that the techno-economic conclusions are robust. Points Worth Considering - Scenario 1 - Stable value but limited growth potential - Scenario 2 - Robust value and significant upside - Scenario 3 - Moderate value but highly sensitive to OPEX - Scenario 4 - Very high risk and therefore more variable value.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

This thesis evaluated the technoeconomic feasibility of introducing hybrid LTE/5G mission-critical communication infrastructure to the Addis Ababa–Adama Toll Road 78km-long passage with high rates of accidents and a significant need to be provided with the best emergency response systems. Grasses surveys, infrastructure audits, radio network design, cost modelling, and multi domain analysis showed that the legacy systems which still exist, together as a major part narrowband voice, intermittent CCTV connectivity and STM4 backhaul cannot be used in the management of current emergencies. Their shortcomings hinder real-time transmission of videos, coordinated dispatch, remotely available diagnostics, effective broadband quality and incorporation with state-of-the-art traffic-management systems.

Linked with the development of four deployment scenarios namely Scenario 1 (Minimal Upgrade), Scenario 2 (STM-4 Optimised), Scenario 3 (Shared RAN) and Scenario 4 (Full Hybrid Upgrade). Such situations represent different cost, capability, and risk trade-offs, and thus can provide informative suggestions to operational decision makers and national policymakers. The techno-economic analysis identified three key sources of network performance and viability including effective service coverage efficiency (ESCE), service utilisation rate (SUR) and technical improvement factor that together dictate reductions in incident-management expenditures and operational delays that can be achieved.

Key Scenario Insights:

- **Scenario 1—Budget Alternative:** Gives marginal benefits due to limited coverage and small advances in technology. Although efficient on cost, its sustainability over time as well as the contribution to emergency response is limited. Its high robustness and low upside potential is supported through sensitivity analysis.

- **Scenario 2—Balanced Optimization:** Achieves considerable gains through optimal reuse of available fibre, migration to IP/MPLS, augmented LTE bandwidth, and operationally enabled through analytics. It is most favourable ROI-to-risk ratio, high robustness, and strong upside potential are evident making it the model of choice to be deployed at the earliest time.
- **Scenario 3 —Operational Lease Model:** Provides cost effectiveness with a short term duration by exploiting common RAN infrastructure. It however, has recurring OPEX and SLA dependency coupled with the lack of control over its operations, which reduces its suitability in the long term. The sensitivity analysis shows a medium-to-large variation in terms of the major economic uncertainty.
- **Scenario 4 —High-End Vision Model:** Provides almost universal coverage, dense LTE/5G RAN, expansion in future ITS, and the next-generation services (HD video and IoT-based hazard-sensing). It can be considered transformative although with high risk of financial loss and requires outside funding or a gradual implementation. The sensitivity analysis shows that there is a significant range around NPV, sensitizing the high degree of risk exposure to foreign exchange fluctuations, inflation as well as operating and other costs.

All in all, this paper can be concluded that Scenario 2 offers the best combination of cost, performance, and risk, and is recommended to serve as the base of deployment in the nearest future. Scenario 4 is the long term vision that will enable a modern, upgradable, and resilient mission critical communication framework that will support the digital transport goals of Ethiopia. The sensitivity analyses support the strength of Scenario 2 and the exposure of risk of the Scenario 4, hence allowing the decision-makers to plan deployment in accordance with economic uncertainties.

The results demonstrate that a mixed fibre-plus-wireless infrastructure is critical in improving the safety of corridors, operational effectiveness in addition to facilitating next-generation intelligent transport services, and therefore, the Addis Ababa-Adama Toll Road will become one of the key models of national smart corridor projects.

8.2 Future Work

In order to overcome the drawbacks of the employed assumption of the economy that have been realized in this paper, subsequent research will have to be conducted using dynamic models of techno-economics models. It may include these structures with an inflation indexed pricing, stochastic exchange rate forecasting and cost development scenarios to include more sound financial information to make a decision in relation to the Ethiopian unique macroeconomic environment.

Technically, future studies need to investigate migration steps of private mission-critical LTE to full 5G Standalone. This involves empirical validation of URLLC performance, network slicing, and artificial intelligence-driven predictive maintenance features to guarantee reliability and operational efficiency of emergency communications of toll-road.

In future studies, further development of a holistic human-in-the-loop transition plan with staged training, operational simulations and monitoring of adoptions needs to be developed. This type of planning would avert risks involved in the process of moving away the legacy LMR systems to LTE/5G to make sure staff members are prepared and operations are smoothed.

Lastly, piloting and field experiment on the Addis AbabaAdama Toll Road should be recommended to test the assumptions of performance, determine the socio-economic effects, and experiment with hybrid architectures. Specifically, to investigate alternative solutions to tackle hybrid terrestrial-satellite systems, future research can consider hybrid LEO satellite backhaul services as a backup layer or service to ensure the availability and resiliency of networks to support mission-critical services in Ethiopian expressway networks within the national highway corridors.

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