Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering
MASTER THESIS

Comparative Analysis of LOS-MIMO and Millimeter Wave Band for Microwave Link Capacity Enhancement: The Case of Ethio Telecom

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Thesis Title

Comparative Analysis of LOS-MIMO and Millimeter Wave Band for Microwave Link Capacity Enhancement: the case of Ethio telcom

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Declaration of Authorship

I, Munir AHMEDNUR, declare that this thesis titled, "Comparative Analysis of LOS-MIMO and Millimeter Wave Band for Microwave Link Capacity Enhancement: The Case of Ethio Telecom" and the work presented in it are my own. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
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This thesis has been submitted for examination with my approval as a university advisor.
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Abstract

Due to high growth of users, enhanced user terminals and service development, the demand for high data rate and new services are growing rapidly. Backhaul networks need to handle these huge volume of traffic or else they will become bottleneck for the rest of the network. LOS-MIMO and millimeter wave band can be applied at wireless backhaul network for capacity enhancement. However, technological advancement alone cannot show the performance acceptability and economic viability of an investment without detail technical and economic feasibility assessment. On the other hand, operators like ethio telecom rather than depending on vendor driven choice, should do localized techno-economic assessments.

This thesis work investigates and evaluates suitable scenarios of link capacity enhancing techniques for delivering broadband services at wireless backhaul. In particular, this work presents techno-economic analysis of four scenarios: Single-Input Single-Output (SISO), Line-of-Site Multiple-Input Multiple-Output (LOS-MIMO), Millimeter wave (mmW) band and Millimeter wave Multiple-Input Multiple-Output (mmW-MIMO) that can be used to boost link capacity of wireless backhaul based on traffic data requirements.

The studies are based on a modeling methodology for network value analysis that involve capital expenditure (CAPEX), operational expenditure (OPEX), total costs of ownership (TCO) and revenue calculation for all scenarios, while the overall technology deployment financial or economic assessment is based on techno-economic evaluations such as net present value (NPV), internal rate of return (IRR) and pay-back period (PBP) economic indicators. For techno-economic evaluation, techno-economic assessment (TEA) model is implemented in MATLAB and MS-excel, and consists of revenue and cost modeling parts.

The results indicate that, the pay-back period of the scenarios are: 0.9, 1.18, 1.226 and 1.426 years for mmW band, MIMO, mmW-MIMO and SISO respectively. Regarding to NPV and IRR, all scenarios have positive NPV for the study periods and greater IRR value than defined discounted rate. Sensitivity analysis also shows that, traffic data rate is the most sensitive parameter over CAPEX, OPEX and TCO that affect the revenue, which in turn influences the rate of return on investment (ROI) period. Thus, the economic indicators imply that all scenarios are technically and economically feasible for deployment but the scenarios should be deployed based on the requirements. Considering long period benefit, mmW-MIMO is the best solution with highest NPV and IRR., and mmW band, MIMO and SISO are in 2^{nd}, 3^{rd} *and* 4^{th} *position. Millimeter wave band is scenario with shortest ROI.*

Keywords—LOS-MIMO, mmW band, mmW-MIMO, SISO, TE analysis.

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Contents

List of Figures

List of Tables

List of Abbreviations

2G	**Second Generation**
3G	**Third Generation**
4G	**Fourth Generation**
ACTS	**Advanced Communication Telecom services**
AR	**Adaptive Rate**
ARPU	**Average Revenue per User**
ATPC	**Automatic Transfer Power Control**
BW	**Band width**
CAPEX	**Capital Expenditure**
CF	**Cash Flow**
CP	**Cross Polarization**
dB	**decibel**
dBm	**decibel-milliwatt**
DCF	**Discounted Cash Flow**
DMUX	**De-multiplexer**
ECOSYS	**Techno-Economics integrated Communication Systems and Services**
EIRP	**Effective Isotropic Radiated Power**
eNodeB	**evolved Node B**
ETB	**Ethiopian Birr**
FCC	**Federal Communication commission**
FDD	**Frequency Division Duplex**
FM	**Fade Margin**
FODU	**Fully Outdoor Radio Unit**
GB	**Giga Byte**
GHz	**Giga Hertz**
GSM	**Global System for Mobile Communication**
GUI	**Graphical User Interface**
HOM	**High-order Modulation**
IDU	**Indoor Unit**
IEEE	**Institute of Electrical and Electronics Engineers**
IF	**Intermediate Frequency**
IMPEX	**Implementation Costs**

IRR	**Internal Rate of Return**
ITU	**International Telecom Union**
LA	**Link Aggregation**
LOS	**Line-Of-Site**
LOS-MIMO	**Line-of-Site Multiple-Input Multiple-Output**
LTE	**Long Term Evolution**
MATLAB	**Matrix Laboratory**
Mbps	**Mega bit per second**
Mhz	**Mega hertz**
MIMO	**Multiple Input Multiple Output**
mmW	**Millimeter wave band**
mmW-MIMO	**Millimeter wave Multiple-Input Multiple-Output**
MUX	**Multiplexer**
NF	**Noise Figure**
NGN	**Next Generation Network**
NLOS	**Non-LOS**
NPV	**Net Present Value**
ODU	**Outdoor Unit**
OMT	**Orthomode Transducer**
OPEX	**Operational Expenditure**
OPTIMUM	**Optimized Architectures for Multimedia Networks and Services**
PBP	**pay-back period**
PHC	**Packet Header Compression**
PMP	**Point-to-Multipoint**
PTP	**Point-to-Point**
QAM	**Quadrature Amplitude Modulation**
RACE	**Research in Advanced Communications in Europe**
RF	**Radio Frequency**
ROI	**Return on Investments**
SD	**Spatial Diversity**
SISO	**Single-Input Single-Output**
SM	**Spatial Multiplexing**
SNR	**Signal to Noise Ratio**
TCO	**Total Cost of Ownership**
TEA	**Techno-economic Assessment**
TERA	**Techno-Economic Results from ACTS**
TITAN	**Tool Introduction Scenario and TE Evaluation of Access Network**
TONIC	**Techno-economics of IP optimized networks and services**
UMTS	**Universal Mobile Telecommunications System**

Chapter 1

Introduction

The demand for high data rate and services are increasing globally due to the development of services and increased penetration rate of users and enhanced user terminals like laptops and smart phones. In Ethiopia, this trend is demonstrated by the traffic data usage, number of subscribers and service demands reported by the sole telecom operator, ethio telecom. To fulfill the demands in telecom sectors, wireless technologies are fast evolving continuously [1, 12]. These growing mobile data traffic is an opportunity for operator as it leads to revenue maximization. To fulfill the demands, ethio telecom has expanded its services and network infrastructures by deploying enhanced radio access technologies like 3G and 4G (in Addis Ababa) at radio access part. These increase the growth in the volume of data exchanged between end terminals which in turn exert a pressure on backhauling networks. Backhaul networks need to handle these huge volume of traffic or else it will become bottleneck for the rest of the networks.

Backhauling is the portion of the network infrastructure that provides interconnectivity between the radio access and core networks. To handle this huge volume of data from radio access networks, the operator either has to expand its backhaul infrastructures or implement enhancing techniques that improve reliability, and increase spectral efficiency and capacity of the systems. But high infrastructure costs for new infrastructures pose new challenges and force operators to move to the second option. On the other hand, the optical networks used in some aggregated links in Addis Ababa are underutilized or over-provisioned. But, the resources are scarce and limited, so there is a need to use them properly and efficiently.

Looking to the backhaul options, operators have the choice among several transmission technologies for building a backhaul networks based on cost effectiveness, performance, reliability, capacity and ease of deployment. Microwave system is one of the backhaul technology that operators prefer for its cost effectiveness, scalability, easy and fast deployment coupled with its sufficient capacity. Ethio telecom uses microwave system for most of its mobile backhauling and as back up for optical networks. Even though, spectral efficiency, capacity, reliability and availability of microwave links are more challenging due to limited available bandwidth and fading nature of propagation channel, there are different enhancing techniques and possible technological solutions.

Possible enhancing techniques and available technological solutions that can be used for wireless link capacity enhancement and reliability improvement are: high-order modulation (HOM) techniques, automatic transfer power control (ATPC), multi-layer header compression (PHC), cross polarization (CP), link aggregation (LA), wider bandwidth (WB), millimeter wave (mmW) band and Line-of-Sight Multiple-Input Multiple-Output (LOS-MIMO) [13]. Except for mmW band and LOS-MIMO, all other solutions are already applied in case of ethio telecom and they have their own drawbacks in related to efficiency, scarcity, reliability and interference impacts.

As an example, high order modulation schemes, as the modulation level increases the sensitivity to noise and signal distortion increases. For every increased step in modulation level the receiver sensitivity will be reduced by 3 dB which in turn reduce the communication ranges, while the related capacity gain gets smaller in percentage terms (efficiency decreases as it goes up to high level). Multi-layer header compression removes unnecessary information from the headers of data frames and releases capacity for traffic purposes. On compression, each unique header is replaced with a unique identity on the transmitting side. This process will be reversed on receiving side. But the effectiveness of packet compression depends on the traffic mix and the size of packet, and it is most beneficial when the network is transporting small packets. Multichannel approach or link aggregation creates a virtual link from two or more underlying channels. The resulting capacity is the sum of every channel's capacity. Despite the orthogonality of two signals at dual polarization, due to imperfect antenna isolation and channel degradation (typically rain depolarization effects), some interference between the signals almost inevitably occurs and causes signal degradation[14].

Line-of-Sight Multiple Input Multiple Output and millimeter wave band are the focus of thesis. Line-of-Sight Multiple Input Multiple Output is a recent technology in microwave communications which is different from the well-known non-line-of-sight MIMO technology widely used in access networks. LOS-MIMO revolutionizes microwave communication in terms of capacity and spectral efficiency, and use multiple antennas at both terminals. To increase the link capacity and spectral efficiency, LOS-MIMO system operates spatial multiplexing(SM) in good environmental conditions and spatial diversity(SD) in challenging conditions to improve system performance or reliability. Similarly, mmW band provide un congested wider bandwidth (up to 10 GHz) to support high capacity communication[14].

Report in 2017 from [1], as can be seen in Figure 1.1 indicates that, the majority share of backhaul links (an aggregate of macro cells and small cells) deployed was in the traditional microwave 7 GHz to 40 GHz bands which is (56.1%) share. Microwave Line-of-Sight

(LOS) in these frequency bands is still a long-term viable solution for macro cell sites and continue to fulfill the demands by applying different enhancing techniques. On other hand, usage of microwave links that operate in higher frequency (Millimeter wave) bands will double from 5.1% to 12.6% in 2025. Due to their advantages, LOS-MIMO and millimeter wave bands (E-band) are globally deployed in many countries. The research in 2017 from [1] show that, the usage of microwave system that operate in millimeter wave bands (E-band) is globally increasing, and Nigeria and South Africa are the countries in Africa that have already deployed it.

Technologies vary in their functions, performance and costs. Thus, technological advancement alone cannot show the performance acceptability and economic viability of an investment or technologies without detail technical and economic feasibility assessment. From ethio telecom's perspective, the deployment of mobile technologies are commonly vendor driven and it is rarely supported by localized techno-economic assessments. Therefore, even if analyzing and evaluating these technologies are not simple tasks or decisions, ***it is possible to study technical and economic viability of the technologies under different scenarios through techno-economic assessment method but it needs detail investigation from different perspectives.***

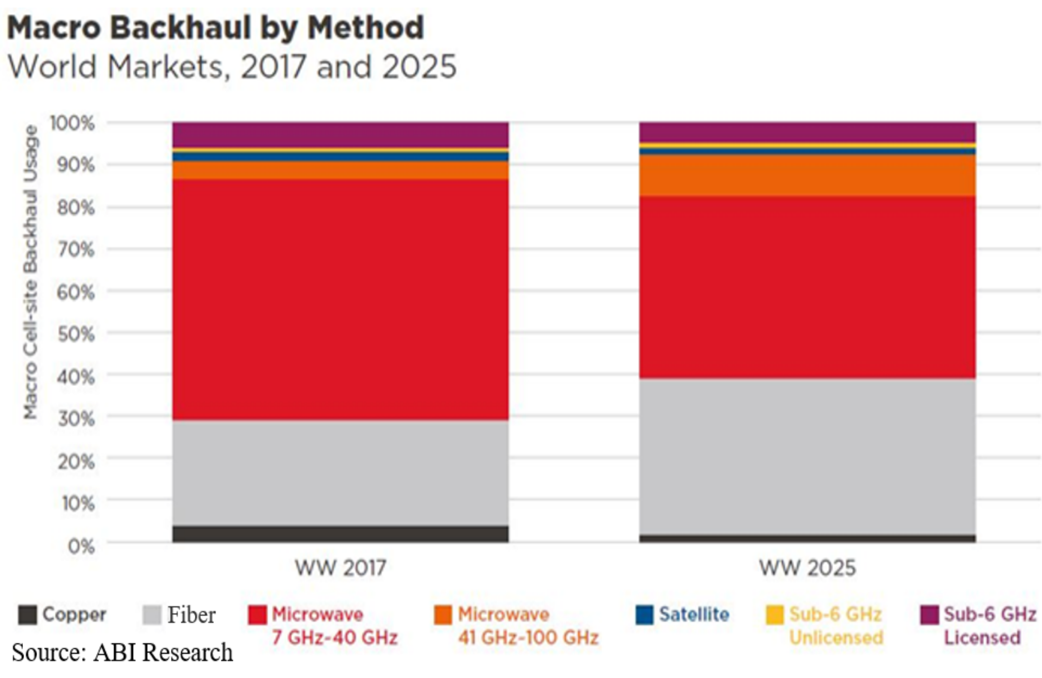

FIGURE 1.1: Macro cell-site backhaul usage share[1]

1.1 Statement of the Problem

Cost effectiveness, increased capacity, reliability and spectral efficiency of backhaul networks are some of the key-factors for deployment of next generation systems. Microwave system is one of the backhaul technology that operator prefers for its cost effectiveness, scalability, easy and fast deployment coupled with its sufficient capacity [13, 14]. Ethio telecom uses microwave for most of its mobile backhauling networks, as a backup for optical backbone and even for long-haul service in remote area. The ambitious capacity requirements for future broadband wireless networks and high infrastructure costs for new infrastructures pose new challenges in the design of high capacity point-to-point (PTP) microwave links.

Even though, spectral efficiency, capacity, reliability and availability of microwave links are more challenging due to limited available bandwidth and fading nature of the propagation channel, there are possible enhancing techniques and technological solutions.

Simple way of increasing capacity of the system is over-provisioning which most operators opt to instead of applying spectrum efficiency or enhancing techniques to fulfill the requirements which results in unnecessary investments and low level resource utilization. LOS-MIMO and millimeter wave band are among possible capacity enhancing techniques or systems which is the focus of this thesis. But, technological advancement alone cannot show the performance acceptability and economic viability of an investment or technology without detail technical and economic feasibility assessment. Possible technology options can be evaluated either by their performance or from economic perspective alone but techno-economic assessment considers both performance and economic analysis to investigate and evaluate the technology technically and economically.

Regarding to ethio telecom, the deployment of networks are commonly vendor driven, even without being supported by localized techno-economic assessments. ***Therefore, there is a need to carry out detail techno-economic feasibility assessment of LOS-MIMO and millimeter wave band under different scenarios before implementation.*** These will improve resource utilization and make understanding on total cost of ownership and performance of different scenarios.

1.2 Objective

General Objective
The general objective of this research is, to perform techno-economic viability assessment of LOS-MIMO and millimeter wave band for aggregated microwave backhaul link capacity enhancement in the case of ethio telecom.

Specific Objectives

- To investigate and evaluate the performance (capacity) of aggregated microwave link under different deployment scenarios: single-input single output (SISO), LOS-MIMO, millimeter wave band and millimeter wave-MIMO (mmW-MIMO).
- Economic investigation and comparison of different deployment scenarios.
- To investigate the economic feasibility indicators using techno-economic model for all scenarios for further evaluation.
- To analyze and interpret the results.
- Finally, recommend the scenario that is more viable technically and economically for its deployment.

1.3 Methodology

The objective of this thesis is to study and evaluate LOS-MIMO and millimeter wave band scenarios for microwave link capacity enhancement technically and economically.

In this study, the research approach followed is technology evaluation and comparison. The aggregated link in the capital of Ethiopia, Addis Ababa, was considered. Ethio telecom, vendors' manual and literatures are the source of data or information for this work. The detailed analysis of this work was categorized into three parts.

Firstly, revenue is calculated and forecasted for each scenario which is derived from forecasted traffic data demand. The second part is cost modeling and analyzing for each scenario which is driven from economic part. In this case, identifying the key components and their corresponding costs for each deployment scenarios including their operational costs are performed. At last, feasibility analysis and comparison of the scenarios using techno-economic analysis model, which is modified and implemented for this research based on the research model are done. Modified model uses discounted cash flow (DCF) method and implemented in MATLAB and MS-excel. The technical inputs such as operating frequency, link length, bandwidth, transmitting power and economic inputs like capital expenditure (CAPEX) and operational expenditure (OPEX), and other related factors were also taken into consideration for each scenario.

An assumption of five years study period and 10% of interest or discounted rate are also considered as an input to the system model. The decision making economic parameters like net present value (NPV), internal rate of return (IRR) and pay-back period of the scenario are the outputs of system model for each scenario. The procedures or methodology followed to do the whole works are presented with the Figure 1.2 below.

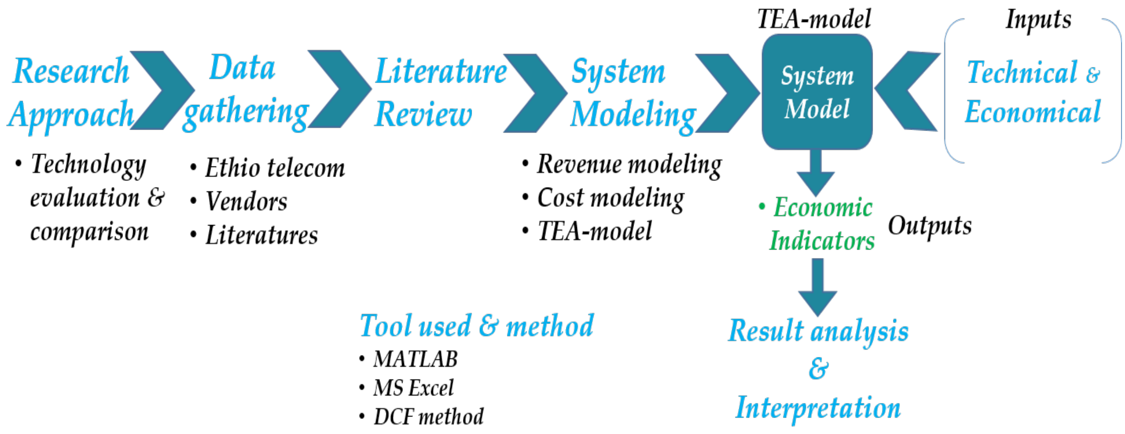

FIGURE 1.2: Methodology followed

The following Figure 1.3 shows implemented model that was used to analyze the scenarios and it holds technical, economic, scenario selection part and DCF method.

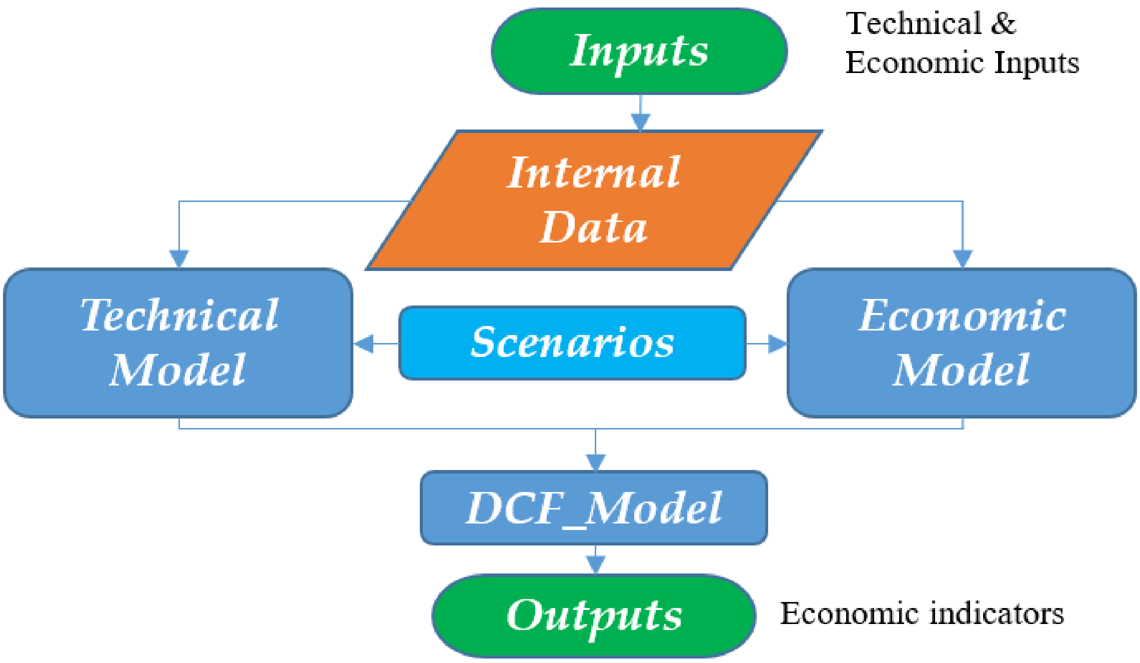

FIGURE 1.3: General system model

1.4 Literature Review

Several studies have been conducted in relation to wireless technology from techno-economic perspectives. In this subsection, the main concepts and related streams of literature on LOS-MIMO, mmW band and techno-economic assessment for different systems were introduced.

The author in [15] evaluates whether it is feasible for an LTE operator to deliver a 30 Mbps fixed service in rural areas in Spain and if this is not the case, whether passive network sharing could make it feasible. The research is conducted through a techno-economic assessment in an infrastructure competition scenario, passive network sharing and non-sharing. A discounted cash flow method is used to determine the total cost of the deployment for the operator and the minimum average revenue per user (ARPU) which would be required to recover the investment in both approaches. The results indicate that, given the socio-economic characteristics of the assessed area, demand is very sensitive to price and that the existence of other broadband products forces the operator to lower the ARPU. As a result, only very high take-up ratios would make the deployment feasible. The research shows that passive network sharing does not constitute a solution; nevertheless, a single network deployment could solve the unfeasibility problem in rural areas.

Techno-economic analysis of UMTS or $3G$ network was conducted by [16] at 900 MHz and 2100 MHz scenario for rural connectivity in Tanzania. Results show that, $3G$ at 900 MHz is a feasible and cost-effective connectivity technology in Tanzania. Cost reduction on $UMTS900$ is due to its implementation strategy of re-using existing GSM network infrastructure. Another aspect which brings about cost efficiency on $UMTS900$ is its wider coverage compared to the coverage achieved by $UMTS2100$ which reduces the numbers of equipment to be deployed and the operational costs. Economic indicator used for comparison was only the total costs of ownership (TCO) of the scenarios.

The techno-economic analysis of two different wireless backhaul architectures at millimeter waves, in Point to Multi-point and Point to Point, are investigated by authors cited in [17]. The TCO comparison clearly shows the advantage of a Point to Multi-point over Point to Point architecture for the same coverage. This was due to lower network equipment in number for point to multi-point scenario which in turn reduce investment and operational costs. The authors considered TCO alone for comparison and didn't use any other economic indicators. On the other hand, different frequency for two scenarios are used by authors that offer different communication range which in turn alter the numbers of sites but the authors didn't consider this issue.

Based on TCO (CAPEX and OPEX) model, financial analysis that compares fiber, PTP microwave, PMP microwave and PTP E-band backhaul are conducted by [18]. From the observations, the author recommended wireless solutions that provide the capacity, performance, flexibility, and cost-effectiveness that they need to backhaul 3G and 4G traffic. Among wireless solutions, PMP microwave is the most cost-effective because it requires fewer radios to meet the backhaul requirements than either PTP microwave or E-band PTP does. This is due to lower equipment and installation costs (fewer radios to install), as well as lower opex (fewer links to operate). Leased fiber is the most expensive, and PTP E-band and microwave are ranked at 2^{nd} and 3^{rd} level next to PMP microwave.

The author in [19] numerically investigate 2x2 spatially-separated, 4x4 spatially-separated and dual-polarized line-of-sight MIMO. Optimal antenna separations at transmitter and receiver were found to depend on the operating frequency and distance; inverse and direct relationship respectively. The author proposed adaptive algorithms for a space-time equalizer to evaluate against detrimental effects such as frequency selective channels, mast swing (antenna movement), polarization leakage and phase noise (correlated and differential).The simulations show that line-of-sight MIMO needs higher system margins and a more complex receiver structure. Deviation from optimal antenna separations can affect the capacity and system performance but can be compensated by increasing transmitting power or by varying the antenna separation on the other end of the link.

Line-of-sight MIMO systems, using geometric arrangement of antennas, which are suitable for practical microwave radios is proposed by [20]. The author found the optimal antenna separation that is used to achieve high capacity of fixed point microwave radio systems for a given hop length and operating frequency. Signal to noise ratio (SNR) of the system from the proposed method are analyzed for variable antenna element separations and maximum signal to noise ratio is found at optimal antenna separation which indicates high capacity is achieved at optimal antenna separation.

The switching mechanism between spatial multiplexing and transmit diversity in LOS-MIMO is studied by [21] and propose it as a simple way to improve the diversity performance of spatial multiplexing. The proposed approach, for a fixed rate, either multiplexing or diversity is chosen based on the instantaneous channel state and the decision is conveyed to the transmitter via a low-rate feedback channel. The minimum Euclidean distance at the receiver is computed for spatial multiplexing and transmit diversity and is used to derive the selection criterion. The author prefers fixed data rate in order to use minimum Euclidean distance at the receiver for the selection criterion and it studied for NLOS MIMO environment in a different context and application.

Reviewed literatures for this work can be categorized into three. Literatures that have been done on techno-economic assessment. From these literatures model used, method applied, tools used for implementation and evaluating parameters (economic indicators) are understood. For this purpose, available researches that have been done on techno-economic assessment, Example [15, 16], are used. Even if they have no direct relation with LOS-MIMO and millimeter wave band, they are used from techno-economic assessment perspective.

The others are, available literatures that are concerned on LOS-MIMO and millimeter wave band for mobile backhaul. Researches that have been done on LOS-MIMO, [19, 20, 21], are concerned on design issues alone like switching mechanism between spatial multiplexing and diversity, the effect of operating frequency and hop length on antenna separation and impact of antenna separation deviation from optimal length on performance which are important from technical perspective to present the difference of LOS-MIMO from SISO but economic part is not considered here. Similarly, some researches,[17, 18], compare CAPEX or TCO of PTP and PMP microwave system, millimeter wave band (E-band) and optical fiber against each other without considering technical part.

As evident in this sub-section, there are several noticeable gaps in the currently available literatures. Firstly, none of the above-mentioned works evaluate the future diffusion aspects of the technology and, hence, do not perform rigorous forecasting of the future demand of data volume. Secondly, some researches restrict themselves to estimate TCO of the scenarios, without considering the projected revenue from services and the overall profitability aspects of the investments. Thirdly, the sensitivities of the cost and profitability parameters with the individual decision variables in the techno-economic model have not been extensively explored in prior works.

To fill in the above gaps, this work analyze and evaluate the scenarios technically to project revenue from services and considers the overall profitability aspects of the investments and economic viability of the scenarios. So performing techno-economic assessment (considering both technical and economic viability) of LOS-MIMO and millimeter wave band is essential and important to improve resources utilization and to investigate the feasibility of technologies before implementation.

1.5 Scope and Limitations

The scope of the thesis

The scope of this research is to study and evaluate the viability of four defined deployment scenarios technically and economically for aggregated microwave link capacity enhancement. Two scenarios are considered from lower frequency band and the other two are from higher frequency band (E-band). Doing techno-economic investigation on possible scenarios before implementation is profitable regarding to resource utilization properly. Five years investigation period and 10% discounted rate or interest rate are considered. The study was carried out for the capital of Ethiopia, Addis Ababa.

The limitations

Thesis work is limited to 2x2 LOS-MIMO, spatial multiplexing operation, millimeter wave band (E-band) and point-to-point microwave aggregation link in Addis Ababa. Some of specific limitations that are faced during investigation are: Due to immaturities of TEA model, and for it is an industry specific and not accessible for external users, TEA model for this work is developed. Generated revenues from each scenarios are contributed by all network parts, so need to distribute it among all parts. To do this, overall cost contribution in percent of total network related costs for $2G/3G$ networks covering urban area which is done by author [7] was used for revenue distribution among network parts. Getting per link energy cost, and operation and maintenance costs by bottom up approach is difficult. So it is obtained from literature.

1.6 Contributions

Techno-economic assessments of LOS-MIMO and millimeter wave band under different scenarios are the contribution of this work. Some researchers compare the CAPEX or TCO of PTP and PMP microwave systems, millimeter wave (E-band) and optical fiber against each other without considering technical part. On the other hand, the researches that have been done on LOS-MIMO are concerned on design issues like the dependency of antenna separation height on operating frequency and hop length. In addition to that, studies focused on switching mechanism between spatial multiplexing and spatial diversity, and the impact of antenna deviation from optimal separation on performance or capacity. Techno-economic assessment model is also modified from Techno-economic results from ACTS (TERA) framework and implemented for this work which can be used for any backhaul technologies.

Techno-economic feasibility assessment is important for an operator to prepare the strategy towards these scenarios to optimize its backhaul networks, improve resource utilization level, and make understanding on total cost of ownership and their performance under different scenarios which is useful for understanding of the viability of each scenario technically and economically. The operator can uses the outputs of this techno-economic analysis either for the decision making for implementation of the scenario for its next expansion projects or used as an inputs for further investigation purpose.

1.7 Thesis Layout

The background or introduction, problem statement, objectives, methodology, literature reviews, contributions, and scope and limitations of this thesis are described in this chapter. The second chapter will present the background of microwave communication system, LOS-MIMO and millimeter wave band. Techno-economic models and evaluation methods including different mathematical models are described in chapter three and followed by deployment scenarios and techno-economic analysis in chapter four. Chapter five presents detail results obtained from techno-economic analysis and interpretation for each scenario. Finally, in chapter six, the conclusions and suggestions for future work were presented.

Chapter 2

Microwave Communication

In this chapter, background of digital microwave communication systems, radio system components and basics of microwave communication including microwave network topology, applications, link design, limitations and possible enhancing techniques are presented. In addition, basics of LOS-MIMO and millimeter wave band are also introduced.

2.1 Background

The use of broadband wireless technology to provide access to the Internet and high-speed networks is attractive to operators because of its low construction cost, quick deployment, and flexibility in providing access to a range of services. Microwave system is one of broadband wireless technologies used for mobile backhauling and it is a digital wireless communication system which uses electromagnetic spectrum in the range of 6 GHz to 42 GHz and requires a clear line of sight and directional antennas [22].

Nowadays, microwave can connect two places many kilometers away with Gbps of capacity. Spectral efficiency, capacity, reliability and availability of microwave links are more challenging due to the limited available bandwidth and the fading nature of the propagation channel. But there are possible technical solutions that enhance microwave link capacity and improve the reliability of microwave system. High order modulation, ATPC, packet header compression, cross polarization, link aggregation, multiple band usage, wider bandwidth, LOS-MIMO and mmW band are some but LOS-MIMO and mmW band are the focus of the thesis.

In future, microwave backhauling communication will keep on satisfying the requirements even with the advancement of 5G networks by implementing enhancing techniques like LOS-MIMO and mmW band for high capacity requirement [1]. Microwave system can be deployed as point to point or point to multi point and currently, ethio telecom implemented point to point scenario. In Ethiopia, microwave system was used as backup for optical network, long-haul and for mobile backhauling service, and uses 6, 7 and 11 GHz frequencies for long-haul (or as backup) and 15, 18 and 26 GHz frequencies for mobile backhauling services. The bandwidths used are 28 and 56 MHz.

2.2 Digital Microwave Radio System Components

A microwave radio system is a system of radio equipment used for microwave data transmission between two end terminals or locations. Digital microwave equipment can be categorized as trunk (Indoor radio), split-mount and all outdoor equipment. In trunk microwave (indoor radio) system, radio frequency (RF), IF, signal processing, and multiplexer (MUX) and de-multiplexer (DEMUX) units are all indoor. Only the antenna system is outdoor. A major components of a split-mount microwave equipment are indoor unit (IDU), outdoor unit (ODU), antenna, and waveguides. See Figure 2.1 below. Except RF unit (ODU) and antennas, all others, IF, signal processing, and MUX/DEMUX units are indoor. The ODU and IDU are connected through an IF cable. The ODU can either be directly mounted onto antenna or connected to antenna through a short soft waveguide. In the case of all outdoor, all the units are outdoor, and easy for installation and the equipment room can be saved [23]. It can be observed from Figure 2.2.

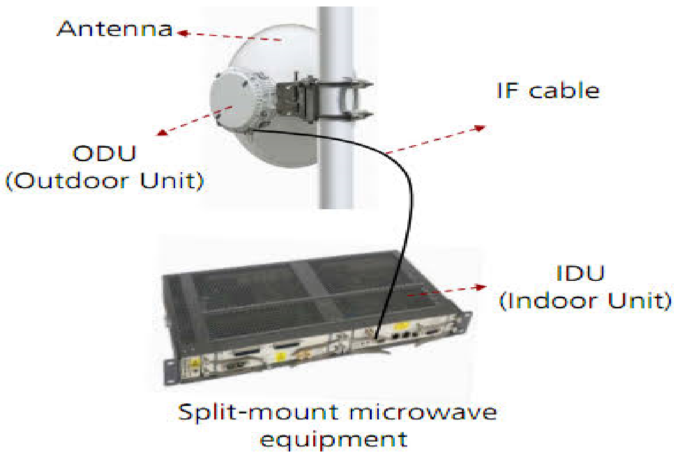

FIGURE 2.1: Split-mount microwave equipment [2]

Advantage of All Outdoor Wireless Back-haul Systems

Over the years, manufactures in the outdoor wireless microwave system have migrated their designs of radio systems. Most radios used in Point to Point microwave wireless systems in the past contain radio units that were mounted indoors (only antennas are outdoor, trunk type). These radios hardware platforms required radios that were rack mounted indoors and large coax or Elliptical Waveguide (requiring dehydrators) running out from the indoor radio unit up the tower (or to the roof top) that is used to connect the radio with antenna. This waveguide needed to be perform the dehydration process frequently to remove the water, and also it make high line loss between radio and antenna.

To compensate large amount of line loss between radio and antenna, large cable or waveguide and larger antennas had to be used but greater infrastructure is needed that support these high loads. The advantages of this type of wireless backhaul radio system is that a technician can walk into a data room closet or outdoor radio shelter to service the radio or replace it in event of a radio failure, but there are a lot of disadvantages with this set up [2].

The industry later came out with a split mount design radio system consisting of an indoor modem unit (IDU) and an outdoor RF Unit (ODU) that mounts the actual radio RF component hardware directly onto the back of the antenna. This system typically uses a smaller IF (intermediate feed) coax cable to pass DC power to ODU and the data between ODU and IDU. The advantages of this type of system are greater system gain due to elimination of line loss between radio and antenna, and lower costs of system components (less cabling and no need for expensive waveguide or dehydrators). The need for indoor space requirements and costlier power consumption are still some of the disadvantages [2].

Today, the industry has migrated to full outdoor radio unit systems (FODU) comprised of a single outdoor unit that is either directly mounted to the back of the antenna or through soft waveguide. These FODU's contain radio modems, RF components and network interface. The network switch is connected to FODU by typically outdoor shielded twisted pair or fiber. The FODU design has far greater advantages over the indoor radio or IDU+ODU spit mount designs and listed below [2, 23]:

1. FODU's consume a minimum of 20% less energy (typically use 25W to 30W DC).
2. Systems can be powered by solar or battery.
3. No equipment room or rack space is needed.
4. Lower overall OPEX.
5. Higher gain to virtually no loss between radio and antenna.
6. No cost for expensive coax or waveguide even for dehydrators.
7. Single component which makes for simple troubleshooting.
8. Easy to spare equipment.
9. Quicker and easier install and maintenance.
10. Easy to daisy chain radios at repeater sites or for dual radio set ups (1+1 or 2+0).
11. Easy to apply LOS-MIMO system for capacity enhancement.

Full outdoor unit system offer far greater advantages over others and as technology gets better so does the quality of radio design and performance. Currently, ethio telecom uses all indoor radio and split-mount types for its microwave services. Full outdoor unit system is available in the market for lower frequency and high frequency band operation. ***So, it is better for operator to move forward to full outdoor radio unit systems for its new deployments in the future.***

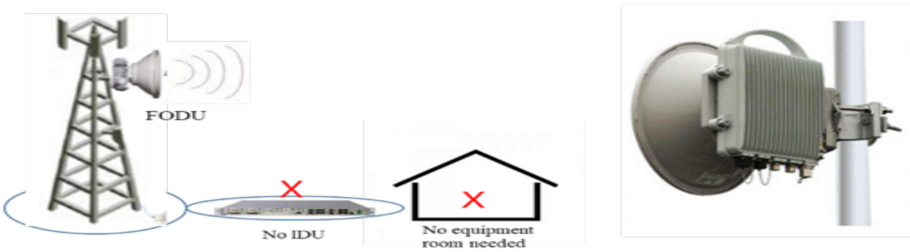

FIGURE 2.2: All outdoor microwave equipment

2.3 Basics of Microwave Communications

In this section the basics of microwave communication are highlighted. These include: microwave network topology, applications, propagation, link design and capacity scaling mechanisms.

Microwave Network Topology and Applications

The main backhaul topologies used in microwave communication are chain, star, ring and mesh. Network topology seriously affects network cost, path length, distribution of link load, and reliability. These multiple criteria with different units must be considered simultaneously when designing network topology.

The major application areas of digital microwave are: mobile backhaul transmission, redundancy backup of important links, complementary networks to optical networks (access the services from the last mile), emergency communications, special transmission conditions (rivers, lakes, islands, etc.) and for VIP customer access.

Microwave Propagation

Wireless communication from one point to another requires a transmitting and receiving parts at end terminals. Antennas direct the electromagnetic waves that are modified in some way in response to the information being communicated and transmit or receive information from propagation media. Electromagnetic wave propagating mechanisms are free space propagation, reflection, diffraction, refraction and scattering. Limiting factors that affect electromagnetic propagations in microwave system are terrains, atmospheric absorption, rain attenuation and depolarization.

Microwave link design

The main objective of point-to-point microwave link design is, to make sure that the microwave network gives high performance in all types of atmospheric conditions. Point-to-point line-of-sight microwave systems can be designed for two scenarios: long range links over mixed path and short range links over strictly urban areas. The design process consists of identifying the end points of the link where the transmitter and receiver are located, examining the details of the propagation environment along the circle path between those points, and on the basis of this information, postulating a link configuration (tower heights, antenna gains, operating frequency, the hop length, path loss, transmitting and receiving equipment, etc.) and, finally, calculating the performance of this proposed design to determine whether it meets the required service and reliability objectives [24].

Path profile

The path profile is a graphical representation of the path between the transmitting and receiving antenna sites. The path profile in conjunction with the Fresnel zone calculations helps to define the antenna heights. Also, antenna heights can be adjusted based on the path profiles in order to avoid obstructions, reflective surfaces, etc. The typical design objective for an LOS path is to adjust the transmitting and receiving antenna centerline heights so that the 0.6 first Fresnel zone is free of obstructions.

Microwave system fading

Variability of the atmosphere results in fading and thus impacts link performance. In wireless communications, fading is variation of the attenuation of a signal with various variables. These variables include time, geographical position, and radio frequency. If the received signal fluctuates rapidly it is called fast fading; whereas if it changes slowly it is called slow fading. Fading can also be classified into flat and frequency selective. The former one affects all the frequency components of the signal equally and the later type affects some frequency components of the signal more than the other ones. Fading in microwave systems generally occur due to free space propagation, multi-path, atmospheric absorption and rain [23, 25].

Link Power Budget Calculation

Microwave link design starts with a link power budget calculation. The calculation involves the gains and losses associated with the antennas, transmitters, receivers, transmission lines, as well as the signal attenuation due to propagation in order to obtain the mean signal level (and other related parameters) at the receiver. These values can then be used to assess the availability of the link under a variety of fading mechanisms.

Fade margin

Fade margin is defined as the difference between received signal and receiver threshold. The fade margin is necessary as it gives the necessary guard band to prevent link failure against unpredictable atmospheric conditions and should be positive.

Microwave Communication Protection and Performance Parameters

One of microwave link protection mechanisms is diversity, in which two or multiple transmission paths are used to transmit the same information and the receiver output signals are selected or composed, to reduce the effect of fading. They include: space diversity, frequency diversity, polarization diversity and angle diversity. Wireless backhaul performance parameters include: Throughput, latency, and resiliency (Reliability, survivability and availability).

Microwave System Advantages and Drawbacks

Low construction cost, quick deployment, and flexibility in providing access to a range of services with sufficient capacity are some of microwave system advantages. Limited available bandwidth and the fading nature of the propagation channel are its drawbacks.

Capacity Scaling Mechanisms

High order modulation schemes, as the modulation level increases the sensitivity to noise and signal distortion increases. For every increased step in modulation level the receiver sensitivity will be reduced by 3 dB which in turn reduce the communication ranges, while the related capacity gain gets smaller in percentage terms (efficiency decreases as it goes up to high level). Multi-layer header compression removes unnecessary information from the headers of data frames and releases capacity for traffic purposes. But the effectiveness of packet compression depends on the traffic mix and the size of packet, and it is most beneficial when the network is transporting small packets.

Multichannel approach or link aggregation creates a virtual link from two or more underlying channels. The resulting capacity is the sum of every channel's capacity. Despite the orthogonality of two signals at dual polarization, due to imperfect antenna isolation and channel degradation (typically rain depolarization effects), some interference between the signals almost inevitably occurs and causes signal degradation[14]. LOS-MIMO and millimeter wave band (E-band) which are the focus of thesis illustrated in next sub-sections.

2.4 Basics of LOS-MIMO

Multiple-Input Multiple-Output system is a wireless technology that uses multiple antenna at receiver and transmitter to enhance the link capacity and improve system performance. In this thesis, MIMO technology applied to Point-to-Point is described in comparison to the Single-Input Single-Output technique, which represents the conventional PTP link application. In LOS microwave, Non-LOS multi-path signal is weak and unusable for the purpose of MIMO. Instead, LOS signal is the dominant and used for the purpose of MIMO. A MIMO system operating under these conditions is often referred to as a LOS-MIMO communication system. Line-of-Sight Multiple-Input Multiple-Output is a new technology in microwave communications which is differ from the well-known non-line-of-sight MIMO technology widely used in access networks. LOS-MIMO revolutionizes microwave communication in terms of capacity and spectral efficiency [3].

Line-of-sight MIMO operations are spatial multiplexing and spatial diversity. LOS-MIMO uses multiple transmitter and receiver antennas to increase spectral efficiency (and to enhance capacity) by spatially multiplexing multiple bit streams over the same frequency channel on different antennas and improve reliability through spatial diversity by transmitting the same data stream on different antennas over the same frequency channel.

Currently, all outdoor system architecture was more widely available on the market and used by different operators in the world, and it contain multi-core radio unit that can be activated per core or per device basis through licensing as needed which is compact module. The radio unit can be connected to antenna either directly or through flexible waveguide. The capacity of the system also can be upgraded through licensing based on the requirement. Figure 2.3 presents fully outdoor LOS-MIMO system.

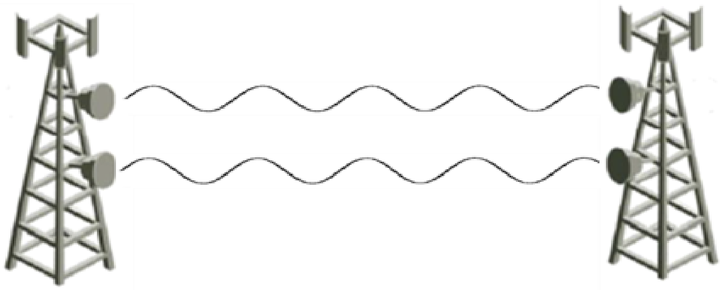

FIGURE 2.3: All outdoor LOS-MIMO system [3]

A Single-Input Single-Output system contain single multi-core radio and antenna on each side of the link. To upgrade it to 2x2 MIMO, it need to add one additional antenna on each side, and activate additional core of the radio and enable MIMO through licensing. Hence, a 2x2 MIMO microwave link comprises two antennas that share single transceiver (single multi-core radio) on each side. 4x4 MIMO is also achievable in this setup by using two antennas and two radio at each end, and by enabling both H and V polarization. To upgrade it from 2x2 MIMO, the system needs to add one additional radio unit at each terminal and enable dual polarization through licensing on all four multi-core radios. Licensing can be applied remotely.

In order to keep things simple, here it is considered only a single polarization 2x2-MIMO. Spatial separation between antennas is denoted by d_t and d_r at the transmitter and receiver respectively, and the different signal path lengths are denoted by h_{ij} for the length of the path between transmitter and receiver.

In case of spatial multiplexing, two different signals are transmitted on the same frequency and polarization through different antennas. Separation between signals is achieved by having them arrive at a specific and constant phase difference at different receiver's antennas. A signal processing algorithm is then applied to cancel cross-interference and to separate the signals [3]. Control of the phase at which signals arrive is achieved through the length of the paths over which the signals traverse.

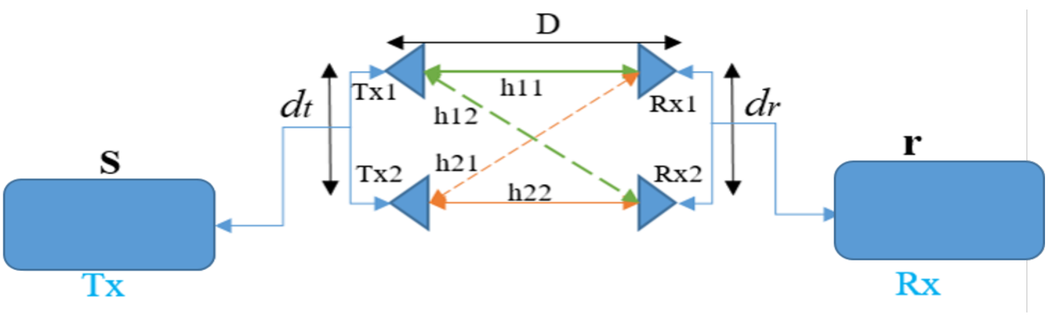

FIGURE 2.4: A 2 x 2 spatially separated LOS-MIMO system

The MIMO phase difference must satisfy certain conditions in order to enable the LOS-MIMO receiver to remove interference and recover transmitted data that is the phase shifts together must provide a proper MIMO channel. In a 2 x 2 LOS-MIMO system, there are two possible paths between one transmitter T_{x1}/T_{x2}) and two receivers $R_{x1}\&R_{x2}$. As illustrated in Figure 2.5, the signal from one transmitter antenna travels through two different paths and arrives at the two receiver antennas. At the receiver, the interference from the other transmitter antennas can be removed using signal processing techniques and add coherently the signal from the same transmitter as shown in Figure 2.5 below.

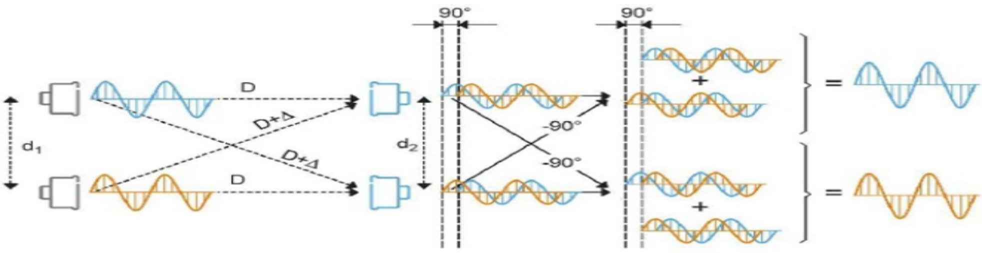

FIGURE 2.5: 2 x 2 LOS-MIMO system of rectangular geometry[3]

By using ideal transmitter and receiver characteristics, the interference is completely removed; thereafter, the two copies of signal from the same transmitter to the different receiver antennas can be coherently added, which provides additional 3 dB fade margin (similar to space diversity receiver gain) with respect to a single receiver antenna. Hence, given the same overall sum of transmitter output power and same frequency bandwidth, an optimal LOS-MIMO system can support multiple streams with equally good performance as one single stream link (SISO configuration).

The maximum capacity and system performance is achieved at optimal LOS-MIMO operation. That is, when antenna spacing fulfill the frequency and link distance separation relation, and the receiver can totally remove the signals from different transmitters and coherently add the signals from the same transmitter at receiver. The deviation from optimal antenna separation will affect the capacity and performance of the system. There are two kind of assumption on transmitter's power allocation: "Sum power constraint" $(P_{\text{tx}1}MIMO = P_{\text{tx}2}MIMO = 1/2P_{\text{tx}}SISO)$ and "Per-antenna power constraint",$(P_{tx1}MIMO = P_{tx2}MIMO = P_{tx}SISO)$ [3]. The availability planned for the specific link can maintained, due to the combination gain of the multiple receiver antennas without increasing the overall effective isotropic radiated power (EIRP) of the LOS-MIMO system [3]. Due to regulatory and other technical issues, a "Sum power constraint" $(P_{\text{tx}1}MIMO = P_{\text{tx}2}MIMO = 1/2P_{\text{tx}}SISO)$ was preferable.

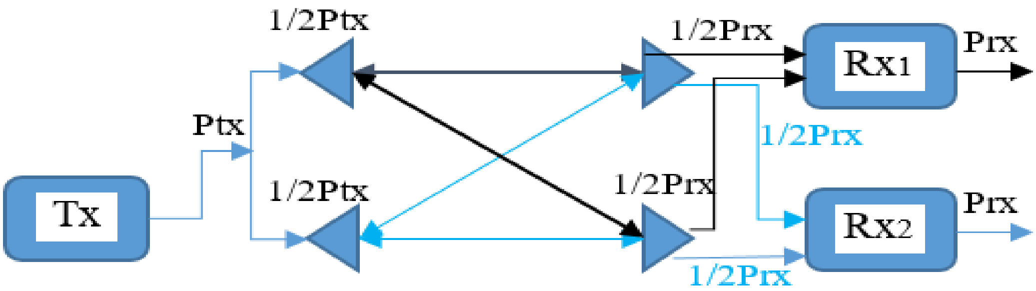

FIGURE 2.6: Transmitter power distribution for 2 x 2 MIMO systems

Where P_{tx} and P_{rx} denote the maximum possible transmitter power and received power of the system. For the same frequency and power resources, an NxN LOS-MIMO system provides N times data capacity.

During spatial diversity, the same signal data is transmitted from N antennas to N receiver's antennas at the same time and based on kind of receiver, the receiver can select either better received signal or add all copies of the same signal to increase system signal to noise ratio that increase system reliability.

LOS-MIMO System Configurations

2x2 LOS-MIMO

LOS-MIMO system can be configured as 2x2 and 4x4. Figure 2.7 show that a 2x2 LOS-MIMO direct mounted configuration. 2x2 LOS-MIMO utilizes a single multi-core radio unit that can be connected to both antennas and utilizes the same exact RF channel.

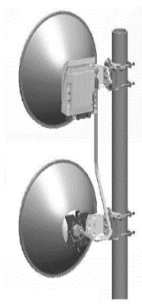

FIGURE 2.7: 2x2 LOS-MIMO direct mount configuration [4]

4x4 LOS-MIMO

Figure 2.8 illustrates a 4x4 LOS-MIMO direct mounted configuration and utilizes two radio units and two antennas. Each radio unit is connected to an antenna using an Orthomode Transducer (OMT) and uses dual polarization.

FIGURE 2.8: 4x4 LOS-MIMO direct mount configuration [4]

Optimal Antenna Separation

In order to perform optimal interference cancellation of signals from different transmitters and coherent addition the signals from the same transmitter at receiver, the antenna separations at both sites, d_t (at transmitter) and d_r (at receiver), are critical in order to allow the digital combination or cancellation processing of the receiver to properly recover the signals sent by T_{x1} and T_{x2} of transmitter. The inter-antenna distances must be carefully set as a function of transmission frequency and path length in order to provide suitable phase shifts along the different propagation paths, which allow a LOS MIMO receiver to successfully recover transmitted data. One example of optimal antenna separation is when the relative phase difference between the two paths arrived at the same receiver antenna is of 90 degree [3].

At optimal antenna separation the receiver can fully remove crosstalk interference and coherently add receiver power from multiple receiver antennas. The optimal antenna separation is derived based on carrier frequency and hop geometry, by assuming radio signal travels in a straight line between transmitter and receiver. Optimal separation between signals can be achieved by satisfying the following condition and the equation below formulates the antenna separation distance required for optimal LOS-MIMO operation [3]:

$$d_t * d_r = \frac{D * C}{2 * f} = \frac{D\,[km] * 300}{2 * f\,[GHz]} \quad [m] \tag{2.1}$$

Where d_t and d_r denote the respective antenna separation distances on either side of the link (in meters), D denotes the overall link distance (in meters), C denotes the speed of light

$(3*10^8 m/s)$ and f denotes the link frequency (in Hz). For the special case of equally separated antennas on both sides of the link, the following expression for the optimal separation between antennas will be obtained: $d_t = d_r = d_{optimal}$

$$d_{optimal} = \sqrt{\frac{D*C}{2*f}} = \sqrt{\frac{D\,[km]*300}{2*f\,[GHz]}} \quad [m] \tag{2.2}$$

Figure 2.9 below sketched by using optimal antenna separation formula in equation 2.2 for different operating frequency against different hop length.

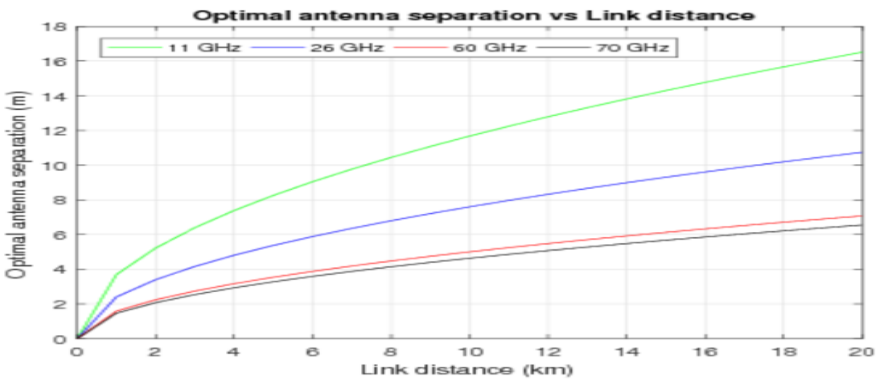

FIGURE 2.9: Optimal antenna separation vs link distance

Optimal antenna separation is directly proportional to link length and inversely proportion with operating frequency. In addition, there is a trade-off between optimal antenna separation at the transmitter site and the receiver site, which provides flexibility to practical deployment. The optimum distances are calculated for just one frequency; however, FDD systems use one frequency for each direction. The best compromise is to calculate with the average frequency.

Generally, MIMO system is more suitable for short communication range and at high frequency band. Comparing to lower frequency band microwave system, mmW band is more suitable for LOS-MIMO system due to its short communication range and high frequency band. This is illustrated with Figure 2.9 above.

It is important to note that antenna separation does not have to be symmetrical. Link topologies will often be constrained by factors that limit antenna separation on one side of the link, such as tower space and mechanical load. Link planners can compensate for such constraints by adjusting the antenna separation on the other side of the link so that the product of the antenna separation length satisfies the equation 2.1 for optimal antenna separation.

Non-optimal Antenna Separation and Link Budget Degradation

The maximum capacity and system performance is achieved at optimal LOS-MIMO operation but in some situations, antennas can be installed in a sub–optimal separation. Sub-optimal separation degrades performance in terms of capacity and system gain but the degradation can be relatively small and still maintains significant improvement with respect to a SISO system [3]. For cancellation-based LOS-MIMO receivers, the power penalty due to non-optimal antenna separation for a 2 x 2 system is illustrated in Figure 2.10 below.

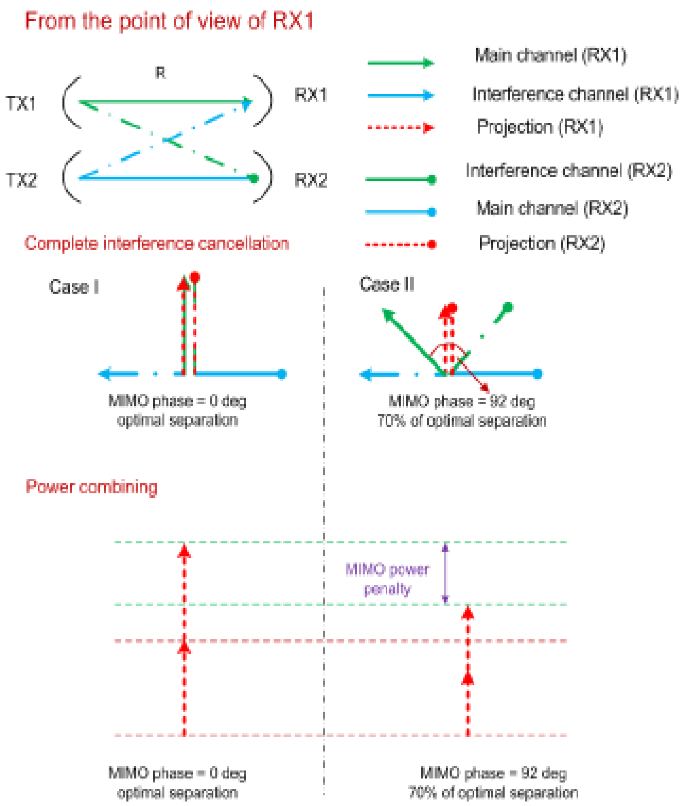

FIGURE 2.10: MIMO power penalty and phase variation caused by non-optimal antenna separation[3]

The degradation of performance in terms of capacity and system gain due to sub-optimal separation can be compensated by increasing antenna separation from other side, increasing transmitting power, preferring antenna with higher gain and using better transceiver.

LOS-MIMO Planning Aspects

The first aspect of LOS-MIMO design is, to choose correct installation in a way to maximize the capacity and system gain by choosing spatial installation (vertical or horizontal).

The other is, to design or calculate best effective antenna separation for both sides. Understanding the effect of LOS-MIMO link interference on other network or the effect of other network interference on LOS-MIMO should also be considered[3].

LOS-MIMO Benefits

Increase spectral efficiency or enhance capacity

2x2 LOS-MIMO enables transmission of two independent signals over the same frequency and the same polarization. In this set up, in addition of increasing spectral efficiency, it will doubles the capacity compared to a 1+0 SISO link without occupying additional spectrum resources. This will halved the use of spectrum and spectrum cost. The use of both dual polarizations of a frequency channel, i.e. employing a 2 x 2 LOS-MIMO + XPIC scheme enables transmission of four independent signals over the same frequency channel and provides four times the capacity of standard 1+0 SISO link.

Improving system gain

Transmitting two similar streams over the same frequency channel on single polarization through two antennas will double signal to noise ratio of the system. This improve the system performance and reliability. On the other hand, it will allow longer communication range, increase system capacity due to SNR increment and allow to use antenna with smaller in size for the same link.

System protection

In case of one link failure the other link can provide the services but the capacity will be halved.

Draw Back/Weakness

One of the main considerations with LOS-MIMO operation is the sensitivity of the link to the accuracy of the installation. The complexity of the system and the need for more margin (It depends on link length) are other draw backs of MIMO over SISO.

System comparison:

To identify the pros and cons or the trade-offs among various lower frequency microwave system, the performance comparison among different vendor's technologies are mentioned and provided in Table 2.1 below. A microwave system that operate at lower frequency band can support up to 5 Gbps with the combination of MIMO and other techniques.

TABLE 2.1: Lower frequency band technologies performance comparison [8, 9, 10]
.

Vendors	**Cambium Networks**	**Ceragon**	**DragonWave**
Technology	PTP 820C	FibeAir IP-20C	Harmony Enhanced
Operating frequency (GHz)	6 to 38	6 to 42	6 to 42
Bandwidth (MHz)	Up to 80	28/40/56/112	28//56/80/100/112
Modulation (QAM)	Upto 2048	Upto 2048	Upto 2048
Capacity (Gbps)	Upto 2	Upto 5	Upto 4
MIMO	2x2, 4x4, XPIC	2x2, 4x4, XPIC	2x2, 4x4, XPIC
Power consumption (W)	55-70	55	55

2.5 Basics of Millimeter Wave Band

The demand for broadband services grows rapidly in recent years. At the same time, backhaul network needs to handle this huge volume of traffic or else it will become bottleneck for the rest of the network. One of the possible solutions that provide high data rate at access and backhaul network is the use of millimeter wave band system. Multi-Gigabit wireless communications can be achieved using millimeter-wave (mm-wave) frequency bands due to its wider bandwidth. Even though the available bandwidth in the millimeter band is very high, radio signals in this band are more adversely affected by environmental factors (Oxygen and rain are the main). Millimeter-wave band ranges from 30-300GHz frequency bands [17]. Figure 2.11 presents fully-outdoor direct mounted millimeter wand system.

FIGURE 2.11: All outdoor millimeter wave band system [4]

Typical mm-wave bands suitable for wireless backhaul application include 60 GHz V-band (spectrum range 57-64 GHz) and 70/80 GHz E-band. The available data rate from commercial point-to-point links in 60 GHz band is up to 1.25 Gbps at communication range for outdoor applications to 0.5-0.8 km based on manufacturers. However, it is highly affected by oxygen and there is high propagation loss due to oxygen absorption (15 dB/km) compared to 70/80 GHz E-band (0.5 dB/km) [11, 26, 27]. Electromagnetic waves are absorbed in the atmosphere according to wavelength. Two compounds are responsible for the majority of signal absorption: oxygen (O_2) and water vapor (H_2O). Figure 2.12 below shows the effect of oxygen and water against frequency.

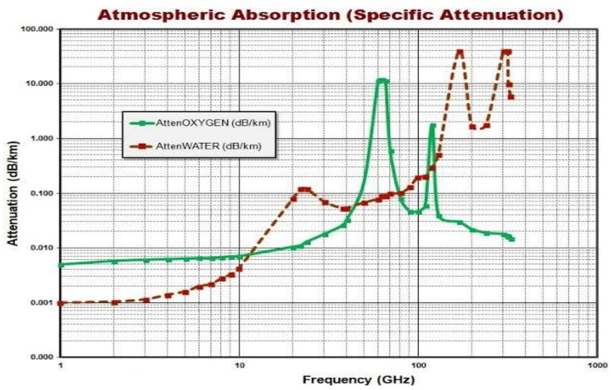

FIGURE 2.12: Atmospheric attenuation vs frequencies [5]

From the Figure 2.12, the first peak occurs at 22/23 GHz due to water, and the second at 60 GHz due to oxygen. E-band frequency is less affected than V-band as indicated on the figure. Regarding to water effect, both bands are relatively equally affected.

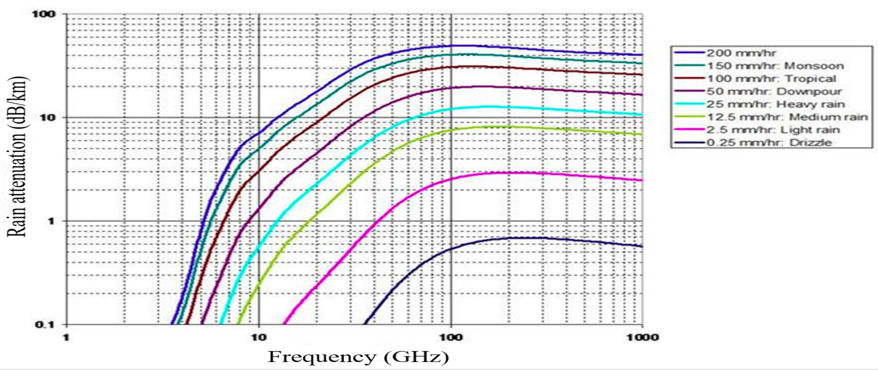

FIGURE 2.13: Rain attenuation at microwave and millimeter-wave frequencies[5]

Rain attenuation depends on rain rate and Figure 2.13 above shows rain attenuation against frequencies for different rain rate in millimeter per hour. Rain attenuation has a direct relation with rain rate and it increases as rain rate increases.

Radio signals lose power as they pass through the air and the rate at which they lose power is a function of frequency and link distance. As a transmitted signal traverses the atmosphere its power level decreases at a rate inversely proportional to the distance traveled and proportional to the wavelength of the signal. The higher the frequency, the more quickly signal-strength drops off over distance. On the other hand, path loss increase with operating frequency and link distance, but thanks to the logarithmic nature of the decibel, the increase in path-loss over distance and frequency is relatively slow over long distances. Regarding to 60 GHz, there is also an additional attenuation due to oxygen and it is highly affected after one km which indicates, 60 GHz is more suitable in less than one km communication ranges. Figure 2.14 below sketched using free space path loss formula and supports statements stated in this paragraph.

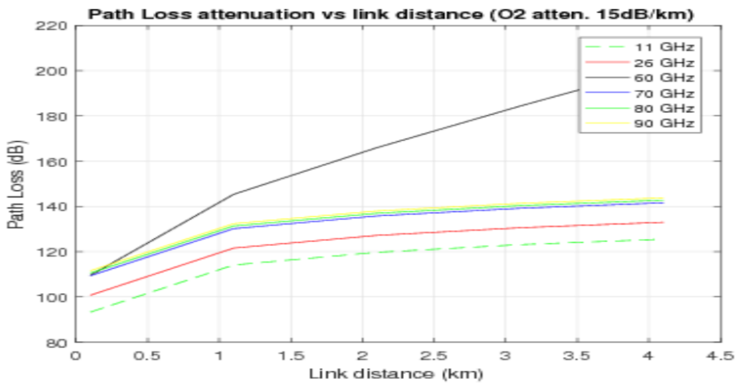

FIGURE 2.14: Free path loss attenuation by link distance and frequency

For mmW band backhaul communication, line of sight channel is preferable due to high loss in non-line of sight (NLOS) link. On the other hand, LOS is more secured than NLOS channel. The recent availability of the E-band spectrum worldwide provides an opportunity for line of sight links with longer range and higher data rates suited for back=haul applications [**?**]. The main focus of this study is on the spectrum (71-76 GHz and 81-86 GHz) range with 70/80 GHz E-band that offers 5 GHz bandwidth from each and 10 GHz from overall. Unlike 60 GHz band, E-band less affected by oxygen (0.5 dB/km). E-band can offer the data rate from 10-25 Gbps within the communication range of less than 5 km. 60 GHz V-band is license free but 70/80 GHz E-band is light license band. The reasons for selecting E-band (70/80 GHz) over V-band (60 GHz) are listed in the following table.

TABLE 2.2: E-band (70/80 GHz) vs V-band (60 GHz) [11]

Comparison parameters	**E-band (70/80 GHz)**	**V-band (60 GHz)**
Communication range (km)	Up to 5	0.5 to 0.8
Band width (GHz)	5+5=10	7
Capacity (Gbps)	Up to 10 in single 1+0	Up to 1.25
Spectrum licensing	Light license	License free
Oxygen effect	0.5 dB/km	15 dB/km

E-band System Configurations and Protection

Millimeter wave system supports 1+0, 2+0, 1+1 HSB (protection) and 2+0 XPIC configuration.

E-band System Parameters and Bandwidth Allocation

In US the entire 10 GHz bandwidth in 71-76 GHz and 81-86 GHz is available for utilization (only applied on single channel). The federal communication commission (FCC) sets the Effective Isotropic Radiated Power (EIRP), maximum transmit power and minimum antenna gain 55 dBW, 35 dBm and 43 dBi respectively for E-band system[27]. The Europe, Conference of European Postal and Telecommunication has taken a different approach and divided 10 GHz bandwidth in 70/80 GHz bands into 19 channels with 250 MHz bandwidth each and two guard band of 125 MHz at top and bottom end of each band.

The Conference of European Postal and Telecommunication sets the Effective Isotropic Radiated Power (EIRP), maximum transmit power and minimum antenna gain 55 dBW, 30 dBm and 38 dBi respectively for E-band system. EIRP and maximum transmit power is a function of antenna gain and expected to be lowered as the antenna gain increases. The European approach is a better way because of its strong regulation compared to US [27].

The Benefits of E-band Wireless Communication

- The vast, uncongested, inexpensive spectrum with total 10 GHz of available RF bandwidth which enables very high data rates beyond 10 Gbps.
- The small and highly directional antenna.
- Low output power
- Low infrastructure cost.

- Light license band and
- Lower end-to-end latency compared to fiber.

Drawbacks of E-band Wireless Communications

- Short communication rang compared to microwave
- High path loss
- Affected by environmental factor (rain)
- Use of lower modulation
- Antenna alignment and mounting difficulties
- Due to received signal's large band width and high sampling rate, E-band systems require the application of high speed digital signal processing, digital-to-analog conversion (D/A), and analog to- digital conversion (A/D) units at transceivers.

Further Enhancing Techniques and Possible Technological Solutions

- Antenna array with beam-forming in order to achieve long range communication as well as to compensate path loss in E-band.
- LOS-MIMO system to increase the capacity and improve performance of the system. MIMO system is more suitable on mmW band than microwave due to small antenna spacing, and small and highly directivity antennas.
- Dual polarization to enhance the capacity.
- The small and high gain directional antenna to guarantees signal delivery and to compensate high path loss in E-band communications.
- Adaptive Rate (AR) to keep the modulation constant but to reduce the data rate during rain fading by reducing bandwidth.

System Comparison

To summarize the pros and cons or the trade-offs among various mmW band system, performance comparison among different vendor's technologies are mentioned and provided in Table 2.3 below. As seen from the Table 2.3, mmW band system can provide up 10 Gbps data rate over medium distance at low latency, and with minimum transmitting power and energy consumption. The availability of 10 GHz spectrum in E-band provides an opportunity for high capacity wireless link, ideally suited for fiber replacement in some aggregated and backbone networks. If combined with dual polarization and LOS MIMO, the data rate can be further increased beyond 40 Gbps for high spectral efficiency system and low latency.

TABLE 2.3: mmW-band technologies performance comparison [28, 29, 4, 30, 31].

Vendors	**HUAWEI**	**BridgeWave**	**Elva-1**	**Ericsson**	**LightPointe**
Technology	RTN 380H	Flex4G-10000	PPC-10G-E	MINI-LINK 6352	AireX-Stream
Operating frequency	E-band 70/80 GHz	E-band 70/80 GHz	E-band 70/80 GHz	E-band 70/80 GHz	E-band 70/80 GHz
Bandwidth (MHz)	Upto 2000	Upto 2000	Upto 2000	Upto 750	Upto 2000
Modulation (QAM)	Upto 1024	Upto 256	Upto 256	Upto 256	Upto 256
Capacity (Gbps)	Upto 10	Upto 9.7	Upto 10	Upto 5	Upto 10
Transmit Power(dBm)	8 to 18	17	20-23	12 to 15	20 to 23
Latency	NA	12μs	NA	NA	10 ns
Operation range (km)	NA	NA	10	8	8.5
P. consumption(W)	79	73	45-60	65	20

Chapter 3

Techno-economic Models and Evaluation Methods

Techno-economic assessment models, revenue modeling, economic modeling and techno-economic assessment evaluation methods including decision making economic indicators are introduced in this chapter.

3.1 Introduction to Techno-economic Assessment (TEA)

Techno-economic assessment (TEA) is a methodology framework to analyze the technical and economic performance of a process, product, technology or service. Techno-economic analysis normally combines process modeling, engineering design and economic evaluation[6]. Examples of applications or usage of TEA include the evaluation of the technical and economic feasibility of a specific project or technology, a forecast on the likelihood of the deployment of a technology at certain scale, or a comparison of the economic merit of different technological options that provide the same service.

Various telecom technologies are emerging from time to time for the customers. The available competitive telecom technologies need to have significant advantage in technical and economic viability. Technical and economic viability assessment of the investment or technology is crucial step before implementing the technologies. On the other hand, TEA is a decision-making tool used to evaluate available technology options based on technical, economic, environmental, social and regulatory criteria. For this work the technologies or scenarios are analyzed based on identified technical and economical criteria's on selected or implemented suitable TEA model. To obtain meaningful, acceptable and actionable TEA results, it needs to provide up to date information to the tool.

3.2 Techno-economic Assessment Models

Many researches were done to develop techno-economic analysis models since 1980s'. In the context of telecommunications, the term techno-economics was introduced during the European research program called Research in Advanced Communications in Europe (RACE) in 1985-1995[6]. Early techno-economic modeling work was done for different RACE projects where alternative scenarios and strategies for evolution towards broadband systems were analyzed. Later, the RACE 2087 Tool for Introduction scenarios and techno-economic studies for the Access Network (TITAN) project developed a methodology and a tool for techno-economic evaluation of new narrow band and broadband services and access networks was developed (1990-1994). Since the late 1990s, many European research projects have used and extended the methodologies and tools created in the early projects for different application areas. Optimized architectures for Multimedia networks and services (OPTIMUM) from 1994-1998; Techno-economic results from ACTS (TERA) from 1994-1998, Techno-economics of IP optimized networks and services (TONIC) from 1998-2002 and Techno-economics of integrated communication systems and services (ECOSYS) from 2004-2007 were introduced for different purposes and application area based on the projects[6].

These researches or projects resulted in providing framework, model, methods and tools used for evaluating the techno-economics viability of the system. From models stated above, it can be understood that there is no one specific techno-economic model that is enough to use for different projects and application areas because of the objectives of the analysis, inputs, required outputs and application areas are different from project to project. On the other hand, the development process is still not matured, and extension and improvement of earlier model is continued. The model for this work is extended from TERA model and implemented since TERA model is more approaching to the model needed for this work than other models.

3.2.1 Techno-Economic Results from ACTS (TERA) Model

The popular techno-economic analysis framework in telecom industry is Techno-economic Results from ACTS framework. TERA enables techno-economic evaluations by combining technical, market, economic and costs of key network elements[6].

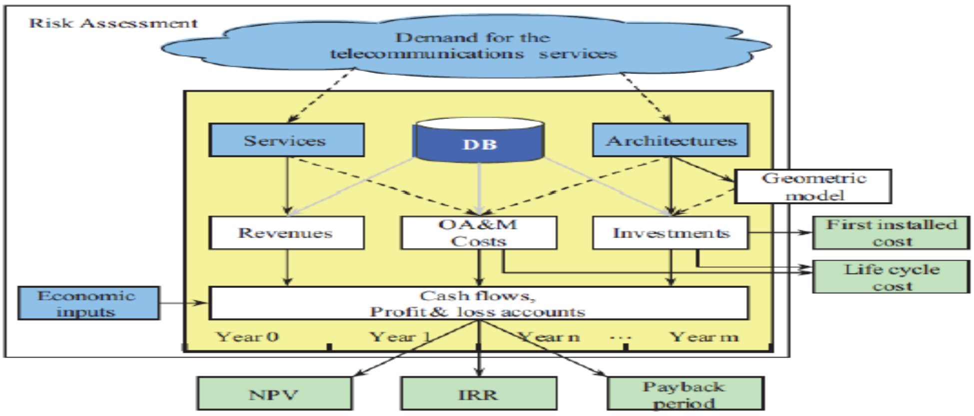

FIGURE 3.1: TERA Framework[6]

The TERA framework shows clearly the two main starting points of techno-economic modeling: services and architectures. Based on forecasts and assumptions regarding these as well as a few generic economic inputs such as the discount factor, time period of study, and rest value of investments at the end of the time period, the models calculate revenues, operational costs, and investments, as well as cumulative cash flows and decision-making criteria such as net present value (NPV), internal rate of return (IRR), and payback period[6].

3.2.2 Implemented Techno-economic Analysis Model

A techno-economic model is a method used to determine or evaluate the economic feasibility of the systems or technologies considering all the system parameters based on the framework the model is derived from. Based on objectives of the analysis, system input and output, techno-economic approaching model was modified from TERA and implemented for this work. The details are presented in chapter four.

3.3 Revenue Modeling

Revenue is defined as the benefits generated by the investment. For this work, revenue is the benefit obtained by selling data delivered over the backhauling network developed. The revenues for different scenarios are calculated and compared against each other. The first step for revenue modeling is path loss calculation and followed by link budget and capacity calculation. Then, revenue is modeled or formulated from link capacity or data generated. To estimate the initial traffic data and revenue as well as to forecast for the next four years, one year per month used traffic data per eNodeB were used and applied linear regression approach.

Path Loss Calculation

In telecommunication, the free-space path loss is the attenuation of radio energy or signal between end points of two antennas due to distance and carrier frequency.
Free space path loss model: Typically used for unobstructed LOS signal path in wireless communication.

$$P_L = 92.44 + 20\log(f) + 20\log(d) \quad [dB] \tag{3.1}$$

Where
P_L is the path loss in dB
f is the carrier frequency in GHz and d is link distance in km.
For the case of millimeter wave band, it needs to consider additional loss from atmosphere and rain attenuation.
Additional loss for mmW band:

- O_2 Absorption 15 dB/km and 0.5 dB/km for 60 and 70/80 GHz respectively.
- ITU-R models $\gamma_R = kR^{\alpha}$ for rain loss prediction.
- Attenuation 22 dB/km @ R=70 mm/hour, for 70/80 GHz.

Link Budget Calculation

A link budget is an accounting of all of the gains and losses from the transmitter, through the medium (free space, cable, waveguide, etc.) to the receiver in telecommunication system. From link budget calculation the received power at receiver will be obtained.

$$P_r = P_t + G_t + G_r - P_{tl} - P_{rl} - P_L \quad [dBm] \tag{3.2}$$

Where
P_r is the received signal at receive in dBm
P_t is transmitting power in dBm
G_t is antenna gain at transmitter in dB
G_r antenna gain at receiver in dB
P_L path loss in dB
P_{tl} is cable loss at transmitter in dB and
P_{rl} is cable loss at receiver in dB.

Channel Capacity Calculation

In the context of networks, capacity is the measurement of the maximum amount of data that may be transferred between network locations over a link or network path. Channel

capacity is calculated from signal to noise ratio required for the system. From link budget received power was obtained and now need to calculate channel noise power.
Channel Noise Power No

$$N_o = 10\log[K * T * Bw * 10^3] \quad [dBm] \tag{3.3}$$

Where
N_o is a noise power in dBm
K is a Boltzmann constant
Bw is bandwidth in Hz and T is temperature in kelvin

$$SNR = 10\log\left[\frac{P_r(w)}{N_o(w)}\right] = P_r[dBm] - N_0[dBm] \quad [dB] \tag{3.4}$$

SNR is signal to noise ratio.
The capacity of a SISO system is given by the Shannon-Hartley theorem [19].

$$C = \log_2(1 + SNR) \quad [bps/Hz] \tag{3.5}$$

The capacity of a MIMO system was derived by Telatar in 1999 [32]. The result is:

$$C = \log_2\left[\det\left(I_M + \frac{\gamma}{N}HH^H\right)\right] = \sum_{i=1}^{\min(N,M)} \log_2\left(1 + \frac{\gamma}{N}\lambda_i\right) \; [bps/Hz] \tag{3.6}$$

Where λ_i is an eigenvalue of HH^H. The eigenvalues and singular values are related by $\lambda_i = \gamma * \sigma_i^2$ where γ is SNR, N numbers of minimal antenna. I_M Is identity matrix.
λ_i is 2 for spatial multiplexing and 4 for spatial diversity of MIMO operation. The capacity of 2x2 LOS-MIMO (N=2) can thus be calculated for spatial multiplexing using

$$C_{SM} = \sum_{i=1}^{2} \log_2(1 + \gamma) \quad \left[\frac{bps}{Hz}\right] \tag{3.7}$$

and for spatial diversity of MIMO operation, using

$$C_{SD} = \log_2(1 + 2 * \gamma) \quad \left[\frac{bps}{Hz}\right] \tag{3.8}$$

Revenue

As stated in section 3.4 above, revenue is defined as the benefits generated by the investment and calculated by multiplying average price per unit with total units. In this work, the total unit is the total data in GB delivered on the link in a year and average price per unit is average cost per GB.

$$R = C_m * Cst \quad \left[\frac{\$Millions}{year}\right] \tag{3.9}$$

Where $Cm = \frac{Total\ [GB]}{year}$ is the total GB delivered in a year, $Cst = \frac{60\ ETB}{GB}$ is an average cost per GB. Because currently ethio telecom sells 30 GB for 1800 Ethiopian birr (ETB) per month which is 60 ETB/ GB per month. [33].

3.4 Cost Modeling

3.4.1 Total Cost of Ownership (TCO)

In this section the discussion will be on the major components of the total cost of ownership and cost modeling. It is applied to all scenarios on the same procedures. Total cost of ownership is a financial estimate to determine the direct and indirect costs of a product or a system over a certain time period, which is composed of CAPEX and OPEX.

$$TCO = CAPEX + OPEX \tag{3.10}$$

The concepts of CAPEX, OPEX and their applications in LOS-MIMO systems and mmW band are discussed in this section, followed by a brief introduction of the techno-economic Assessment (TEA) methods used in the techno-economic analysis.

3.4.2 Investment Related Cost (CAPEX)

Investment related costs (CAPEX) are the cost of equipment and implementation expenditure (IMPEX). Capital expenditure is the first time investment cost in the network deployment and it includes: all initial network equipment, software investment costs and implementation costs. Implementation expenditure is a deployment cost and part of CAPEX that is associated with planning, installation and system testing. It is considered as the fixed investment cost.

$$CAPEX_0 = \sum_{i=1}^{n} N_i * C_i^{capex} \quad [\$Millions] \tag{3.11}$$

$$CAPEX_t = CAPEX_0(1+r)^t \ \ [\$Millions] \tag{3.12}$$

Where i is the key element or component type of the network or system; N_i is the numbers of i type elements; C_i^{capex} is per unit investment cost; t is time period and r is an interest rate.

3.4.3 Operation Related Cost (OPEX)

Operational expenditure (OPEX) is the ongoing cost for running a product, business, or system. It includes:

Network driven costs:

- Network operational and maintenances costs
- License fees or renewal
- Utility or Energy cost
- Site rental

Business driven costs:

- Service provisioning
- Customer service related costs.
- Marketing and sales (advertising)
- Billing, customer care and Management/ Administration costs

$$OPEX_0 = \sum_{j=1}^{m} M_j * C_j^{opex} \quad [\$Millions] \tag{3.13}$$

$$OPEX_t = \sum_{t=1}^{T} OPEX_0 (1+r)^{t-1} \quad [\$Millions] \tag{3.14}$$

$$\text{TCO}_t = CAPEX_t + OPEX_t \tag{3.15}$$

Similarly, j is type of element of all variable costs incurred during operation and management of the system; M represents for the numbers of items in j type that are operated in year t; C_j^{opex} is the per-unit operation cost of item j and T is the study period. The assumptions considered are: the component types, numbers and per-unit cost which are fixed throughout the study periods for CAPEX and OPEX.

3.5 Techno-economic Assessment (TEA) Evaluation Method

Techno-economic assessment evaluation methods applied here are discounted cash flow and cash flow (CF) method. Discounted cash flow (DCF) is an evaluation method used to estimate the value of an investment based on its future cash flows. Discounted cash flow analysis finds the present value of expected future cash flows using a discount rate. A present value estimate is then used to evaluate a potential investment. From DCF analysis, decision making economic parameters like net present value, internal rate of return and payback time are obtained. In this section, this method and each economic indicators will be discussed.

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

Cash flow is the net amount of cash that is received or generated in a given time period. Based on the outputs from cost and revenue model, the CF model is drawn as in the equation below.

$$CF_i = R_i - TCO_i \tag{3.16}$$

$$CF_T = \sum_{i=1}^{T} CF_i \tag{3.17}$$

Where CF_i *and* CF_T are the cash flow at year i and total cash flow at time period of T. R_i *and* TCO_i are revenue and total cost at time i. DCF analysis finds the present value of expected future cash flows using a discount rate that accounts for the time value of money. It adds or sums the discounted cash flows for every year of the project/system.

$$DCF_t = \frac{CF_0}{(1+r)^0} + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \ldots \frac{CF_{t-1}}{(1+r)^{t-1}} = \sum_{i=1}^{t} \frac{CF_{i-1}}{(1+r)^{i-1}} \tag{3.18}$$

Where DCF_t , is total or cumulative discounted cash flow to year t, CF_i is the cash flow in year i and r is discounted rate.

3.5.2 Decision Making Economic Indicators

Net Present Value

Net present value (NPV) is a standard method for the financial appraisal of projects. This is the most common technique used by most professional practitioners of techno-economic assessment. It effectively accounts for the fact that capital investment is outlaid at the start of a project, but returns are not received until later. This is accounted for by the introduction of a discount rate, which represents the decrease in value of the payment because it is not paid at the time of the capital outlay but a number of years. So the overall economic result of a project realization can be expressed in present money. The net present value of every year is discounted to the year 0 by the discount rate using the following formula.

$$NPV_i = \frac{NCF_i}{(1+r)^i} \tag{3.19}$$

Where NPV_i is net present value or discounted cash flow of year i, NCF_i is net cash flow of year i and r is discount rate. The net present value of the system NPV_t is the sum of the discounted cash flows for every year of the project period. The sum of discounted cash flows for every year of the system is the total discounted cash flow of the system.

$$DCF_{total} = \sum_{i=1}^{t} \frac{CF_{i-1}}{(1+r)^{i-1}} \tag{3.20}$$

$$NPV_t = DCF_{total} = \sum_{i=1}^{t} \frac{CF_{i-1}}{(1+r)^{i-1}} \tag{3.21}$$

The net present value gives an indication how much the implemented system will increase benefits over the whole project period in today's money value. The net present value NPV should have the value zero at pay-back period. In this case the revenue and cost of investment (TCO) become equal at assumed discount rate. If the NPV is positive, the owner's benefits will be increased by this value after pay-back period. If NPV has a negative value, the project is not to be realized without suffering losses taking into account the assumed discount rate. From net present value, key indicators IRR and pay-back period will obtained. These indicators discussed in next subsection.

Pay-back Period

Pay-back period is a return on investment period and it is obtained when net present value equal to zero or when the revenue and initial investment cost become equal. The shorter the pay-back period of the project the more better or beneficial the project. If the projects have equal pay-back period time, there is a need for a further evaluating parameter that is internal rate of return which is discussed next.

Internal Rate of Return

The internal rate of return (IRR) is the average annual return rate on the initial investment when considering all costs and benefits over the given project period. It is calculated on present money value. It is obtained when net present value equal to zero or when revenue and investment cost become equal. If there are more than one possible projects to be compared to each other, the internal rate of investment gives an indication on the most profitable one, independent of project size and technology. It allows some judgments of the efficacy of the investment. If the IRR is low (less than could be obtained with bank cash deposits or interest rent) it would be pointless investing in a project where the capital was unsecured and the return not guaranteed to get only that rate of return.

Sensitivity Analysis

Sensitivity analysis: The purpose of sensitivity analysis is to study the impact of changes in the input assumptions on the profitability (e.g. the NPV) of the project. The results of the sensitivity analysis can be visualized by sensitivity graph, in which the sensitivity of each input variable is reflected by the variation or change on output in percent from normal value.

Chapter 4

Deployment Scenarios and Techno-economic Analysis

The discussions in these sections are concerned on what are done and the way or methods followed to do them. The chapter includes implemented model, techno-economic assessment process, scenario definition with their assumed parameters, technical analysis, economic analysis and techno-economic analysis.

4.1 Implemented Techno-economic Analysis Model

A techno-economic model is a method used to determine or evaluate the economic feasibility of the systems or technologies considering all the system parameters based on the framework the model is derived from. Based on objectives of the analysis, system input and output, techno-economic approaching model is modified and implemented. The model is used to evaluate the scenarios based on economic indicators obtained from the given inputs and followed broadly a similar process for each scenario. The scenarios are SISO, MIMO, mmW band and mmW-MIMO.

The core of this method consists different mathematical models that are used to estimate future gain benefits or revenue from the system and costs required to invest, operate and maintain the system, and apply discounted cash flow analysis method that combines all related costs and revenue, then finally, calculates decision making economic parameters like NPV, IRR, back-pay period that are used for decision making to evaluate the systems. Parts or blocks of techno-economic model implemented for this work is shown below with Figure 4.1.

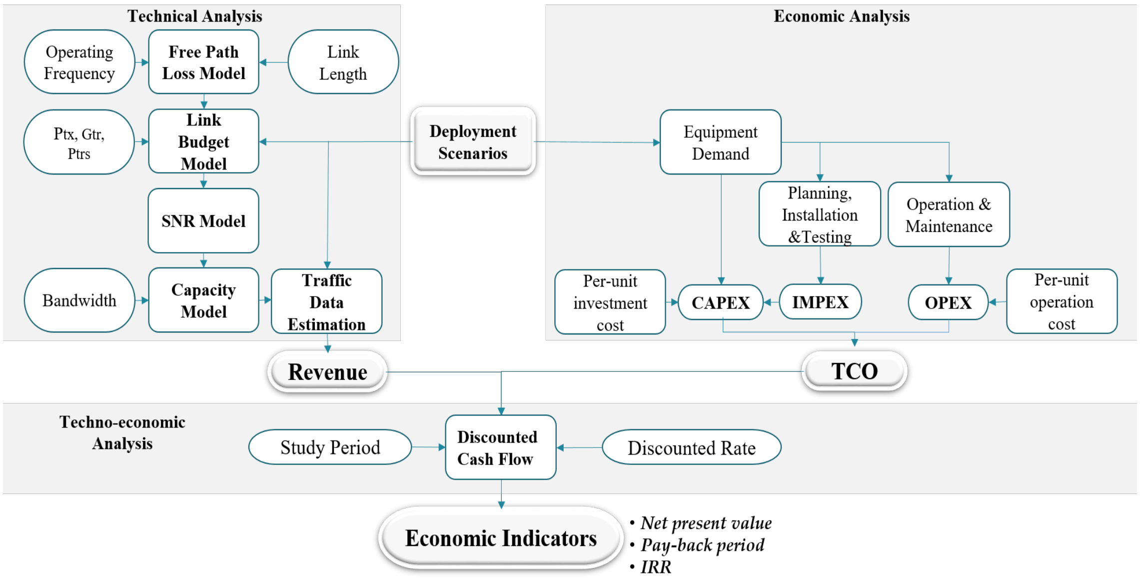

FIGURE 4.1: Modified and implemented techno-economic analysis model block diagram

To elaborate the model further in detail, the model consists of three parts: technical part, economic part and techno-economic analysis part or discounted cash flow method. Based on selected scenario the model will take technical inputs like operating frequency, hop length, bandwidth, transmitter power, antennas gain and calculates link capacity. Then traffic data demand will be estimated and forecasted for the study periods. At last, the revenue is mapped from traffic data and forecasted for the study periods at technical part. From economic part, economic inputs like CAPEX and OPEX are taken as an inputs and calculate TCO for the study periods based on scenario. Finally, discounted cash flow combines revenue and TCO to provide decision making economic indicators like net present value, internal rate of return and return on investment period or payback period. This model can be used to evaluate any backhaul technology for its feasibility.

4.1.1 Techno-economic Assessment Process

Techno-economic assessment process introduces the work done from the start to the end and holds scenario dimension, modeling (revenue and economic modeling) and techno-economic analysis.

The first step of the assessment process is technical and performance dimension of each scenario to determine the investment related cost and revenue of the system. This help to estimate the overall total cost of investment including operation and maintenance costs and the revenue generated or estimated per link in each year. The second step is modeling the cost and revenue of each scenario. At last, techno-economic analysis is performed by combing cost and revenue model through discounted cash flow method and sensitivity analysis was done to determine the impact of input variables on the outputs.

Based on the scenario, technical inputs that are provided from external to the system are operating frequency, link length, bandwidth, antenna gain and transmitting power. Economic inputs include equipment costs which is calculated from required key network components, OPEX that is estimated from annual operation and maintenance of the system, IMPEX which is part of CAPEX and the overall planning, installation and system testing costs. Interest or discounted rate and study period are also part of inputs. System parameters are receiver power sensitivity, noise loss and line loss.

The technical part estimates the capacity, traffic data demand and revenue of each scenario; scenario selection part used to select the scenario to be analyzed; economic part estimates the total cost of ownership, and discounted cash flow provides economic indicators like NPV, IRR and payback period.

- Deployment Scenario Dimensioning: Identifying:
  - Technical architecture and components of the systems.
  - Technical performance of system.
  - Cost of key components in the system.
  - Costs for planning, installation and testing the system
  - Cost of operating and maintaining the system during operation.
- Modeling
  Revenue Modeling:
  - Estimating and forecasting data demand and revenues

  Cost Modeling:
  - Initial investment costs (CAPEX)
  - Implementation costs (IMPEX)
  - Operating and maintaining costs (OPEX)
  - Total cost of ownership (TCO)
- Analysis:
  Discounted cash flow analysis:
  - Net present value (NPV)

- Internal rate of return (IRR)
- Payback period (PBP)

Sensitivity analysis:

- Net Present Value sensitivity to changes in input variables

4.2 Deployment Scenarios

There are four scenarios that are studied in this thesis. Two scenarios are SISO and MIMO from lower frequency band, and the others two are, mmW band and mmW-MIMO from higher frequency band. Ethio telecom deployed point to point microwave system for most of mobile backhauling that operated at 15, 18, 26 GHz frequencies, and uses 28 and 56 MHz bandwidth. The studies focused on these backhaul networks and the system configurations considered for this work are presented as follow in table 4.1. For lower frequency band, the values of parameters applied in Addis Ababa by ethio telecom are considered. The same assumptions are considered for higher frequency band on some parameters except operating frequency, fade margin and bandwidth. The required minimum SNR for 256 QAM at bit error rate of 10^{-6} is 32 dB. At 500 MHz BW, E-band equipment provides 3.2 Gbps of data rate without MIMO application [34].

TABLE 4.1: System configuration and assumed parameters

System Parameters	Lower frequency bands	Higher frequency bands
Transmitter power (dBm)	13	13
Frequency band (GHz)	15,18 & 26	73
Bandwidth (MHz)	56	500
Antenna gain (dB)	34	42
Modulation schems QAM	256	256
Required SNR (dB)	32	32
Noise Figure (dB)	6	6
Required Fade Margin (dB)	10	22 dB/km*d (km)
Capacity (Mbps)	368/736	3200/6400

4.3 Technical Analysis

Technical analysis concerned on technical parts such as existing links feasibility analysis, capacity calculation and comparison, traffic data demand and revenue estimation and forecasting across the scenarios.

4.3.1 Existing Links Feasibility Analysis

The feasibility analysis on existing microwave links is performed for the case of LOS-MIMO and millimeter wave bands based on antenna separations height and path loss.

Multiple Input Multiple Outputs (LOS-MIMO)

Regarding to antenna separation height for 2x2 LOS-MIMO, available data for 566 microwave links in Addis Ababa were used to calculate the antenna separation for each link. Frequencies used for different links are 15, 16 and 26 GHz. The sites tower height vary and ranges from 16 meters to 80 meters. Similarly, antenna is located on the tower in different positions or heights. Based on the formula in equation 2.1, the antenna separations are calculated.

Concerning to link budget for LOS-MIMO, the links are already deployed for the case of SISO and the difference is the implementation of second antenna for the second link. In case of fade margin (FM) problem, it can be compensated by increasing transmitter power or using antenna with higher gain. Currently, used transmitter power in Addis Ababa microwave links are in the range of 0 dBm to 21 dBm.

Millimeter wave band (mmW band)

To calculate the link budget and antenna separation height for 566 microwave links in Addis Ababa for the case of millimeter wave band, 73 GHz frequency band, 500 MHz bandwidth, 42 dB antenna gain, 13 dBm transmitter power, 22 dB/km*d (km) required fade margin and 256 QAM modulation scheme are considered. Where d is hop length in km. The required minimum SNR $(SNR_{minimum})$ for 256 QAM modulation scheme at bit error rate of 10^{-6} is 32 dB.

The receiver sensitivity $(P_{sensitivity})$ is the ability of a receiver to identify and amplify signals at the receivers input and it is expressed in dBm. The receiver sensitivity level tells the weakest signal that a receiver will be able to identify and process. The sensitivity of a receiver can be calculated if one knows the following performance parameters: the thermal noise power(N_o), noise figure (NF) and the signal to noise ratio (SNR) required to achieve the desired quality signal.The receiver sensitivity is calculated as follows:

$$P_{sensitivity} = 10\log(kTBW) + NF + SNR_{minimum} \quad [dB] \tag{4.1}$$

This equation defines the signal power in dB or Watts that is present at the demodulator for a desired carrier to noise ratio.The total thermal noise power (kTB or N_o) is a function of three quantities, 1) Boltzmann's constant "k" in Joules/K ($1.38 * 10^-23$), 2) temperature in Kelvin (290), and 3) the overall bandwidth of the channel selective filtering in the receiver. This is referred to as "Thermal Noise" because of the dependency on temperature. To calculate noise power the following formula is used.

$$N_o = -174\,(dBm/Hz) + 10\log(BW)\,(Hz) \quad [dBm] \tag{4.2}$$

$$P_{sensitivity} = -174 + 10\log(BW)\,(Hz) + 6 + SNR_{minimum}\,(dB) \quad [dBm] \tag{4.3}$$

The sensitivity is the sum of noise figure (NF=6 dB), signal to noise ratio (SNR=32 dB) and noise power N_o=-87 dBm and becomes -49 dBm from above calculation.

From ITU-R P.530-8, ITU-R PN.837-1 and Rec.838-3 standard [5], rain attenuation is given as $\gamma_R = kR^{\alpha}$. Where k and α are coefficients found in the table for the relevant frequencies and R is the rain rate in millimeter per hour for a percentage of time in a given rain region of the world. Addis Ababa is in rain climate region E. Thus rain intensity exceeds 70 mm/hr for 0.001% of time.
For 28 GHz and vertical polarization, k=0.1964 and α=0.9277,and γ_R becomes 10.11 dB/km.

For 73 GHz and vertical polarization, k=1.0711 and α=0.715,and γ_R becomes 22 dB/km.

For the availability of five 9s, the attenuation due to rain become 22 dB/km. So the attenuation ($Atten_{loss} = 22\ dB/km$) loss due to rain was considered for the case of millimeter wave band. Considering 22 dB/km*d km of fade margin (FM), the minimum power to be received (P_{min}) at receiver for the link to be available is the sum of fade margin and receiver sensitivity and it become -49 + 22 dB/km*d km dBm accordingly.

$$P_{min} = P_{sensitivity} + FM \quad [dBm] \tag{4.4}$$

From required minimum power at receiver, the allowable maximum path loss(PL_{AlMax}) can be calculated and it is the sum of transmitted power and antennas gain (Ga) from both sides, and then subtract the required minimum received power at receiver.

$$PL_{AlMax} = P_{tx} + 2 * Ga - P_{min} \quad [dB] \tag{4.5}$$

The allowable maximum path loss of the links for the requirements stated above become 146 -22 dB/km*d (km) in dB. To check the feasibility of existing microwave links in Addis

Ababa for the case of millimeter wave band regarding path loss of the links, need to calculate free space path loss (FSL_{pl}) of each existing microwave link and compare against allowable maximum path loss calculated above. Free space path loss is calculated by the following equation:

$$FSL_{pl} = 92.44 + 20\log(f) + 20\log(d) \quad [dB] \tag{4.6}$$

Where FSL_{pl} is free space path loss in dB, f is frequency in GHz and d is link length in km. In addition, based on link distance and considered frequency, antenna separation height of the links are calculated by using equation 2.1, and all the results including link availability in percent are presented in chapter 5. Link budget model is implemented in MATLAB for these purposes and shown in Figures 5.1 and 5.2.

4.3.2 Link Capacity Calculation

Based on technical parameter assumptions considered in table 4.1, the following formulas are used to calculate link capacity for each scenario.

$$N_o = 10\log[K * T * Bw * 10^3] \quad [dBm] \tag{4.7}$$

Where
N_o is a noise power in dBm
K is a Boltzmann constant
Bw is bandwidth in Hz and T is temperature in kelvin

$$SNR = 10\log\left[\frac{P_r(w)}{N_o(w)}\right] = P_r[dBm] - N_0[dBm] \quad [dB] \tag{4.8}$$

SNR is signal to noise ratio and P_r is received power obtained by equation 3.2.
For the case of single input single output, Shannon formula is used [19].

$$C_{siso} = BW\log_2[1 + SNR] \quad [Mbps] \tag{4.9}$$

For the case of 2x2 LOS-MIMO, the formula derived by Telatar in 1999 [32] is used.

$$C_{mimo} = BW\log_2\left[\det\left(I_M + \frac{\gamma}{N}HH^H\right)\right] = BW\sum_{i=1}^{\min(N,M)}\log_2\left(1 + \frac{\gamma}{N}\lambda_i\right) \ [Mbps] \tag{4.10}$$

Where
C_{siso} and C_{mimo} is capacity of SISO and LOS-MIMO in Mbps respectively. BW is band width in MHz.
λ_i is an eigenvalue of HH^H. The eigenvalues and singular values are related by $\lambda_i = \gamma * \sigma_i^2$ where γ is SNR, N numbers of minimal antenna. I_M Is identity matrix.

λ_i is 2 for spatial multiplexing and 4 for spatial diversity of MIMO operation. The capacity of 2x2 LOS-MIMO (N=2) can thus be calculated for spatial multiplexing using

$$C_{mimo} = BW \sum_{i=1}^{2} \log_2 (1+\gamma) \quad [Mbps] \tag{4.11}$$

Finally, capacity of all scenarios against different SNR are evaluated and presented in chapter five in Figure 5.3.

4.3.3 Traffic Data Demand Estimation and Forecasting

To estimate the initial traffic data demand and forecast for next four years for each scenario, one year per month used traffic data from eNodeB are taken. These data are used to plot the graph to obtain equation from curve fit. Equation obtained was applied to estimate first year data demand and forecast traffic data demand for the next four years. For this purpose different techniques are evaluate or analyzed under regression analysis and better model is applied for this work.

Regression analysis

Regression analysis is a form of predictive modeling technique which investigates the relationship between a dependent (target) and independent variable (s) (predictor). This technique is used for forecasting, time series modeling and finding the causal effect relationship between the variables. Regression analysis is an important tool for modeling and analyzing data. Linear, exponential, power and logarithmic models are analyzed and evaluated to select better model that fit the data. After curve fit is done for different models using regression analysis, it needs to determine how well the model fits the data. R-squared value is used to evaluate or analyze model's fitness to a given data. R-squared is a statistical measure of how close the data are to the fitted regression line and applied here. It is also known as the coefficient of determination, or the coefficient of multiple determination for multiple regression [35].

The definition of R-squared is fairly straight-forward; it is the percentage of the response variable variation that is explained by a model.

R-squared = Explained variation / Total variation.
R-squared is always between 0 and 100%:

- 0% indicates that the model explains none of the variability of the response data around its mean.

- 100% indicates that the model explains all the variability of the response data around its mean.

In general, the higher the R-squared, the better the model fits a given data. Here, a curve / line is fitted to the data points for different models, in such a manner that the differences between the distances of data points from the curve or line is minimized.

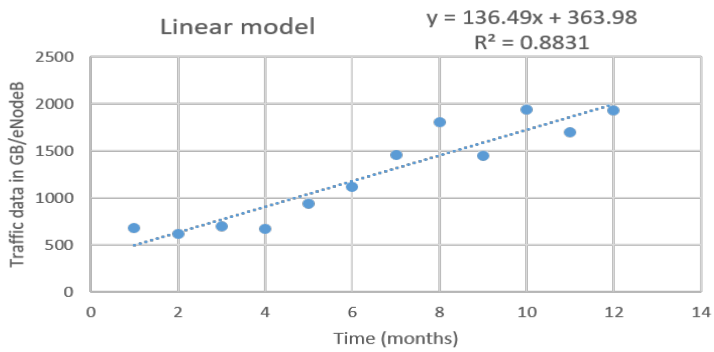

FIGURE 4.2: Curve fit for traffic data forecasting (Linear model)

Linear model approach fits data with an accuracy of 88.31% and 11.69% error.

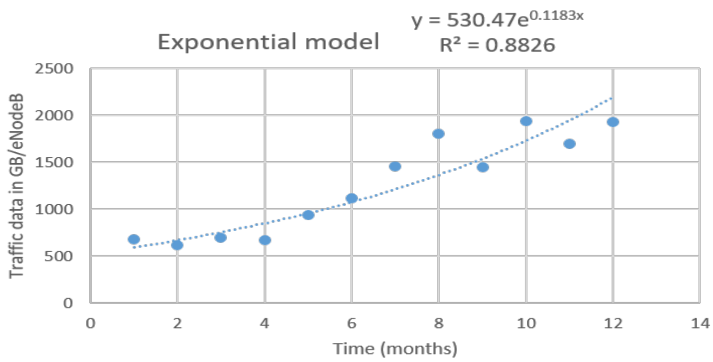

FIGURE 4.3: Curve fit for traffic data forecasting (Exponential model)

Exponential model approach fits data with an accuracy of 88.26% and 11.74% error.

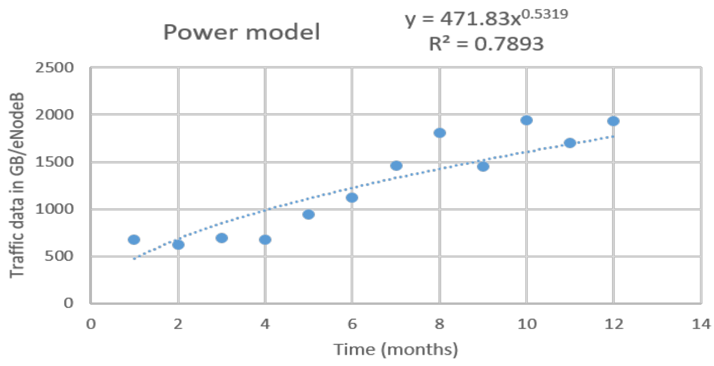

FIGURE 4.4: Curve fit for traffic data forecasting (Power model)

Power model approach fits data with an accuracy of 78.93% and 21.07% error.

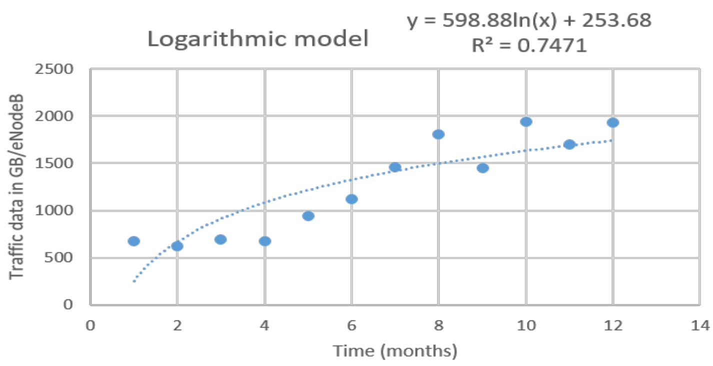

FIGURE 4.5: Curve fit for traffic data forecasting (Logarithmic model)

logarithmic model approach fits data with an accuracy of 74.71% and 25.29% error.

From Figures 4.2, 4.3, 4.4 and 4.5, it can be concluded that, linear model fits data with better accuracy or approach and least error than other models, and it is used for this work.

Figure 4.6 below shows forecasted traffic data demand for next five years for single eNodrB and used to map across scenarios.

FIGURE 4.6: Five years per eNodeB forecasted traffic data demand

Scenario Application Area Options

These options are used for scenarios evaluation purpose based on application area. The first option, Figure 4.7, is applying all scenarios on the same link that offer equal traffic data. In this case, delivered traffic data or generated revenue by all scenarios will become equal and evaluating parameter will goes to TCO alone, and scenario with least TCO will be selected. Applying each scenario on different link with different traffic load is the second option, Figure 4.8. Here, delivered traffic data or generated revenue by all scenarios are different and the evaluating parameters can go further to economic indicators like NPV, IRR and payback period. This option was applied for this work and the load difference on each scenario was made based on numbers of eNodeB sites applied for each scenario.

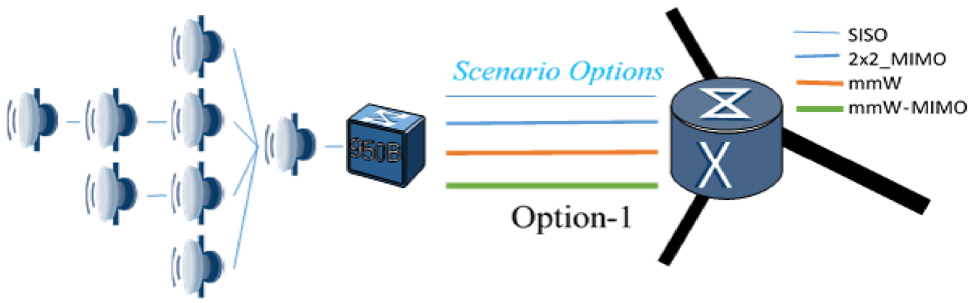

FIGURE 4.7: Option one scenarios application area

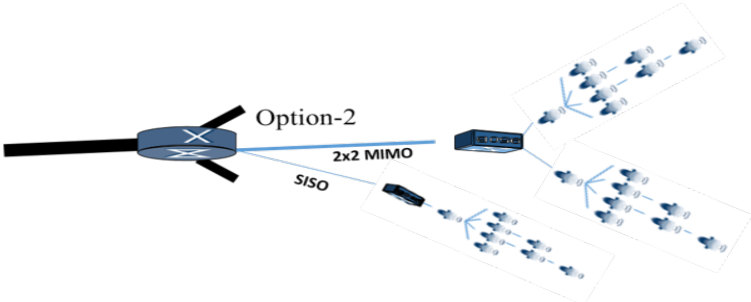

FIGURE 4.8: Option two scenarios application area

Regarding to option two application, first, per eNodeB traffic data demand are forecasted for the next five years and different numbers of eNodeB are assigned for each scenario. To specify, the traffic data of six and twelve sites are assigned to SISO and mmW band scenarios respectively. Then additional 50% of SISO and mmW band were assigned to MIMO (that is nine sites) and mmW-MIMO (eighteen sites) to keep proportionality. Because, to upgrade MIMO from SISO, it requires only some parts that should be added on SISO.

4.3.4 Revenue Estimation and Forecasting

One of the most important key parameters in economic analysis is revenue forecast. Revenue projection per year is obtained based on monthly or yearly basis data consumption level of service users, charging and pricing policy sated and number of forecasted data service users. For this study, the revenue was modeled and forecasted from the data delivered over backhaul link per year.

As stated, the revenue was mapped from traffic data offered per link throughout the year for each scenario and the initial value at first year and next four years revenue was obtained from traffic data forecasted in section 4.2.2. The results are presented in chapter five.

But, the revenues obtained were contributed by all parts of the network from end to end which are radio and backhaul (access, aggregated and core) parts. So, it needs to distribute the revenue among each network parts. To do this, cost contribution of each part from total network cost should be known. Based on the area, size and density of the mobile network, and organization of the network and its operation and maintenance, the author in [7] distributed in percent the total network related costs for 2G/3G networks covering urban and suburban areas, and networks covering either large rural areas or having high numbers of small cells. For this study, the distribution for covering urban and suburban areas are applied, Figure 4.9.

Figure 4.9 shows typical network's share in mobile operator total network related costs for 2G/3G networks covering urban and suburban areas (on the left), and backhaul networks cost distribution between parts (to the right).

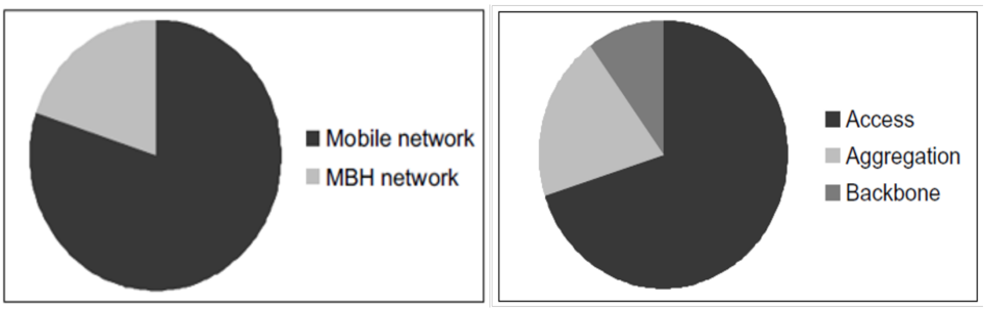

FIGURE 4.9: Typical network's share in mobile operator total network related costs [7]

4.4 Economic Analysis

Economic analysis focused on economic related works. Identifying per link key components of the system was carried out to determine the CAPEX and OPEX of network equipment required to offer the planned services to the end users or to offer the required capacity of the link. The cost of the network is one of the core elements for measuring the feasibility of deployment scenarios and directly depends on the capacity and performance requirement. The total cost of ownership of the transport network comprises a number of capital outlays (CAPEX) and ongoing operation expenditures (OPEX). The costs can be incurred by terminal sites, or the links themselves. The equipment costs were driven based on the vendors' price obtained from different vendors and the average cost was considered. The TCO evaluation in this thesis is based on the equipment costs taken from different vendors in the middle of 2019 and followed by five years of operation costs, increasing with an assumed 10% of interesting rate.

4.4.1 Capital Expenditure (CAPEX)

Initial investment related costs include hardware and software cost including implementation costs. Planning, installation and system testing cost are implementation related costs. Key components of wireless backhaul system were presented in table 4.2 below.

Equipment Cost

Equipment pricing can vary dramatically depending on the volumes and timescales involved, as well as the manufacturers. In relating to equipment costs, based on identified solutions,

TABLE 4.2: Key components of wireless back-haul

All outdoor key components per link	
S/N	Components
1	Radio Unit
2	Antenna(60/30cm)
3	Accessories
4	Software and license per link

per link price and detail technical specification were requested to different microwave equipment vendors through their sales address. Different prices from different vendors were received. The use of least price alone for selection criteria is not enough. To decide the appropriate price, different mechanisms were performed.

The first way was, considering all parameters that affect TCO and revenue of the system as a merit for evaluation. These parameters include price, capacity, price per MB and energy that affect the bill. But all solutions support the same capacity and this will make the selection criteria to go to least price, so better to find another mechanisms. As it has been seen from different literatures, the authors take different prices from different literatures for the same equipment and use the average value.

For this work also, average value was considered and further sensitivity analysis was done on lowest and highest equipment price to see its impact. In case of shipment cost, the average cost of two price that were obtained from two vendors was considered and added on to equipment cost. Sensitivity analysis was also done on OPEX, TCO and revenue to see their effect on the system outputs by changing 10% upward and downward from normal value. The E-band solution prices per link were in the range of \$10,889 to \$17,920 and \$14,404.5 average value was taken. In the case of microwave solution that operate at lower frequency band, prices per link were in \$7,100 to \$10,090 ranges and \$8,595 average value was used.

Installation cost

New site is considered here and installation cost assumptions was taken based on the labors (Engineers and Technicians) cost of installing a sites. Installation manual from different vendors indicate that, all outdoor system takes 6-8 hours with two team per link to install single link. This assumption was taken into consideration and calculated for ethio telecom case and considered the same for all scenarios. The same team was assumed for site acquisition and planning for one additional day. To specify, for equipment implementation, a team with five persons including a driver for two days per link was considered to obtain installation costs. Per link capital expenditure for each scenario is defined in table 4.3.

TABLE 4.3: Initial CAPEX cost per link

S/N	Scenarios	Equipment Cost $	Installation Cost $	CAPEX $
1	SISO	8,595	700	9,295
2	MIMO	11,131	700	11.831
3	mmW	14,404.5	700	15,104.5
4	mmW-MIMO	28,809	700	29,509

4.4.2 Operational Related Costs (OPEX)

The operational costs are the ongoing costs used to run the system after deployment and include power, spectrum, site rent, and operation and maintenance costs. It should be noted that costs for solutions are presented as per link basis, the same way the cost for ongoing was also presented as per link basis. Unlike CAPEX, the combination of top-down and bottom-up approach was followed to estimate the operational expenditure and 15% of CAPEX was considered for energy consumption, operating and maintenance excluding spectrum license fees[14]. Because, getting energy consumption, operational and maintenance cost per link basis is very difficult from bottom up approach and it is taken from Ericson's report.

Spectrum Dimensioning

Concerning to spectrum, licensing fees depends on frequency band and bandwidth used for microwave communication system. Unlike microwave, worldwide approaches show that, E-band PTP spectrum was typically licensed on per-link basis to motivate the users because of congestions at lower frequency spectrum. The UK spectrum licensing fees, £50 ($55.5) per link per year, was used and mapped onto ethio telecom case for E-band in the model for this work because they are publicly available and they are in the middle of the price range across different countries. The value of £50 includes the registration of the first link for the first year of the license. Any further links registered by the licensee will be charged at £50 ($55.5) per link per year[36, 37]. Regarding to spectrum for lower frequencies, the price depends on frequency band, bandwidth used and other factors. £88 is per 2 x 1 MHz for each bi- directional link and for 56 MHz bandwidth operated at 28 GHz frequency band with 0.3 band factor gives £1,478.4 ($1,641)[38].

For the case of microwave spectrum in Ethiopia, the information from regulatory body (as requested an expert in tele agency) in Ethiopia indicates that a unit price of 528 ETB per MHz and 433 ETB per MHz are per unit cost price that should be used to pay (for tele agency by ethio telecom) per year for radio link communication that operate at less than 1 GHz and greater than or equal to 1 GHz carrier frequency respectively based on bandwidth used. But currently, ethio telecom pay only 528 Birr or 433 ETB per year for less than 1 GHz and greater than or equal to 1 GHz frequency band based on frequency used for radio link. For this work, the appropriate way was followed to calculate spectrum fees (433*56 ETB/year).To map E-band spectrum price, the proportionality at lower frequency band was used ($840.48: $1,641) and it becomes $28.425 per link per year. Table 4.4 below shows per year OPEX for each scenario.

TABLE 4.4: Assumed initial OPEX costs per link

S/N	Scenarios	Spectrum Fees $	Site Rent $	Power, O & M $	OPEX $
1	SISO	840.48	4,160	1,394.25	6,394.73
2	MIMO	840.48	4,160	1,774.65	6,775.13
3	mmW	28.425	4,160	2,265.675	6,454.1
4	mmW-MIMO	56.85	4,160	4,426.35	8,643.2

4.4.3 Total Cost of Ownership (TCO)

Total cost of ownership is a financial estimate to determine the direct and indirect costs of a product or a system over a certain time period, which is composed of CAPEX and OPEX. TCO of all scenarios are indicated in the following table 4.5.

TABLE 4.5: Year one total costs of ownership (TCO)

S/N	Scenarios	CAPEX $	OPEX $	TCO $
1	SISO	9,295	6,394.73	15,689.73
2	MIMO	11,831	6,775.13	18,606.13
3	mmW	15,104.5	6,454.1	21,558.6
4	mmW-MIMO	29,509	8,643.2	38,152.2

4.5 Techno-economic Analysis and Evaluation

For this work, new sites and link with different traffic load was considered for each scenario. In relating to spectrum, 433 ETB per MHz unit price was used to pay (for tele agency in Ethiopia) the value for the spectrum at each year for lower frequency band microwave system and per link basis was considered for higher frequency band. The CAPEX, OPEX costs and revenue analysis used in the TE evaluation is based on inputs discussed in section 3.5 and 4. Finally, techno-economic analysis is performed (by cash flow and discounted cash flow methods) and the evaluation was done based on economic indicators like revenue, TCO, NPV, IRR and payback period.

Chapter 5

Results and Interpretations

There are four deployment scenarios that are studied in this work and they are named as SISO and MIMO from lower frequency band, and mmW band and mmW-MIMO from higher frequency band. In the future, these scenarios can be used or applied for mobile backhauling service based on traffic data requirements. Before deployment, feasibility assessment is essential for each scenario to justify the viability of scenario regarding to economic and technical aspects. Accordingly, techno-economic analysis was done for each scenario, and the results and interpretations are presented in the next sub-sections.

5.1 Technical Analysis

Final output from technical part is the capacity of the link that deliver data per month or year for each scenario. These delivered data from each link were mapped into revenue to perform further techno-economic analysis of each scenario. The technical assumptions considered for initial planning were 56 MHz bandwidth and 256 QAM modulation schemes for lower frequency microwave system, and 500 MHz bandwidth and 256 QAM modulation schemes for higher frequency band (E-band). The following table shows initial planned capacity of each scenario based on assumptions considered in table 4.1.

TABLE 5.1: Technical assumption considered

Scenarios	Bandwidth (MHz)	Modulation schemes	Capacity (Mbps)
SISO	56	256	368
MIMO	56	256	736
mmW band	500	256	3,200
mmW-MIMO	500	256	6,400

5.1.1 Existing Links Feasibility Analysis

The feasibility analysis on existing microwave links are performed for the case of LOS-MIMO and millimeter wave bands based on antenna separation height and path loss. In the next subsections the evaluation results are presented for each scenario.

2x2 LOS-MIMO

For 566 existing microwave links in Addis Ababa antenna separation height are calculated based on links' hop length and used frequency for lower frequency band. The numbers in table 5.2 indicate that 85.2% of the links require less than 4 meters antenna separation length. Similarly, 8.66% of the links require antenna separation length in the range of 4 meters to 5 meters and around 6% links require 5 meters to 10 meters length. What is concluded from these are, 94% of microwave links in Addis Ababa are in applicable antenna separation ranges (that is less than 5 meters). Because, most of sites' tower height in Addis Ababa are in the ranges of 25 meters to 48 meters which is almost 80%. But it needs physical investigation on each link for the feasibility analysis of second antenna on both towers for each link. The large numbers of links and the security cases make physical investigation of the links more complex and difficult. This work can be done by link planner during implementation.

It is important to note that antenna separation does not have to be symmetrical. Link topologies will often be constrained by factors that limit antenna separation on one side of the link, such as tower space and mechanical load. Link planners can compensate for such constraints by adjusting the antenna separation on the other side of the link so that the product of the antenna separation length should satisfies the equation 2.1. Another ways of compensation for such constraints are increasing transmitter power and using antenna with higher size or gain.

Concerning to links availability for the case of LOS-MIMO, the links are already deployed for the case of SISO and the difference is the implementation of second antenna for the second link. In case of fade margin (FM) problem, it can be compensated by increasing transmitter power or using antenna with higher gain. Because, currently used transmitter power in Addis Ababa microwave links are in the range of 0 dBm to 21 dBm.

TABLE 5.2: Antenna separation length status for the case of lower frequency band

[1.1m,4m)		[4m,5m)		[5m,6m)		[6m,10m)	
In number	In %	In number	In %	In number	in %	In number	In %
482	85.2	49	8.66	20	3.53	15	2.7

Millimeter wave band

Similarly, for 566 existing microwave links in Addis Ababa antenna separation height are calculated based on links' hop length and considered frequency for higher frequency band also. The results indicate that 100% of the links require less than 4 meters antenna separation length which is practically applicable. This is due to the dependency of antenna separation height directly on hop length and inversely on used frequency band. The results imply that MIMO system is more suitable at higher frequency bands than lower frequency bands. Regarding to the constrains that will happen by factors that limit antenna separation on one side of the link, such as tower space and mechanical load, it can be compensated with similar ways that stated for lower frequency bands. Concerning to the feasibility of the second antenna on each tower, similar idea applied as for lower frequency bands.

Regarding to link budget calculation, based on the requirements (as stated in subsection 4.1), required maximum allowable path loss is calculated by PL_{AlMax} = 146-22 dB/km*d (km) in dB formula for each link. To decide availability of the links for the case of millimeter wave bands, free space path loss of each link is calculated and compare against allowable maximum loss. Based on the calculations, if rain attenuation loss of $(Atten_{loss} = 22\ dB/km)$ is considered, 53.53% of the links fit the requirements. But if rain attenuation is not considered 100% of the links are feasible. To conclude, the effect of rain on higher frequency band communication should be considered and from the results only 53.53% of the links are feasible for millimeter band. This is due to impact of rain attenuation and frequency used on path loss and can be improved by increasing transmitter power and using antenna with higher gain. Figures 5.1 and 5.2 below show Graphical User Interface (GUI) shoot used to present the status of the same link for the case of lower frequency band and higher frequency band. For the same link, antenna separation height is less for higher frequency band which implies MIMO system suitability at higher frequency band.

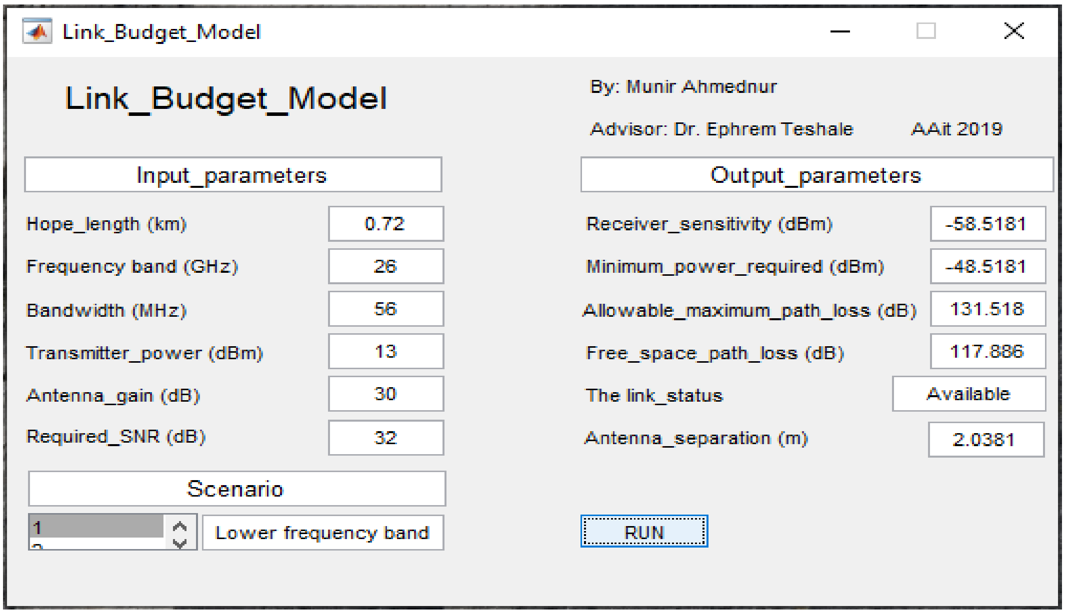

FIGURE 5.1: Link budget and antenna separation calculation for lower frequency band

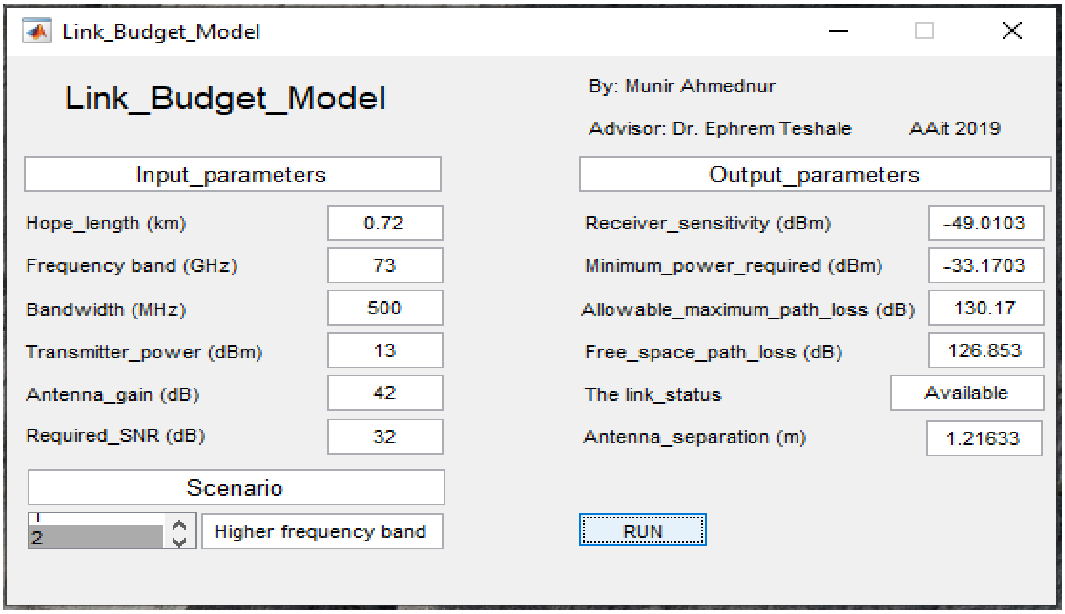

FIGURE 5.2: Link budget and antenna separation calculation for higher frequency band

5.1.2 Capacity Comparison

Figure 5.3 shows capacity comparison across scenarios for different SNR. The graph implies direct relation of capacity with bandwidth and MIMO system in addition to SNR. But after some level the impact of SNR is almost flat.

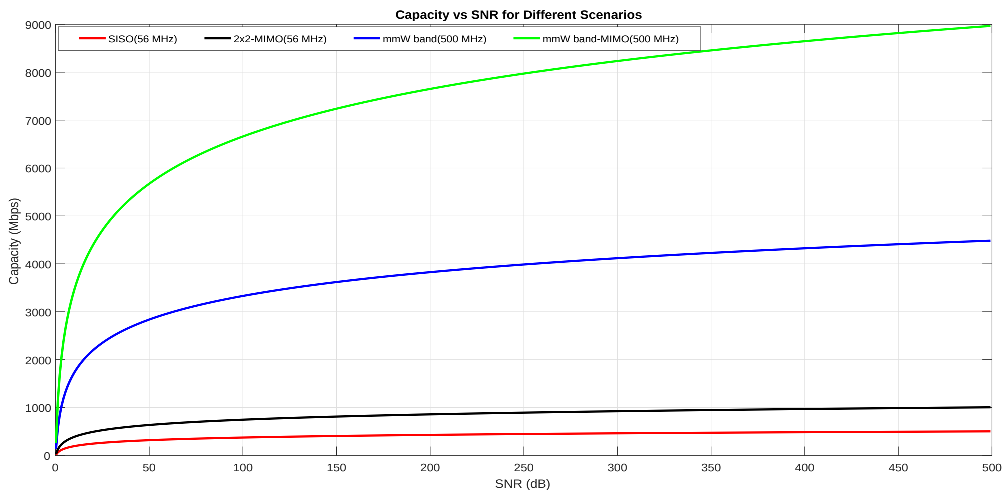

FIGURE 5.3: Capacity vs SNR for each scenario

5.1.3 Traffic Data Estimation and Forecasting

As stated in section 4.2.2, next five years traffic data demand were estimated and forecasted. Figure 5.4 shows estimated and forecasted traffic data demand for next five years for each scenario.

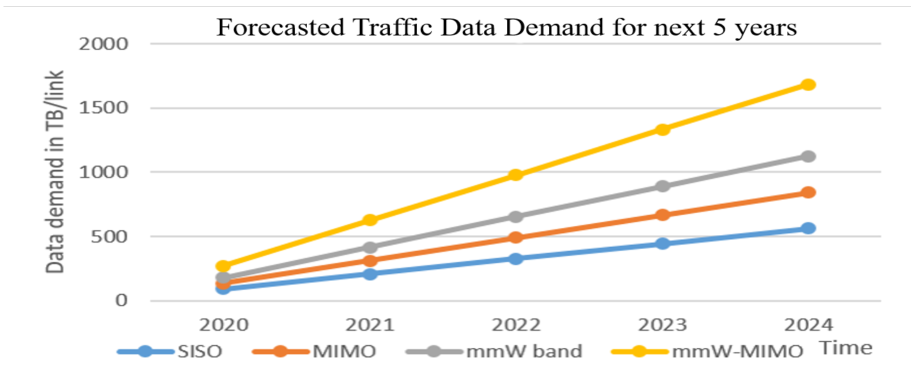

FIGURE 5.4: Five years estimated and forecasted traffic data demand

Increment of traffic data demand in each year is expected numbers because of data usage and numbers of users' increment in each year. Initial traffic data demand (first year) for SISO, MIMO, mmW band and mmW-MIMO are 90,083.88, 135,125.8, 180,167.76 and 270,251.6 GB respectively. At 5^{th} year, reach 561,793.32, 842,690, 1123,586.64 and 1,685,380.4 GB for respective scenario. These values indicate that there is high data demand in the future and need to be ready to use different enhancing techniques on existing microwave system or to deploy cost effective deployment scenarios to keep customers satisfaction. On the other hand, the data offered and capacity have a direct relationship, and the scenario with high capacity can deliver high data on the link.

5.1.4 Revenue Estimation and Forecasting

One of key parameters in this study is the revenue estimation and forecasting for each scenario. The revenue was obtained from data used per month or year that is offered from the link of each scenario. Estimated revenue for each scenario for next five years are shown in the following Figure 5.5.

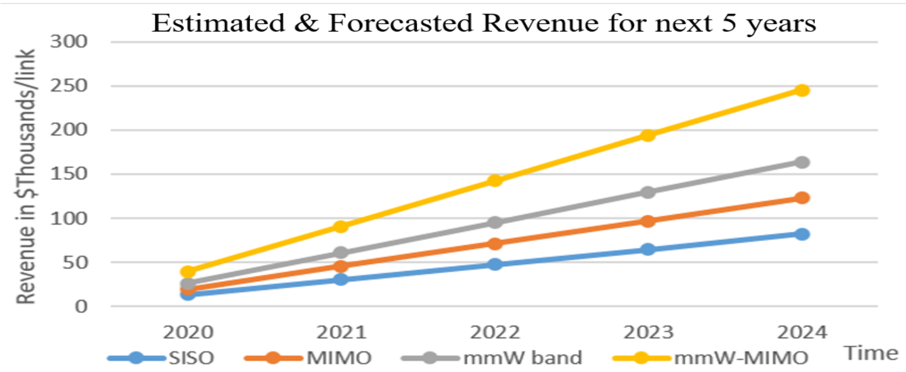

FIGURE 5.5: Five years estimated and forecasted revenue for all scenarios

First year estimated revenue for SISO, MIMO, mmW band and mmW-MIMO are \$13,114.46, \$19,671.7, \$26,228.9 and \$39,343.4 respectively. Similarly, the revenues at fifth year for respective scenario are \$81,786.2, \$122,679, \$163,572.4 and \$245,359. Similar to traffic data, revenue is also increasing from year to year. This is due to direct relation of revenue with data usage and in turn to data rate. The cumulative revenue for five years are shown below with Figure 5.6.

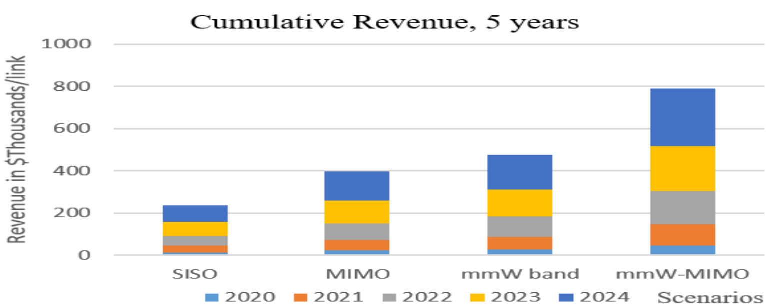

FIGURE 5.6: Five years Cumulative revenue for each scenario

To summarize, the data demand and revenue per aggregated link for each year and five years cumulative for each scenario are shown. The results indicate that revenue, traffic data demand and capacity of the link have a direct relation and the system with high capacity can deliver higher data and revenue for operator. The system with high performance can make money more than that perform less. Revenue increment also increasing from year to year which is the result of time to time traffic data usage and capacity demand increment. mmW-MIMO is making more money than other scenarios and SISO is ranked at last level. This is due to the dependency of data usage or revenue on throughput or data rate of the scenario.

5.2 Economic Analysis

5.2.1 CAPEX

Identifying key components per link for each scenario is the starting point to calculate the cost of equipment per link for each scenario. Identified components for microwave links are radio units, antennas, accessories and software. Based on these components, the initial capital expenditures for each scenario are shown below in Figure 5.7. These include equipment and installation costs.

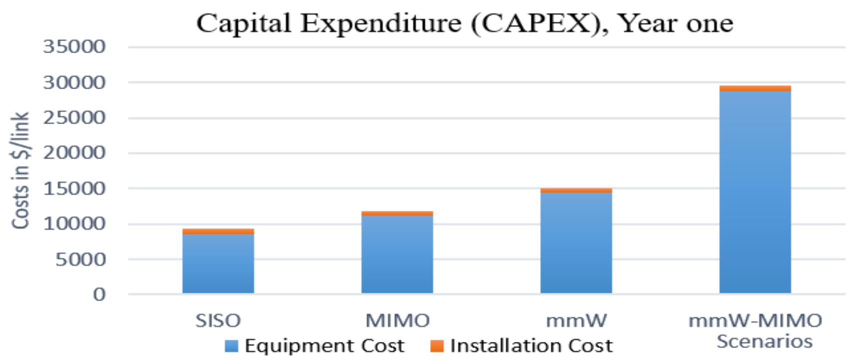

FIGURE 5.7: Year one capital expenditure (CAPEX) comparison across scenarios

The higher equipment cost for E-band is only in part due to the higher individual radio and antenna costs. Substantial cost difference comes from the fact that E-band links support higher throughput than microwave PTP links, so operators using E-band PTP have to buy higher-capacity links than backhaul demands. On the other hand, the differences in costs for different scenarios are due to the dependency of equipment costs on performance of the system. Equipment with high performance (throughput) will costs more than others.

As the time goes, the new technologies will emerge and the cost of existing technology will be decreased. To show equipment costs in the next five years, 5% yearly price trends was considered and the CAPEX cost trend within study period for all deployment scenarios are shown below.

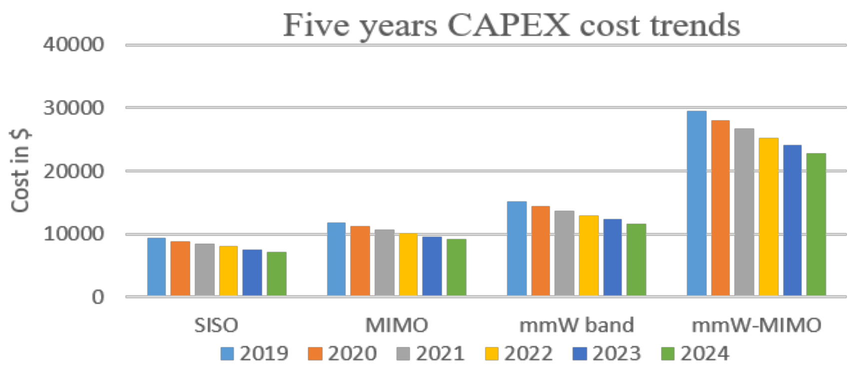

FIGURE 5.8: Five years CAPEX cost trends

The Figure 5.8 above shows the decrement of initial investment cost of each scenario with in study periods.

5.2.2 OPEX

OPEX is the second economic parameter used for economic analysis of the scenarios and it holds spectrum fees, site rents, power consumption, and operation and maintenance which are ongoing costs during operation.

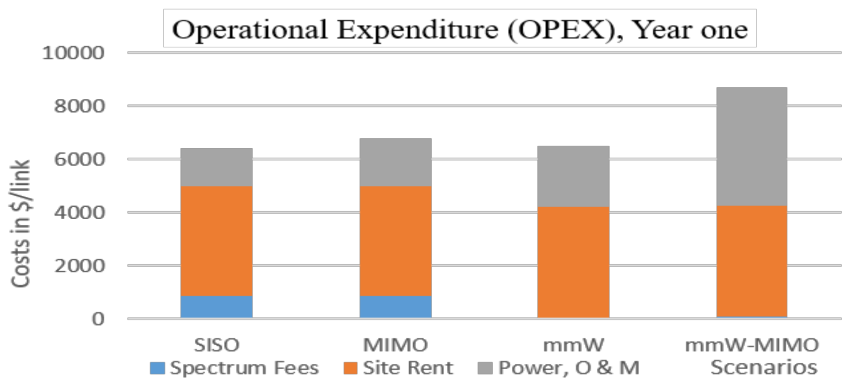

FIGURE 5.9: Year one operational expenditure (OPEX) comparison across scenarios

Figure 5.9, the high share of operational expenditure is taken by site rent, and operation and maintenance holds the second share. Regarding to spectrum fees, the costs for lower frequency microwave system is higher than that of millimeter wave. This is due to per MHz payment for lower frequency band and per link basis payment consideration for E-band frequency operation.

5.2.3 TCO

Figures below present total cost of ownership per link for the different scenario options, representing equipment purchase in the middle of 2019 plus five years of ownership and operation costs increasing at 10% of IR. Figure 5.10 shows TCO trends for five years and Figure 5.11 shows cumulative TCO at the end of five years.

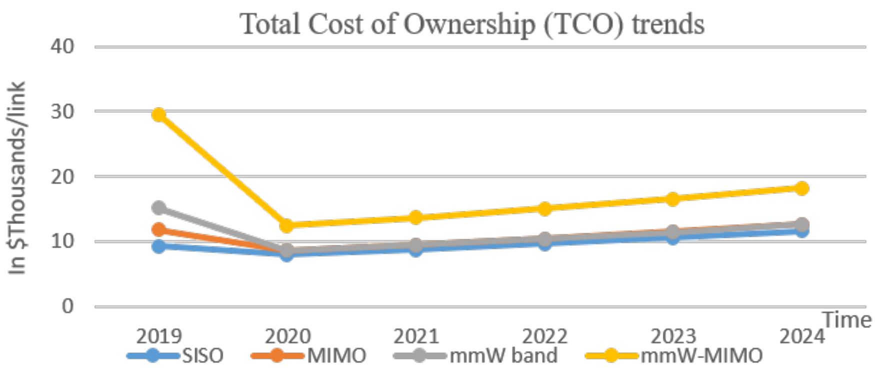

FIGURE 5.10: Five years total costs of ownership (TCO) trends

Five years TCO trend indicate that, at initial time CAPEX is the dominant and then afterwards OPEX takeover the dominance. OPEX trend for SISO, MIMO and mmW band show comparable but mmW-MIMO. This is due to 2+0 configuration considered for cost analysis of mmW-MIMO scenario.

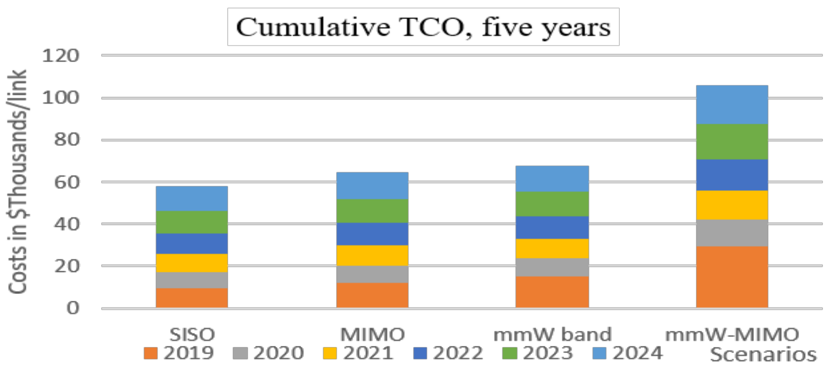

FIGURE 5.11: Cumulative total costs of ownership comparison across scenarios

Cumulative TCO of MIMO and mmW band at the end of five years show, Figure 5.11, that they are at similar level but mmW band serving with higher capacity. The implication is clear that, if long term benefit is preferable for the operator, the operator should choose mmW band system than MIMO system.

Cumulative cost per Mbps

Based on technical assumptions considered, the initial capacity of SISO, MIMO, mmW band and mmW-MIMO are 368, 736, 3,200 and 6,400 Mbps. The corresponding cumulative total costs are also $57,914.2, $64,553, $67,669.16 and $105,568.9. The cost per Mbps of each scenario is illustrated in the following table 5.3. Figure 5.12 shows, year 5 cumulative cost per Mbps, comparison across scenarios.

TABLE 5.3: Year five cost in $ per Mbps

Scenarios	Capacity (Mbps)	Total cost ($)	Cost $/Mbps
SISO	368	57,914.2	157.37
MIMO	736	64,553	87.7
mmW band	3,200	67,669.16	21.15
mmW-MIMO	6,400	105,568.9	16.5

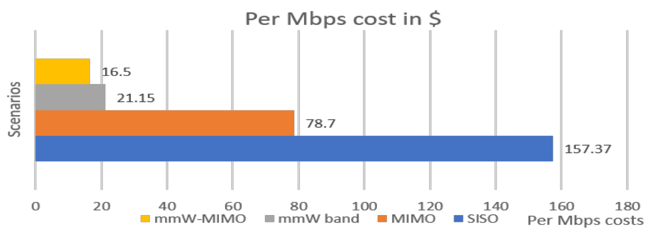

FIGURE 5.12: Year 5 cumulative cost per Mbps comparison across scenarios

Lower per Mbps cost for mmW-MIMO scenario is due to its higher throughput per link. The total cost for mmW-MIMO is the highest than other scenarios but the impact of throughput or data rate is higher than other parameters (equipment cost, OPEX and TCO) as confirmed through sensitivity analysis in section 5.3 below. Therefore, for all scenarios considered, per Mbps cost is the lowest for mmW-MIMO, because this scenario has the highest throughput or data rate by far (6,400 Mbps, compared to 3,200 Mbps for the mmW band scenario, 736 Mbps for MIMO case and 368 Mbps for the SISO scenario). The indications are, SISO is the most expensive and mmW-MIMO is the cheapest solution among the scenarios for the study period.

Cost Contribution

The following figures show first year and after five years cost contribution for MIMO scenario.

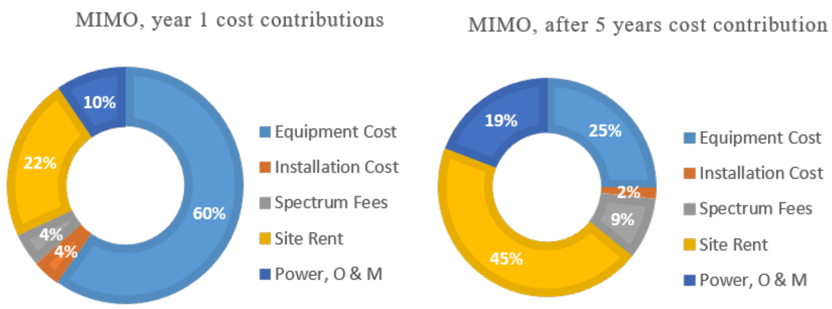

FIGURE 5.13: Five years costs contribution for MIMO scenario

The figure to the left shows that, the dominance or high share of CAPEX at initial time which is 64% of TCO. The one to the right indicates the dominance or high share of OPEX at the end of five years that is 73% of TCO.

The following figures also show first year and after five years cost contribution for mmW band scenario.

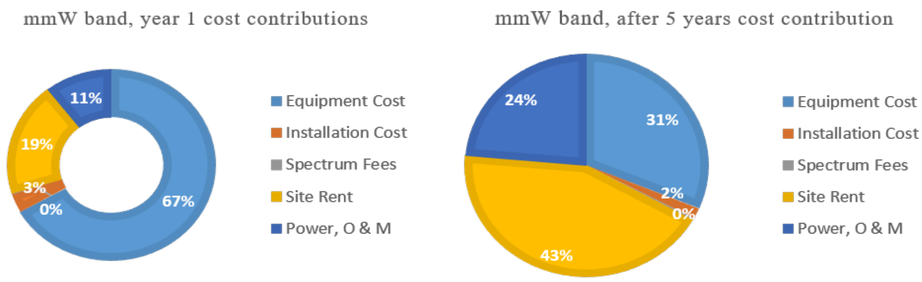

FIGURE 5.14: Five years costs contribution for mmW band scenario

Similarly, figure to the left shows that, the dominance or high share of CAPEX at initial time which is 67% of TCO. The one to the right indicates the dominance or high share of OPEX at the end of five years that is 67% of TCO. What is concluded from these are, real cost of wireless backhaul is OPEX costs and operators should focus more on OPEX optimization to minimize expenditures and increase revenue. This doesn't mean, ignore CAPEX. The ratio is almost 30:70 in average.

The total CAPEX cost, OPEX cost and TCO per each deployment scenarios were estimated and illustrated. The total estimated CAPEX costs per link for SISO, MIMO, mmW band and mmW-MIMO are \$14,969.69, \$19,053.94, \$24,325.95 and \$47,524.54 respectively. Likewise, the total estimated OPEX cost within the study period are \$42,944.5, \$45,499.1, \$43,343.2 and \$58,044.36 for respective scenarios. At the end of five years, the total TCO estimated for respective scenarios which is the summation of CAPEX and OPEX are \$57,914.2, \$64,553, \$67,669.16 and \$105,568.9.

To summarize, looking primarily at CAPEX can be easier to say it is the dominant, but misleading! The impact of equipment costs is often overestimated. Real cost of wireless backhaul is OPEX, operators should focus more on OPEX optimization to minimize expenditures and increase their revenue. This doesn't mean, ignore the CAPEX. This statement is also supported by sensitivity analysis and it shows OPEX has higher impact than CAPEX on the outputs.

5.3 Techno-economic Analysis

The third part of this work is techno-economic analysis to evaluate the economic feasibility of each deployment scenario. This part was used to combine outputs from technical and economic part, and deliver economic indicators like NPV, IRR and payback period. These indicators are used for further evaluation of each scenario. The method applied here was cash flow analysis and interpreted in this section. Tools used for cash flow analysis is MS-excel and MATLAB.

5.3.1 Cash Flow Analysis

Cash flow is the net amount of cash that is received or generated in a given time period by combining revenue and costs of the system. At the end, net amount of cash and payback period value were obtained from cash flow. In this section, cash flow of each scenario was analyzed and interpreted.

Cash flow analysis for SISO scenario

FIGURE 5.15: Cash flow analysis, SISO scenario

The graph of SISO cash flow shows that, 1.426 years and $179,337 payback period and net cumulative benefit at the end of five years respectively. The evaluation at the end of one year indicates, negative net benefit (-$4,144) and it shows the need for more additional time to arrive at return on investment period which is 5 months.

Cash flow analysis for MIMO scenario

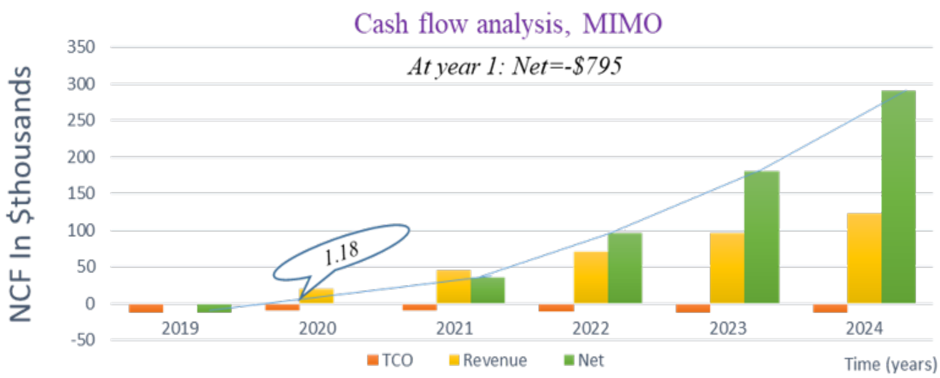

FIGURE 5.16: Cash flow analysis, MIMO scenario

Similarly, 1.18 years and $291,324 for payback period and net cumulative benefit at the end of five years have seen for the case of MIMO respectively. Regarding to evaluation at the end of one year, the result shows negative net benefit (-$795) that indicates the need for more additional time to arrive at ROI period which is 2.16 months.

Cash flow analysis for mmW band scenario

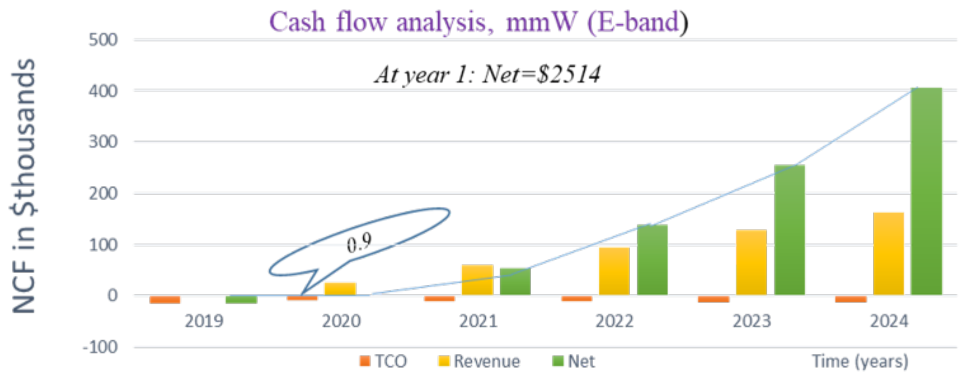

FIGURE 5.17: Cash flow analysis, mmW band scenario

The results from cash flow analysis for mmW band scenario indicate that, 0.9 years and $406,834.1 for payback period and net cumulative benefit at the end of five years respectively. One year evaluation also shows positive net value ($2,514) which indicates the start of generating money early 1.2 months.

Cash flow analysis for mmW-MIMO band scenario

Finally, cash flow analysis for mmW-MIMO band scenario has done and the results indicate that, payback period and net cumulative benefit at the end of five years are 1.226 years and $606,186 respectively. Like SISO and MIMO, net benefit of mmW-MIMO at the end of one year shows negative (-$2,624) value which indicates the need for more additional time to arrive at ROI period which is 2.7 months.

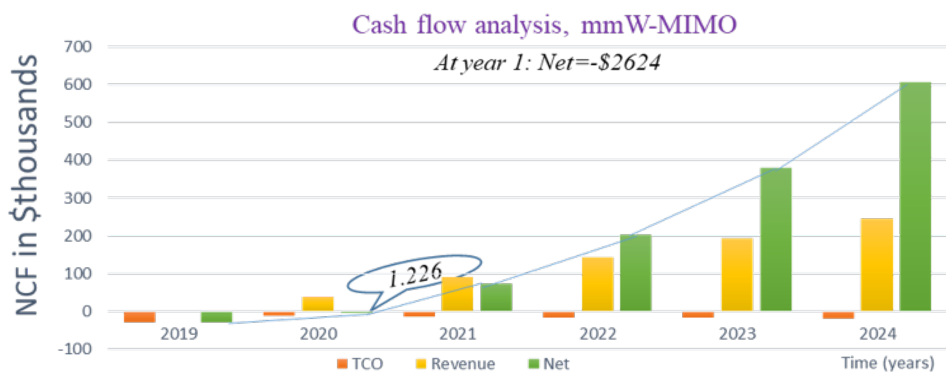

FIGURE 5.18: Cash flow analysis, mmW-MIMO scenario

Similarly, five years cash flow analysis for all scenarios are presented below to visualize their relative status for five years study period.

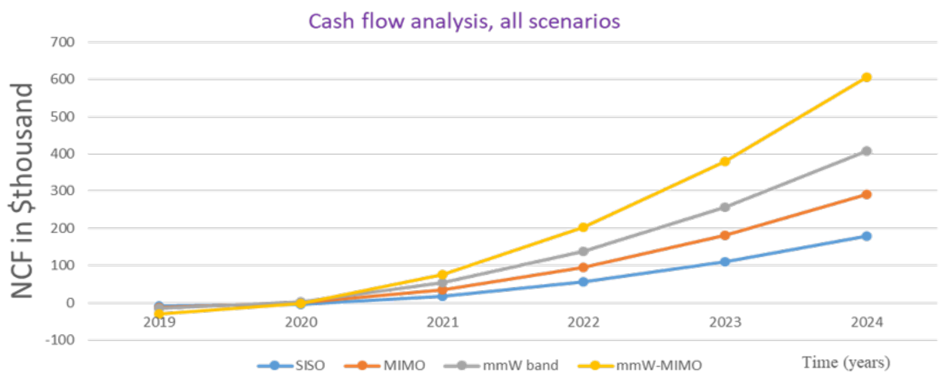

FIGURE 5.19: Five years cash flow analysis comparison across scenarios

The status after year one indicates, fast grow of mmW-MIMO graph relative to others which shows more money making of mmW-MIMO over others at specific time. On the other hand, the gap between all scenarios are running apart with different slope. This is due to performance or data rate and total cost of ownership differences between them but data rate has high impact over total cost. If ROI is critical for the operator, the choice will go to scenario with least payback period. The shorter the payback, the more desirable the investment. Conversely, the longer the payback, the less desirable it is. But if ROI is not critical and need to choice long time cost benefit, the scenario with greater IRR or NPV value was better selection.

Payback period

The payback period is referred to the time it takes to recoup an investment from the revenue or free cash flow it generates. This is a common investment evaluation and ranking measure used to gauge how quickly system and equipment or capital assets purchased can repay themselves. The appropriate payback period for investments and plant or equipment will vary depend on the industry, size of the investment, life of the plant and equipment, cost of capital and other factors. Two years cash flow analysis for all scenarios are presented on figure below to visualize their relative status in terms of payback period.

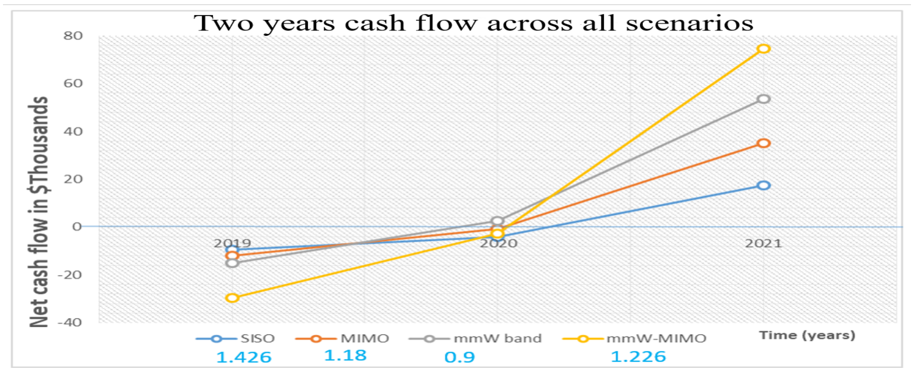

FIGURE 5.20: Two years cash flow analysis to visualize their payback period

Hence, payback period recorded for SISO, MIMO, mmW band and mmW-MIMO are 1.426, 1.18, 0.9 and 1.226 years respectively. This means, respective scenarios can achieve return on investment at 1.426, 1.18, 0.9 and 1.226 years. The payback period of all scenarios are in the range of 0.9 to 1.426 years and their differences are days or months. From these results, it can be concluded that all scenarios are feasible in terms of ROI. Since the difference between shortest payback period (for mmW band) and longer payback period (for SISO) is 6.3 months, and all are arrived at ROI in less than two years.

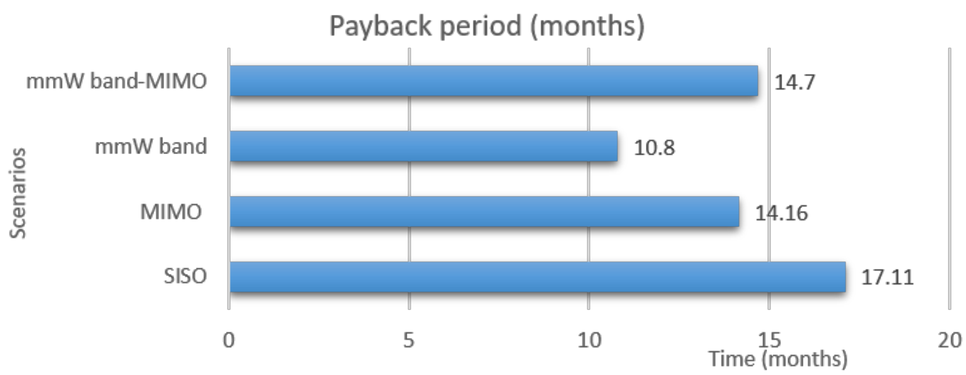

FIGURE 5.21: Payback periods (months) comparison across scenarios

Net present value and internal rate of return

Internal rate of return and net present value are another economic indicators used to evaluate the systems or scenarios. The following graph was plotted with NPV against to different discounted rate. Internal rate of return is a discounted rate (DR) at which net present value become zero. The greater the value of NPV and IRR, the better the system. If two system have equal ROI period, next criteria to be used for evaluation is IRR and then NPV. The results from NPV vs DR graph below show 51%, 71%, 79% and 83% IRR for SISO, MIMO, mmW band and mmW-MIMO respectively. It was noticed that the investment was profitable and feasible if the internal rate of return value was a higher percentage than defined discounted rate (discount factor 10%). Consequently, obtained internal rate of return value for all deployment scenarios are greater than 10%. As a results, all scenarios are economically feasible to implement them in the future, and the implementation can be done based on the requirements like performance and capacity for appropriate area.

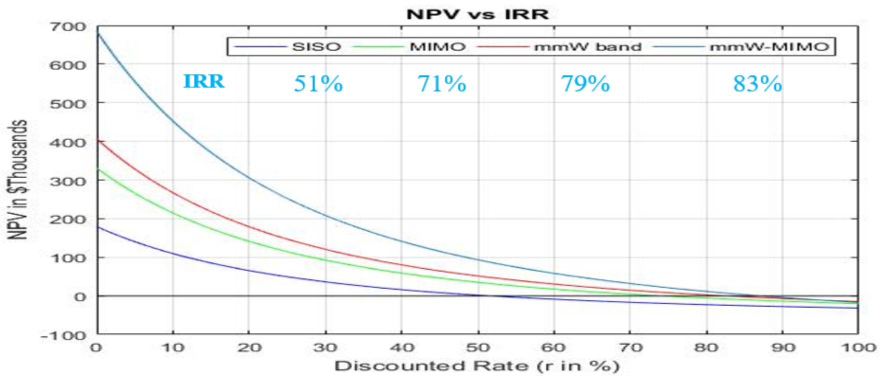

FIGURE 5.22: Net present value vs internal rate of return comparison across scenarios

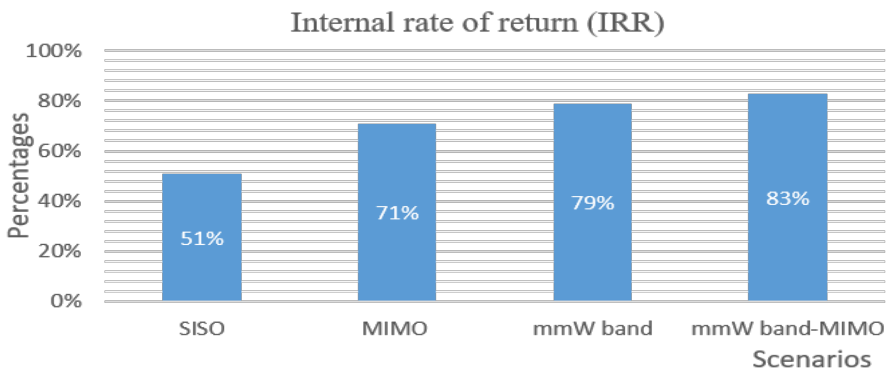

FIGURE 5.23: Internal rate of return (IRR) comparison across scenarios

Net present value

Net present value is the difference between the present value of cash inflows and the present value of cash outflows. Net present value trends in each year per each deployment scenario were estimated and presented below.

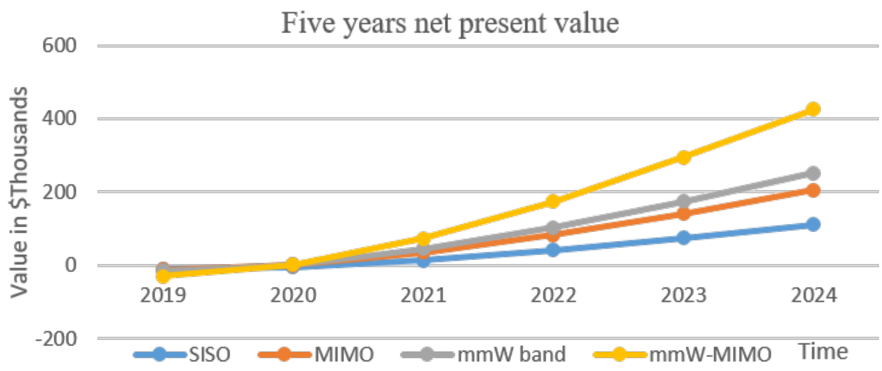

FIGURE 5.24: Net present value trends comparison across scenarios, five years

At the end of year one, net present value for SISO, MIMO, mmW band and mmW-MIMO are -$3,767.5, -$722.8, $2,285.88 and -$2,385.5 respectively. The results indicate that, all values are negative except for mmW band and show the need for more additional time to arrive at ROI period and then they are exponentially increasing to high positive value afterwards. Their respective values at the end of the study period are $111,354.45, $180,890, $252,612 and $376,394. The cost benefit of mmW-MIMO over SISO, MIMO and mmW band are 238%, 108.1% and 49% respectively. Recorded greater than zero net present value or positive value of each scenario for the study period show, economic feasibility of all scenarios.

Economic indicators

The most popular used economic feasibility indicators are the net present value (NPV), internal rate of return (IRR), and payback period (PBP) which are used to maximize the decision maker or indicators. All decision making economic indicators are summarized in the table below. The results in summary table indicate, positive net present value, greater

TABLE 5.4: Techno economic results of all deployment scenarios

Summary of TEA economic indicators; PBP in years/months					
Scenarios	Total TCO($)	Total Revenue($)	NPV($)	IRR(%)	PBP
SISO	57,914.2	237,251	111,354	51	1.426/17.11
MIMO	64,553	355,877.5	180,890	71	1.18/14.16
mmW band	67,669.16	474,503.33	252,612	79	0.9/10.8
mmW-MIMO	105,568.99	711,755	376,394	83	1.226/14.7

internal rate of return values than defined discounted rate (10%) and payback period in the range of 0.9 to 1.426 years for all scenarios which imply the feasibility of all scenarios. Regarding to TCO and revenue, SISO is the lowest with TCO and revenue, and mmW-MIMO is the highest in TCO and revenue. This is due to the dependency of cost and revenue on the performance of equipment.

5.3.2 Sensitivity Analysis

The purpose of sensitivity analysis is to study the impact of changes in the input assumptions on the profitability, (e.g. NPV), of the project. Sensitivity analysis was done on equipment costs, OPEX, TCO and revenue of basic scenarios, that is, system that operate at lower frequency (SISO) and that operate at higher frequency (mmW band).

As stated before in section 4.3, different costs are obtained from different vendors and average value was used for this work. To see the impacts of using average value, sensitivity analysis was done at minimum and maximum value of equipment costs. Figure 5.25 shows the sensitivity analysis done for lower frequency band (SISO).

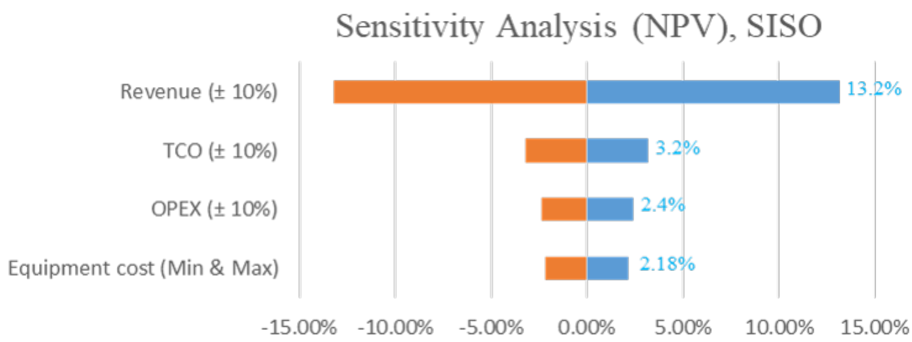

FIGURE 5.25: Sensitivity analysis (NPV) for SISO

Figure 5.26 shows the sensitivity analysis done for higher frequency band (mmW band).

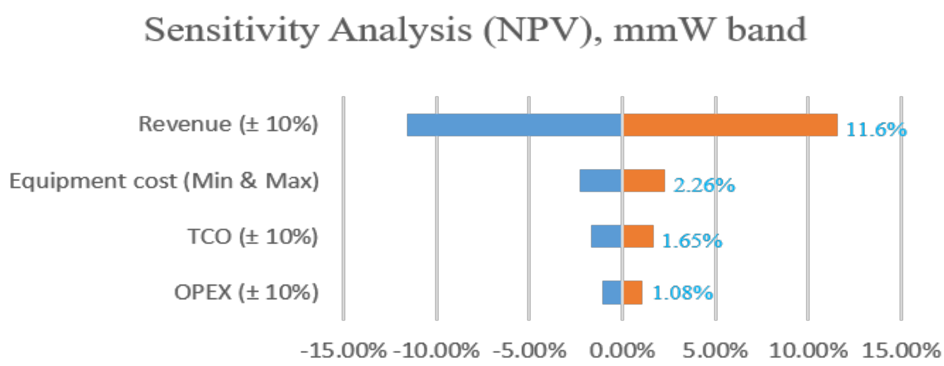

FIGURE 5.26: Sensitivity analysis (NPV) for mmW band

Regarding to equipment costs, the end values (minimum and maximum value) deviation from average value are 17% and 24% for lower (SISO) and higher (mmW band) frequency band respectively. Even if these values are higher than 10% that considered for other parameters, the effect of these deviations are 2.18% and 2.26% on NPV (from output of average value) for respective scenario which are less compared to the effects due to others. The impact of 10% deviation from average value result in less than 1% and can be concluded that, use of average value can't make that much effect compared to others or it has a least impact on the outputs.

Revenue and data rate are the most sensitive parameters compared to TCO, OPEX and equipment costs. The deviation of 10% from normal revenue can causes deviation of 13.2% and 11.6% on SISO's and mmW band's NPV respectively. In addition, revenue is more sensitive on SISO than mmW band but equipment is more sensitive on mmW band than SISO.The effects of TCO and OPEX on SISO scenario are 3.2% and 2.4% deviation on NPV due to 10% change respectively. But, they make 1.65% and 1.08% deviation on mmW band's NPV.

Result Summary

Concerning to existing microwave links in Addis Ababa, 94% and 100% of links are practically in applicable antenna separation height for lower frequency band (<5m) and E-band (<4m) respectively. But only 53.53% of links fit path loss requirements for E-band case. This is due to impacts of higher operating frequency and rain attenuation on path loss. Traffic data demands are increasing which maximize revenue for operator. The scenario with high performance costs more but make more money for the operator after time period. The real costs of wireless backhaul systems is an operational expenditure. Research results indicate that all scenarios arrive in less than 1.5 years return on investment period and all are feasible with respect to all economic indicators but need to implement them based on traffic requirement. Revenue is the most sensitive parameter over CAPEX, OPEX and TCO.

Chapter 6

Conclusion and Future Works

This chapter concludes the findings from research and recommends feasible scenarios to the operator. Finally, future works are presented for next researches.

6.1 Conclusion

The growth in data traffic volume from radio access network are increasing exponentially which in turn exert a pressure on backhaul network and force the operator either to optimize or upgrade its backhaul networks. But the choice of backhaul scenario or technology is a challenging one for a mobile operator because of many factors that have to be taken into account. The complexity, function, performance and costs of the technologies vary and to select the right option it needs a strategic decision. Capacity or performance, construction cost, quick deployment and flexibility in providing access to a range of services are typically the main determinants.

On the other hand, deployment of mobile technologies or network infrastructures in ethio telecom is commonly vendors driven, even without performing localized techno-economic assessments. These will cause underutilization and wastage of the resources, low performance of network and quality of service when the investments run or undergo the operations. Thus, techno-economic assessment is very essential and done to analyze the feasibility of scenarios technically and economically.

In this study, techno-economic analysis modeling approach has been considered and techno-economic evaluation of four possible scenarios, two from lower frequency band (SISO and MIMO) and two from high frequency band (mmW band and mmW-MIMO) have been done and presented. Techno-economic evaluation model was implemented in MATLAB and MS-excel.

All CAPEX, OPEX, TCO and revenue are modeled for all scenarios, and technical and economic feasibility of each deployment scenario was analyzed using popular economic feasibility indicators like NPV, IRR and payback period. Finally, sensitivity analysis was also done on equipment costs, OPEX, TCO and revenue to see their impacts on the output (NPV).

Conclusions drown from research:

- The advantages of full outdoor radio over other ordinary microwave systems motivate the operators migrate to full outdoor radio systems from ordinary one because of its energy saving, low cost, high gain, simplicity of deployment, management, maintenance, ease of capacity upgrading as needed and ease of upgrading to LOS-MIMO for further capacity enhancement. Therefore, this system is recommended for ethio telecom for its future deployment.
- Regarding feasibility analysis on existing links: the calculations of antenna separation length (for lower frequency bands) for 566 microwave links in Addis Ababa indicate that, 94% of the links are in applicable separation ranges (that is less than 5 meters). For the case of higher frequency band, 100% of the links are in applicable separation ranges which is less than 4 meters. The values indicate MIMO system is more suitable at higher frequency bands than lower frequency bands. For the feasibility of second antenna on both towers in each link, it needs physical investigation of the sites which is very difficult and complex to do.
  Concerning link availability: for the case of lower frequency bands, the links are already deployed and operational. In case of more fade margin requirement for MIMO case, the margin can be improved by increasing transmitter power and using antenna with higher gain. Regarding to millimeter wave band, 53.53% of the links fit the requirements. This is due to impact of high frequency band and rain attenuation on path loss.
- The results from TCO model within a five years study period show that, the operator is financially better off choosing SISO scenario over MIMO, mmW band and mmW-MIMO but with the lowest capacity or data rate compared to others. This is due to dependency of equipment cost on performance. Because, equipment costs have a direct relation with the performance, and the equipment with high performance or that supports high capacity costs more than others and vice versa.
- Regarding the results from OPEX and CAPEX models, looking primarily at CAPEX can be easier to say it is the dominant at initial period, but misleading! Impact of equipment cost is often overestimated. But their cost share from total cost (TCO) after study period is almost 70% and 30% respectively. This indicates, the real cost of

wireless backhaul is OPEX and operator should focus more on OPEX optimization to minimize expenditure and increase its revenue. This not mean ignore CAPEX costs!

- Traffic data demand is increasing with time due to growth of number of service users and data service usage which in turn increase the revenue for operator. Revenue is directly proportional to link capacity and data offered or delivered over the link. Five years study period results from revenue model indicate mmW-MIMO is the best scenario over other scenarios. mmW band, MIMO and SISO are ranked 2^{nd}, 3^{rd} and 4^{th} level, and their values are presented in Table 5.4. To further evaluate the scenarios, techno-economic analysis was performed and the evaluation is done based on economic indicators like NPV, IRR and payback period.
- The results from cash flow analysis indicate, the payback period of mmW band, MIMO, mmW-MIMO and SISO are 0.9, 1.18, 1.226 and 1.429 years respectively. The mmW band arrives at ROI earlier period than others but all are around one year. Their differences are counted in days or months. If ROI is critical, the operator can choose the scenario with lowest payback period.
- The results from net present value against different discounted rate show, internal rate of return values of all scenarios are greater than defined discounted rate (10%) and indicate the feasibility of all scenarios. Their values are, 51%, 71%, 79% and 81% for SISO, MIMO, mmW band and mmW-MIMO respectively. From the values it can be conclude that, mmW-MIMO is the best solution and SISO is ranked at the last level. mmW band and MIMO ranked 2^{nd} and 3^{rd} level.
- Five years study period show, positive value of NPV for all scenario which indicate the feasibility of all scenarios. Similar to IRR value, mmW-MIMO scenario is the best solution regarding to NPV than others and SISO is ranked at the last level. mmW band and MIMO are ranked 2^{nd} and 3^{rd} level. If ROI is not critical for the operator and prefers long time profit, the operator can choose the solution with highest IRR or NPV.
- SISO vs MIMO: SISO has an advantage of initial equipment costs or TCO over MIMO but MIMO has an advantages over SISO in all economic indicators like revenue, NPV, IRR and payback period in addition to capacity. The recommendation here is to deploy all outdoor radio system with multicore radio that support MIMO system. In this kind of system, radio unit can be set as a single core radio unit and capacity can be upgraded in different level based on requirement. Finally, other core of radio unit and MIMO feature can be enabled through software for further capacity increment. It can be also used for diversity purpose by muting MIMO feature.

- Regarding to mmW band vs mmW-MIMO: Currently, multicore radio unit that support MIMO is not found and instead 2+0 configuration was considered for cost analysis. If it is found in the future, the recommendation will be the same to MIMO case.
- Even if the average value of equipment was used for this economic analysis, the results from sensitivity analysis show that, its impact on output is the lowest compared to others. Revenue is the most sensitive parameters compared to equipment cost, OPEX and TCO. TCO, OPEX and equipment costs are ranked in 2^{nd}, 3^{rd} and 4^{th} levels.
- To summarize, all scenarios are feasible based on economic indicators. But, due to their difference in performance or capacity, they should be implemented based on performance requirements. Currently, mmW band (E-band) can support up to 10 Gbps with single 1+0 configuration and up to 20 Gbps with 2+0 configuration (mmW-MIMO). Similarly, SISO can support up to 2 Gbps with single configuration and up to 4 Gbps with LOS-MIMO application.

Recommendations

From results or economic indicators, if return on investment is critical, the operator can choose the solution with lowest payback period, that is mmW band. But if return on investment is not critical and long time benefit is considered, operator can choose the solution with higher in IRR and NPV, that is mmW-MIMO.

Currently, fully outdoor systems that operate at lower and higher frequency bands are available on the market . The author recommends ethio telecom to deploy these systems for it's future expansion. Millimeter wave band (E-band) system is recommended for condensed areas or where traffic data usage is fast growing. In addition, millimeter wave band can be applied at road crossing for high data transmission instead of drilling or cutting the road for optical transmission which is very expensive and for emergency communications at area where high mass of peoples gathered together. Lower frequency band system is recommended for the area where the traffic data rate growth is slow.

6.2 Future Works

The implemented techno-economic evaluation approach in this study was limited to point to point microwave system for four deployment scenarios that operate at lower and higher frequency band. It is possible to further go to point to multi-point microwave deployment scenario, and multi-band system that is implemented by combining the advantage at lower frequency band and higher frequency band for long and high capacity transmission usage.

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