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

Techno-Economic Investigation of LTE-Advanced Deployment for Addis Ababa, Ethiopia

By

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Advisor

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A thesis submitted to the School of Electrical and Computer Engineering in Fulfillment of the requirements for the Master of Science in Telecommunications Engineering, Telecom Network Engineering Track.

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Dean, School of Electrical and Computer Engineering

Declaration

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

Gizachew Hailegebriel Mako ____________________

Signature

Addis Ababa

Date of submission: November 15, 2018

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

Beneyam Berehanu Haile (PhD) ________________

Signature

Abstract

Due to innovative data services, the number of mobile subscriptions and amount of mobile data traffic will increase significantly globally. According to Ericsson mobility report, in 2022 the number of mobile data subscribers and traffic is forecasted to reach 9 billion and 71 Exabyte per month, respectively, from the current 7.5 billion and 8.8 Exabyte per month. Likewise, the report presented that Sub-Saharan Africa will also show a faster growth rate than any other region in the globe. 2018's Ericsson interim mobility report shows, Ethiopia is among five countries in the world that score high in mobile subscription growth. In addition, when we see historical records, market potential, and various telecom expansion plans of the country, mobile subscriber and traffic growth is expected in Ethiopia, particularly in Addis Ababa city. To accommodate the increasing mobile traffic, beside Long Term Evolution (LTE), several operators are deploying and optimizing LTE-Advanced and LTE-Advanced Pro mobile technologies. Having partially deployed LTE network in Addis Ababa, ethio telecom has not yet moved to LTE-Advanced but now considers to accommodate significantly increasing mobile subscribers, traffic and future demand of the city. To that end, there is a need of understanding techno-economically viable LTE-Advanced deployment scenarios for the local context.

In this thesis, feasible LTE-Advanced deployment options are developed using scenario planning method. Following, TERA Techno-economic Analysis framework and methodologies are investigated and modified to evaluate possible LTE-Advanced deployment scenarios techno-economically assuming 6 years study period and 10% discount rate. In the framework market analysis and LTE-Advanced radio network dimensioning performed using COST-231 Hata model; existing LTE traffic, standard and demography analysis is conducted for macro and small cells, respectively. In addition, the required bandwidth for the study period is forecasted and determined. Based on resulted Net Present Value and Payback Period of techno-economic evaluation, an LTE-Advanced scenario that applies progressive deployment with out-of-band small cells is feasible for Addis Ababa but not the case for a scenario that applies full deployment with out-of-band small cells. In both scenarios it is shown that LTE-Advanced is feasible if deployed in dense urban and urban areas.

Keywords—LTE-Advanced, Carrier Aggregation, small cell, TEA, TERA, Scenario planning

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List of Acronyms

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACTS	Advanced Communications Technology and Services
ACK	Acknowledgment
ARPU	Average Revenue per User
AS	Access Stratum
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BS	Base Station
BTS	Base Transrecieve Station
CA	Carrier Aggregation
CBS	Coordinate Beam forming and Scheduling
CAPEX	Capital Expenditure
CC	Component Carrier
CC&B	Customer Care & Billing
CDMA	Code Division Multiple Access
CCCH	Common Control Channel
CFI	Control Format Indicator
CIF	Carrier Indicator Field
CoMP	Coordinated MultiPoint
CMC	Connection Mobility Control
CQI	Channel Quality Indicator
CRS	Cell specific RS
DCI	DL Control Information
DL	Down Link
DL-SCH	DL Shared Channel
DCCH	Dedicated Control Channel
DM-RS	Demodulation RS
DRA	Dynamic Resource Allocation
DSL	Digital Subscriber Line
DTCH	Dedicated Traffic Channel
DwPTS	DL Pilot Time Slot
DWDM	Dense WDM
EDGE	Enhanced Date rate for GSM Evolution
eNodeB	enhanced NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
FDMA	Frequency Division Multiple Access

GP	Guard Period
GPRS	General Packet Radio System
GSM	Global System for Mobile Communication
GTP	GPRS Tunneling Protocol
HARQ	Hybrid Automatic Repeat reQuest
HC	Handover Control
HSDPA	High Speed DL Packet Access
HSUPA	High Speed UL Packet Access
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
ICT	Information Communication Technology
IEEE	Institute of Electrical and Electronics Engineering
IMT	International Mobile Telecommunications
IRR	Internal Rate of Return
JP	Joint Processing
KPI	Key Performance Indicator
LA	Link Adaptation
LOS	Line of Sight
LTE	Long Term Evolution
LTE-A	LTE Advanced
MBH	Mobile Backhaul
MBSFN	Multicast Broadcast Single Frequency Network
MCCH	Multicast Control Channel
MIMO	Multi Input Multi Output
MU-MIMO	Multi User-MIMO
MW	Micro Wave
MME	Mobility Management Entity
NACK	Non-ACK
NAS	Non-AS
NLOS	Non-LOS
NPV	Net Present Value
OFDMA	Orthogonal Division Multiple Access
OPEX	Operational Expenditure
OSS	Operation Support Subsystem
PA	Power Allocation
PCCH	Paging Control Channel
PCFICH	Physical CFI Channel
PCH	Paging Channel
PCRF	Policy and Charging Rule Functions
PDCCH	Physical DL Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical DL shared Channel

P-GW	Packet Gateway
PON	Passive Optical Network
PMP	Point to Multipoint
PRACH	Physical RACH
PRB	Physical RB
PS	Packet Scheduling
P-SCH	Primary Synchronization Channel
PTP	Point to Point
PUCH	Physical UL Shared Channel
PUCCH	Physical UL Control Channel
OTT	Over the Top
QoS	Quality of Service
RAC	Radio Admission Control
RACH	Random Access Channel
RB	Resource Block
RDS	Radio Dot System
RE	Resource Element
RLC	Radio Link Control
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RS	Reference Signal
SC-FDMA	Single Carrier FDMA
SCTP	Stream Control Transmission Protocol
S-GW	Serving Gateway
SINR	Signal Interference and Noise Ratio
SMS	Short Message Service
SU-MIMO	Single User-MIMO
TDMA	Time Division Multiple Access
TEA	TE Analysis
TEP	Telecom Expansion Project
TERA	Techno-Economic Results from ACTS
TM	Transmission Mode
TTT	Time to Trigger
UCI	UL Control Information
UE	User Equipment
UL	Up Link
UL-SCH	UL Shared Channel
UMTS	Universal Mobile Terrestrial System
UpPTS	UL Pilot Time Slot
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing

1

Introduction

1.1. Background and Motivation

Over the years, users' requirements for higher data rates, access to new and innovative services and applications like High Definition (HD) videos that demand higher bandwidth and network capacity have resulted in a faster and continuous evolution of wireless technologies [1, 2]. Reports by [4, 8 and 74] indicate, in 2022 the number of mobile subscriptions and data traffic will reach 9 billion, of which 5 billion i.e. 56% are 4G subscribers, and 71 Exabyte, in which 50% of the traffic shared by online video streaming, worldwide respectively, from the current 7.5 billion and 8.8 Exabyte. According to [8, 9 and 55], the number of mobile subscription in Africa is the fourth highest in the global range and the Third Generation (3G) and Fourth Generation (4G) mobile networks overtakes that of Second Generation (2G). The report also showed, the Sub-Saharan Africa region growing in a faster rate than any other region in the globe and Ethiopia is one of the four countries, following the Democratic Republic of Congo, Tanzania, and Nigeria that will yield half of the mobile subscription in the Sub-Saharan-Africa. Local reports also indicate, the number of mobile subscribers in Ethiopia is growing exponentially and in the first quarter of 2018 it have reached 60 million with 80 million network capacity [3]. Similar trend shows, mobile subscribers as well as data traffic are also increasing in the city of Addis Ababa [3, 4, 8 and 55].

Ethio telecom is providing data services for Addis Ababa users using 2G, 3G mobile technologies and, later by deploying Long Term Evolution (LTE) to offer enhanced data services for selected areas of Addis Ababa. However, mobile broadband demand expected to increase for the coming years as it promotes Growth Domestic Product (GDP) growth, creates jobs, stimulates innovation and improve education, health care and other social services. In addition, the city's market potential and various economic plans of the country indicate that the demand cannot handled only by the existing network and signals ethio telecom to have future-proof mobile network.

The above discussion make clear that apps, services and subscribers keep on evolving and growing as well as the demand for digital content is expected to increase mobile data traffic significantly in the coming years as well as the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) cost. Moreover, the revenue generated and the sectors contribution to the GDP of the nation [8, 9]. Thus, it will became difficult to handle the subscriber and traffic growth by only the existing networks, therefore it will then necessities an efficient and high capacity mobile network. To cope with the increasing demand operators are deploying and plan to deploy LTE Advanced (LTE-A) worldwide. LTE-A is the fastest, i.e. 3x faster than LTE, more reliable mobile access technology, easy to integrate with the existing LTE or other 3rd Group Partnership Project (3GPP) network such as it has reduced power consumption in transmission and reception, and reduced carbon emission footprint than earlier technologies. Its features, Carrier Aggregation (CA), enhanced multi-antenna technique, Heterogeneous Network (HetNet) and Coordinated Multipoint (CoMP) provides a high performance and puts it as prime target for the ever-growing data demand [2, 9, 12 and 20]. In addition, it is robust for interference, have fewer dropped connections during mobility, i.e., smoother handoff during traveling between cells and capable of packing more speed into the same amount of spectrum.

On the other hand, however, pre-deployment analysis is an imperative decision that a new technology that is about to be introduced to the market have to be investigated for its significance. Technologies varies in network functionality and cost, so that a detailed study is crucial for operators due to the high cost of network elements. Therefore, feasible LTE-A deployment options have to be developed using scenario planning analysis and viability of the selected scenarios explored techno-economically. Engaging in Techno-economic Analysis (TEA) assists ethio telecom to properly identify network functionalities, manage and utilize resources and it plays a vital role in strategic planning as well as for decision making [6, 10, and 53].

1.2. Statement of the Problem

Ethio telecom is investing hugely in mobile technologies to provide services to its end-users. However, technologies deployed without detailed investigation and decisions are made deprived of techno-economic analysis. Such traditions contributed to observed system performance and efficiency problems such as interference, reduced capacity and underutilization, for example in 3G and LTE networks that affects Quality of Service (QoS), degrade end-user experience, wastage of resources and stimulate ethio telecom from getting more revenue and causes a high CAPEX and OPEX cost. Furthermore, the impact stemmed from lack of proper assessment ranges from individual to national stage as benefit of mobile broadband stretch from personal development to high contribution to country's Growth Domestic Product (GDP) and affects Ethiopia's Growth and Transformation Plan (GTP), as the telecom sector is part of the development plan, consequently showing importance of reviewing technologies techno-economically. Deploying LTE-A as a future-proof network for the increasing demand bounded by uncertainties related with technology feature, cost, resources, user adoption and availability of capable devices. Moreover, deploying it cannot guarantee its viability and acceptance by end-users and from the technology point of view it is unclear which feature of LTE-A can fit with the local context. Therefore, formulating the viable LTE-A deployment scenarios and determining their feasibilities by applying TEA is beneficial.

1.3. Objective

1.3.1. General Objective

This thesis performs techno-economic investigation of LTE-A deployment for Addis Ababa.

1.3.2. Specific Objectives

In particular, the following specific objectives are set:

- ✓ Investigates trends and uncertainties on deploying LTE-A using literatures, standards, and state-of-the-art and plan scenarios to determine LTE-A implementation options.
- ✓ Determine appropriate deployment preference for the selected scenarios and investigates on the utilization of the existing resources for LTE-A.
- ✓ Investigates the existing TEA frameworks, select suitable framework for this thesis and develop TEA tool based on the selected framework.
- ✓ Perform coverage and capacity for macro cell and small cells dimensioning to figure-out the required number of network elements and CAPEX and OPEX.
- ✓ Perform spectrum dimensioning to determine the necessitated bandwidth for the defined period of time.

- ✓ Perform market analysis to forecast and determine subscribers, ARPU, market share and data plan.
- ✓ Based on dimensioning, market analysis and economic inputs, perform cash flow and discounted cash flow analysis.
- ✓ Determine the LTE-A viability applying key decisions parameters and developed TEA tool.

1.4. Methodology

In this thesis much of the work related with detailed literature review by referring standards, publications, vendor reports and related works, therefore, the data source for this thesis relied on LTE-A books, IEEE articles and journals, 3GPP documentations, International Telecommunications Union (ITU) publications and TEA focused dissertations. In addition, ethio telecom documents and project reports are used. Following, scenario planning method applied based on [5, 6, 53, 67, 75 and 83]. Scenario planning is a tool for exploring, analyzing trends, managing uncertainties and disruptiveness of new technologies. Then, the existing ethio telecom spectrum holding investigated and 900, 1800 and 2100MHz bands selected based on their performance and analyzed to identify applicable LTE-A deployment options for Addis Ababa based on 3GPP Technical Specification 36.101 Release 14 (3GPP TS 36.101 R'14).

After relevant deployment options identified, they are investigated using TEA model to seek the economic feasibility of LTE-A. To evaluate selected deployment options in technical and economic terms, different TEA frameworks studied and TERA framework selected for this thesis relying on its applicability in wireless telecommunication sector [83, 89] with 6 years study period and 10% discount rate as an economic input. The framework takes technical and economic inputs and it is modified to include forecasting results such as subscriber, Average Revenue per User (ARPU) and bandwidth required. In addition, a parameter called Efficiency added targeting to increase system performance and reduce cost.

Following, dimensioning performed using COST-231 Hata model and excel based link budget for coverage and forecasted subscribers, cell capacity and data plan for capacity dimensioning for the selected scenarios. To dimension the required indoor and outdoor small cells existing LTE traffic, standard, product survey, demography analysis and forecasted subscribers while ITU-T forecasting method adopted to determine spectrum required for six years study period. Market analysis is performed to obtain target subscribers, market share, device penetration and ARPU. The potential subscriber for Addis Ababa city forecasted taking the existing 3G and LTE subscribers, assuming growth margin and using Bass forecasting method, which helps to explore market potential of new technologies. And taking last ten years ethio telecom subscriber and profit trend and market share of mobile users exponential regression applied to see ARPU growth trend and predicted for the study period. As part of market analysis, the availability and capability of LTE-A devices and survey of small cells for the indoor and outdoor areas also conducted.

The corresponding CAPEX and OPEX cost derived from [3, 65, 85 and 86] and taking technical and market analysis inputs cost and revenue modelling employed in the developed excel based TEA tool for this thesis. The cash flow analysis and discounted cash flow analysis performed using modelling results and economic inputs. Finally, Net Present Value (NPV), Cash Flow (CF) analysis, Discounted CF (DCF) analysis and Payback Period (PP) generated to determine viability of selected LTE-A deployment scenarios for Addis Ababa.

1.5. Contribution

As mentioned in the objective section, this research performs TEA for the deployment of LTE-A by applying the methodologies stated in the above section. A scenario planning developed to identify possible deployment scenarios for Addis Ababa. In addition, to determine the feasibility of the investment TERA framework modified and applied, further a new tool developed grounding on the framework. Afterward, feasible deployment options investigated techno-economically that can be used as an input for the next expansion projects and management decisions. In general, the results obtained in this thesis work can be used as an input for operators, regulators and for the research community.

1.6. Scope and Limitation

The scope of the thesis is to investigate the viability of LTE-A deployment options for Addis Ababa city from the economic and technical perspective using TERA TEA framework. It gives insight into the importance of LTE-A technology and its evaluation in technical and economic values. The thesis plans relevant scenarios, perform dimensioning for macro cell, small cell and spectrum together with market analysis. It then, engage in techno-economic evaluation using the developed TEA tool to determine the feasibility of the selected scenarios by scenario planning method. The thesis only considers LTE-A deployment scenarios for data service. As limitation, unable to get all TERA deliverables as it is industry specific and not accessed for external users. Other limitation is small cell dimensioning result as it takes limited data such as sample areas, assumptions and recommendations to obtain the required number of cells.

1.7. Related Literature Review

The succeeding paragraphs present the summary of reviewed papers on challenges, opportunities and how other operators perceive the implementation of LTE-A.

The author in [6], explain the TEA on deploying LTE-A by analyzing the following inputs and their results: (1) Area modelling and population density as one factor (2) service and demand assumption and penetration (3) tariff assumptions and data plan marketing (4) network dimensioning both coverage and capacity driven results (5) CAPEX based on assumptions made annual breakdown of components like spectrum fee, LTE eNodeB, Mobility Management Entity (MME), etc. and OPEX costs such as maintenance, site rental, leased line rent and energy consumption. Based on the applied assumptions the investment starts profiting after 6 years of investment. Finally, the author conclude that, LTE-A is the right solution to the ever-growing data demand for higher data rates, high-capacity and spectrum flexibility with reduced CAPEX and OPEX.

In [7], the authors analyze an operators' investment view on "Build it and they will come" approach. Higher speed, faster connection times and fewer latency features of the 4G network attracts data users to choose it over the existing broadband mobile network like HSPA, but only this advantage and operators' blind move towards investment cannot charm users. Based on market survey they conducted, taking sample 4G operators around the world and depending operators commercial goals, they have identified key points that have to be considered during strategic marketing decisions before migrating to 4G: (1) pricing plan – the benefits of 4G should be leveraged to introduce QoS differentiation and achieve price uplift vs. other mobile broadband (MBB) offers and subsidizing user equipment and less data price compared to 3G (2) Education – the advantage of 4G should be clearly communicated so that customers understand the benefits and incentivize migration from 3G to 4G.

In [10], the author emphasizes the importance of one of the features of LTE-A, CA to fulfill high data requirement, by considering the following scenarios: (1) two frequency bands 700 and 2600MHz (2) planning using single carrier, contiguous CC, inter-band CC using those bands (3) using the existing network or deploying new BS. Then estimate the cost of building out LTE-A network using CA. The writers perform TEA taking the cost of devices required for CA, cost of UE, population density and assuming a market share. LTE systems that use CA can have better performance than using a single carrier and will allow more access to MBB applications that require high peak rate. In addition, aggregating carriers from multiple bands could permit a system to have a better performance.

1.8. Thesis Layout

The research consists of eight chapters. *Chapter One* states background and motivation, problem statement, objectives, methodologies, contribution, scope and limitation and selected related literature review. *Chapter Two* introduces LTE-A in detail and a brief summary of mobile technology evolutions. TEA framework and modeling are presented *Chapter Three*. *Chapter Four* reviews trends about the deployment of LTE-A, select uncertainties that can impact LTE-A deployment and plan scenarios for possible and practical deployment options. *Chapter Five* discusses the applied TEA framework and developed tool with its inputs for techno-economic evaluations. *Chapter Six* performs network and spectrum dimensioning. Based on the outputs from the earlier chapters, *Chapter Seven* states result and discussion. Finally, *Chapter Eight* presents a concluding remarks for the research and recommendations for future works.

2

LTE-Advanced Network

2.1. Evolution of Mobile Technologies

Mobile telecommunication systems were first known in the early 1980s with the introduction of first generation (1G) systems. It was based on analog communication techniques similar to those used by a traditional analog radio [11]. The cell towers were large and the systems did not use the available radio spectrum efficiently, so their capacity was limited. The mobile devices were large and expensive and were marketed almost exclusively for business users [11]. In 1990s 2G was introduced, called first to use digital technology, which permitted a more efficient use of the radio spectrum and the introduction of smaller and cheaper devices. 2G were originally designed for voice but later enhanced to support instant messaging through the Short Message Service (SMS). The most popular 2G system was the GSM, which was originally designed as a pan-European technology, but which later became popular throughout the world. Next, 2.5G or General Packet Radio Service (GPRS) was built relying on 2G system, by changing the core network to packet switched domain and by modifying the air interface so that it could handle data as well as voice. At the same time, the data rates available over the Internet were progressively increasing and to mirror this, designers first improved the performance of 2G systems using techniques such as Enhanced Data Rates for GSM Evolution (EDGE) and then introduced 3G systems in the years after 2000.

3G systems use WCDMA techniques for radio transmission and reception unlike 2G's Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA), which increases the peak data rates and enhance radio spectrum usage. The Universal Mobile Telecommunication System (UMTS) is the dominant 3G system evolved from GSM by completely changing GSM air interface, while keeping the core network almost unchanged. The system was later enhanced for data applications, by introducing the 3.5G technologies of High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA), which collectively known as High-Speed Packet Access (HSPA) [1, 2, 11]. Then LTE developed by 3GPP by completely changing the air interface and core network.

2.2. LTE

2.2.1. Motivation

For many years, voice calls dominated the traffic in mobile telecommunication industry because the growth of mobile data was initially slow [11]. However, the story reversed and data overrun voice service as the technology advances and because of variant availability of 3.5G communication technologies and services. As a contributing factor, network operators had previously tried to encourage the growth of mobile data by the introduction of flat-rate charging schemes that permitted unlimited data downloads. That led to a situation where neither developers nor users were motivated to limit their data consumption. As a result, 2G and 3G networks started to become congested in the years around 2010, leading to a requirement to increase network capacity. Also, three other issues have driven the move to LTE. First, a 2G or 3G operator has to keep up two core networks i.e. the circuit switched domain for voice, and the packet switched domain for data. Provided that the network is not too congested, however, it is also possible to transport voice calls over packet-switched networks using techniques such as Voice over Internet Protocol (VoIP) such that the operators can move everything to the packet switched domain, and can reduce both their CAPEX and OPEX. The second motivation was the target to reduce end-to end delay or latency. 3G networks experience delays of the order of 100ms for data applications, in transferring data packets between network elements and across the air interface. As this barely acceptable for voice and causes difficulties for applications such as real-time interactive games. Thirdly, the specifications for UMTS and GSM have become increasingly complex over the years, due to difficulties to add new features to the system while maintaining backward compatibility with earlier devices.

2.2.2. LTE Network Overview

The multiple-access scheme in the LTE downlink (DL) uses Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) also called DFT (Discrete Fourier Transform) in the uplink (UL) with Cyclic Prefix (CP), as shown in Figure 2.1. OFDMA and SC-FDMA provide orthogonality between users, reducing interference and improving network capacity [11-13].

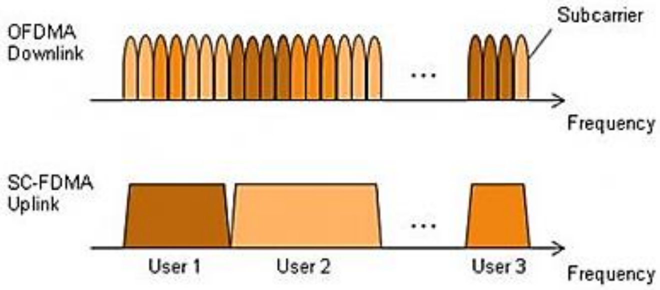


Figure 2.1. LTE multiple access schemes [13]

Resource allocation in the frequency domain takes place with the resolution of 180 KHz Resource Blocks (RB) both in UL and DL. The uplink user specific allocation is continuous to enable single-carrier transmission, whereas the downlink can use RBs freely from different parts of the spectrum. The UL single-carrier solution is also designed to allow efficient terminal power amplifier design, which is relevant for terminal battery life. The LTE solution enables spectrum flexibility, ranges between 1.4MHz and 20MHz depending on the available spectrum [13].

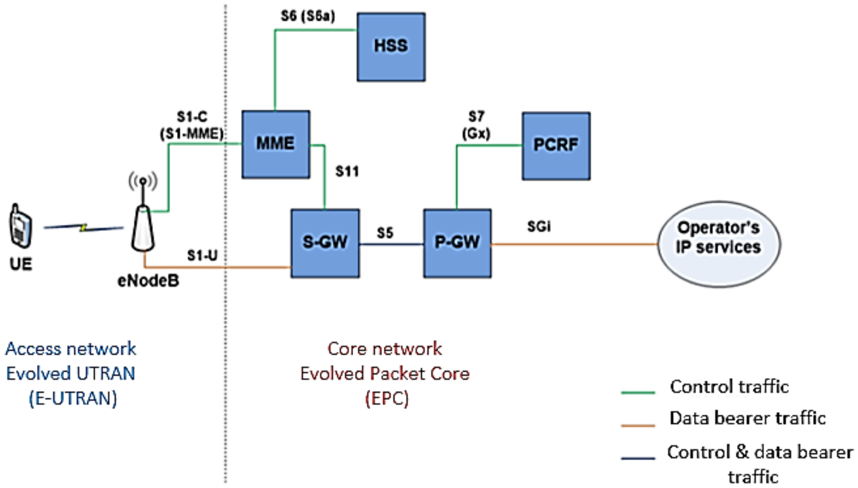


Figure 2.2. LTE network architecture [1, 2]

Evolved Packet System (EPS) is the evolution of the 3G systems introduced by 3GPP [13, 14]. The network core part of EPS, called Evolved Packet Core (EPC) or System Architecture Evolution (SAE), designed to be a completely IP-centric network that provide QoS support and ensures revenue and security [12]. It consists of enhanced NodeBs (eNodeBs) at the RAN, and Mobility Management Entities (MMEs), Serving Gateways (S-GW), Packet Data Network Gateway (P-GW), Home Subscriber Server (HSS) and Policy and Charging Rule

Functions (PCRF) at the core, Figure 2.2. The eNodeBs interconnect through an interface called the X2 interface, while they are connected to entities at the core network using the S1 interface [12]. An eNodeB would handle functionalities such as radio access control, scheduling, measurements at the radio interface, admission control, mobility control and inter-cell radio resource management. The MME, S-GW and P-GW would oversee functionalities such as mobility anchoring, NAS security, mobility while the User Equipment (UE) is in the idle state, and IP address allocation and packet filtering. Whereas, HSS is the concatenation of the HLR (Home Location Register) and the AuC (Authentication Center), gives user identification and addressing, user profile information, mutual network-terminal authentication and radio path ciphering and integrity protection and PCRF support service data flow detection, policy enforcement and flow-based charging.

2.2.3. LTE Protocol Stack

LTE maintains a 3GPP split between two protocol planes, the user plane and the control plane, Figure 2.3 [12, 14].

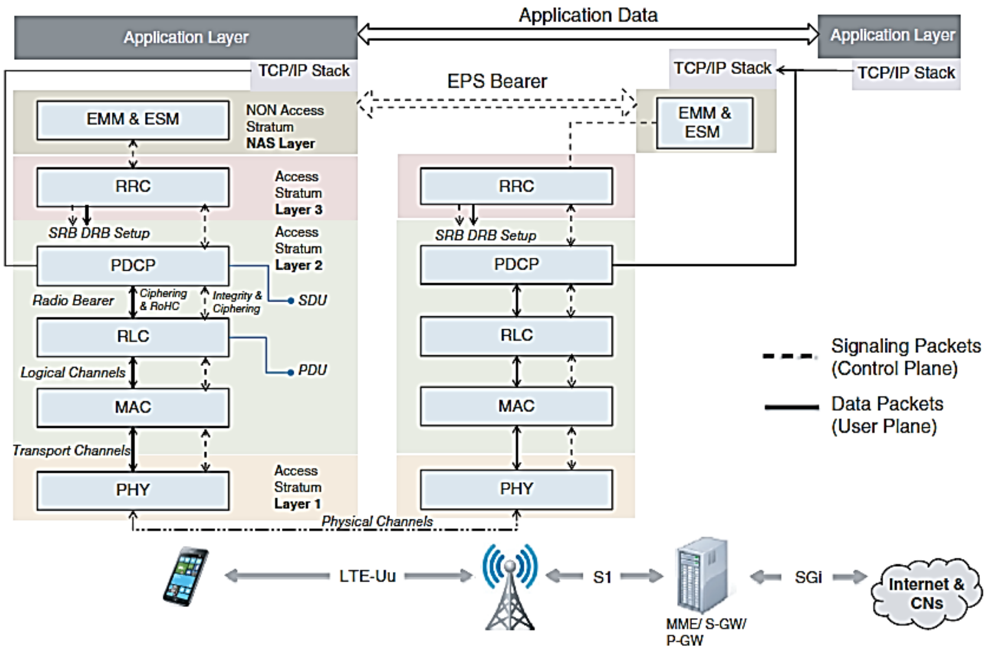


Figure 2.3. LTE protocol stacks [14]

The user plane signaling is provided by the Access Stratum (AS) and carries signaling between the UE and the eNodeB while control plane carries Non-AS (NAS) signaling messages between the UE and the MME, which is piggybacked into an RRC message. The user plane delivers the IP (Internet protocol) packets to and from the EPC, the S-GW and the PDN-GW [14]. The MAC (Media Access Control) performs several functions, including the mapping between logical and transport channels, multiplexing MAC SDUs, relaying scheduling information, error correction (HARQ), and priority handling [18]. The Radio Link Control (RLC) performs error correction (ARQ); concatenation, segmentation and reassembly for RLC SDUs; in addition to reordering and duplication detection. The Packet Data Convergence Control (PDCP), the higher sub layer in layer 2, mainly oversees ciphering and integrity protection, and transfer of control plane data. The Radio Resource Control (RRC) is the RAN component of the control plane and is responsible for the main control functionalities including broadcast of system information related to both the AS and NAS, paging, establishing RRC connectivity between UE and the EUTRAN, security and mobility management functionalities, QoS management and transfer of NAS message [12-14].

2.2.4. LTE Interfaces

The S1-U relies on the GPRS Tunneling Protocol (GTP) which, in turn, relies on User Datagram Protocol (UDP). The S1-C, however, is defined between the eNodeB and the MME, and utilizes the more reliable Stream Control Transmission Protocol (SCTP) for transferring signals [12]. EPC performs the main network management functions including radio access bearer management functions; mobility functions in instances of intra-LTE and inter-3GPP RAT handovers; paging; user context setup, management and transfer, and load balancing between MMEs through S1 [12]. The X2 interface, also has user and control planes. As in the S1-C, the user plane in X2 delivers user plane data in a non-guaranteed fashion based on a GTP/UDP stack, while control plane signaling depends on SCTP for reliable delivery. The control plane functionalities overseen by the X2 interface includes intra-LTE mobility support, load management between eNodeBs, and general X2 management and error handling functions [12].

2.2.5. LTE Frame Structure

The LTE frame structures are of two types based on the duplexing scheme, either FDD or TDD, Figures 2.4 and 2.5 [12]. Total Frame duration is about 10ms, there are a total of 10 subframes in a frame each composed of 2 time slots (Ts).

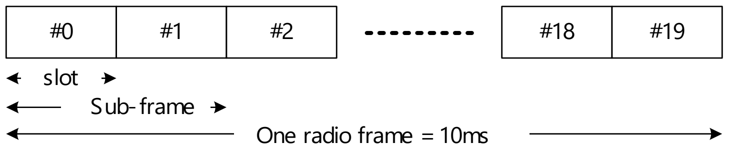


Figure 2.4. Type 1 or FDD frame structure [12, 17]

In Type 1 frames, DL and UL transmissions use two different frequency bands, hence frames are not shared between the two. A frame made of total 20 slots, each of 0.5ms. Two consecutive time slots will form one subframe and 10 such subframes form one radio frame with subframe duration of 1ms. Each radio frame will have 307200 Ts, where one Ts equals 1/ (15000 x 2048) seconds [12, 17].

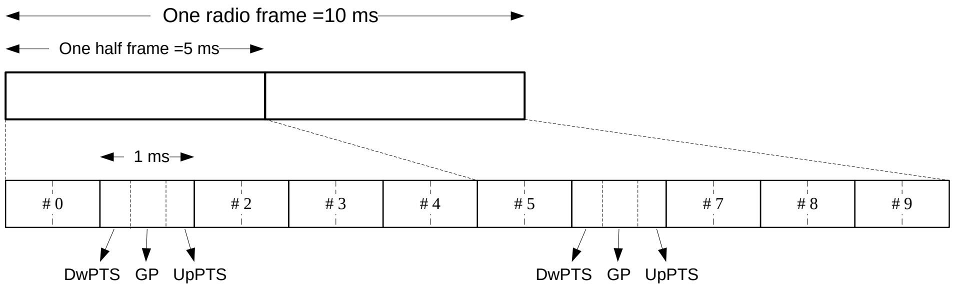


Figure 2.5. Type 2 or TDD frame structure [12, 17]

Type 2 LTE frame structure is an application to TDD system [12]. The radio frame composed of two half frames, each of 5ms duration resulting in total frame duration of about 10ms. Each radio frame will have total 10 subframes, each subframe will have 2 time slots. Subframe configuration is based on UL-DL configuration (0 to 6). Usually in all the cases, subframe #0 and subframe#5 is always used by DL. The Special subframe carries DwPTS (DL Pilot Time Slot), GP (Guard Period) and UpPTS (UL Pilot Time Slot). For the 5ms DL to UL switch point periodicity case, SS (Special subframe) exists in both the half frames. For the 10ms DL to UL switch point periodicity case, SS exists only in the first half frame. The DwPTS considered as an ordinary DL subframe, that is, 1ms, and can be used for DL transmission. It may also be of a shorter duration, as it can vary from three to twelve OFDM symbols. The main difference between an ordinary DL subframe and the DwPTS is the number of controls OFDM symbols. While the DwPTS has two control OFDM symbols; an ordinary DL subframe would have three symbols. This difference is because of the location of the primary synchronization signal (P-SCH), which is located at the third OFDM symbol in the DwPTS. This difference in location enables the UEs to detect the type of duplexing implemented at the cell during network entry. The synchronization signal in FDD is located at the middle of subframe 0 and subframe 5. The GP is reserved for downlink to uplink transition [12, 17].

2.2.6. LTE Channels

In order to transport data across the LTE radio interface, various channels are involved to segregate the different types of data and allow them to be transported across RAN in an orderly fashion. Effectively the different channels provide interfaces to the higher layers within the LTE protocol structure.

2.2.6.1. Logical and Transport Channels

MAC layer offers services to the RLC in the form of logical channels [16]. They are distinguished by the information they carry and classified in two ways, logical traffic/control and dedicated/common logical channels [12]. Logical traffic channels carry data in the user plane, while logical control channels carry signaling messages in the control plane and dedicated logical channels are allocated to a specific mobile, while common logical channels can be used by more than one. On the other hand, transport channels are defined by how and with what characteristics the information is transmitted over the radio interface [13]. Table 2.1 lists the logical and transport channels used by LTE

Table 2.1 LTE Logical and transport channels and their functions [17]

Channel	Name	Information carried	Description
		Logical channels	
DTCH	Dedicated Traffic Channel	User plane data	Carries data to or from a single mobile [UL, DL]
DCCH	Dedicated Control Channel	Signaling on SRB 1 and 2	Carries all the mobile-specific signaling messages on signaling radio bearers (SRB) 1 and 2, for mobiles that are in RRC_CONNECTED state [UL, DL]
CCCH	Common Control Channel	Signaling on SRB 0	Carries messages on SRB 0, for mobiles that are moving from RRC_IDLE to RRC_CONNECTED in the procedure of RRC connection establishment [UL, DL]
PCCH	Paging Control Channel	Paging messages	Carries paging messages, which the BS transmits if it wishes to contact mobiles that are in RRC_IDLE [UL, DL]

BCCH	Broadcast Control Channel	System information	Carries RRC system information messages, which the BS broadcasts across the whole of the cell to tell the mobiles about how the cell is configured [DL]
MCCH	Multicast Control Channel	MBMS signaling	To handle a service known as the multimedia broadcast/multicast service (MBMS) [DL]
Transport channels			
UL-SCH	UL shared Channel	UL data and signaling	Carry the large majority of data and signaling messages across the air interface [UL]
RACH	Random Access Channel	Random access requests	A special channel through which the mobile can contact the network without any prior scheduling [UL]
DL-SCH	DL shared Channel	DL data and signaling	Carry the large majority of data and signaling messages across the air interface [DL]
PCH	Paging Channel	Paging messages	Carries paging messages that originated from the paging control channel [DL]
BCH	Broadcast Channel	Master information clock	carries the broadcast control channel's master information block [DL]

2.2.6.2. Physical Data and Control Channels

Physical channels are transmission channels that carry user data and control messages [11]. Table 2.2 summarizes common physical data and control channels in LTE. Each channels are mapped and the mapping between logical, transport and physical channels illustrated in Figure 2.6.

Table 2.2 Physical data and control channels and functions [17]

Channel	Channel type	Name	Information carried	Description
PUSCH	Data	Physical UL shared Channel	UL channel information	Carries data and signaling messages from the uplink shared channel and can sometimes carry the uplink control information (UCI) [UL]
PDSCH	Data	Physical DL shared Channel	DL channel information	Carries data and signaling messages from the downlink shared channel, as well as paging messages from the paging channel. [DL]
PRACH	Data	Physical Random Channel	RACH	Carries random access transmissions from the random-access channel [DL]
UCI	Control	UL control information	UL control information	Hybrid ARQ acknowledgements UL Channel quality indicators (CQI)Pre-coding matrix

				indicators (PMI) Rank indications (RI) Scheduling requests (SR)
DCI	Control	DL control information	DL control information	Downlink scheduling commands UL scheduling grants UL power control commands [DL]
CFI	Control	Control format indicator	Size of DL control region	Tell the mobiles about the organization of data and control information on the downlink [DL]
PUCCH	Control	Physical UL control channel	UCI	Sent on the PUSCH if the mobile is transmitting uplink Data [UL]
PDCCH	Control	Physical DL control channel	DCI	Carry the downlink control information [DL]
PCFICH	Control	Physical CFI channel	CFI	Carry control format indicators and hybrid ARQ indicators [DL]

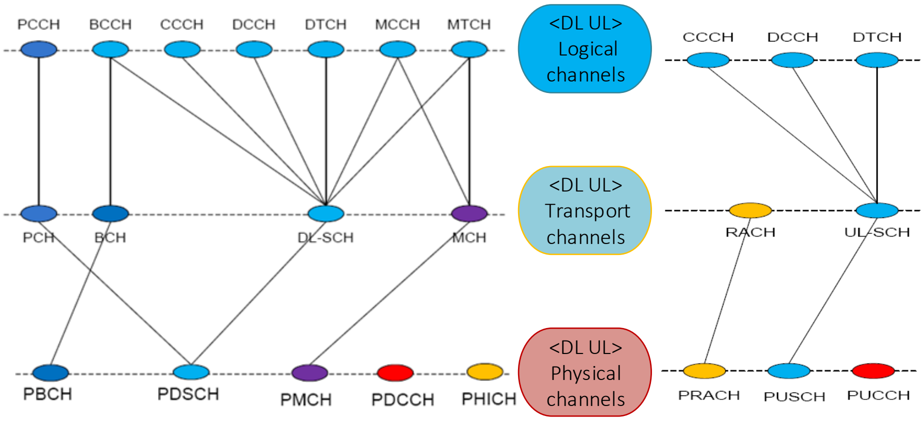


Figure 2.6. Mapping between logical, transport and physical channels [17]

2.2.7. Resource Grid Structure and Resource Block

In LTE, information is organized as a function of frequency as well as time, using a resource grid [11]. The basic unit is a resource element (RE), which spans one symbol by one sub-carrier. Each RE usually carries two, four or six physical channel bits, depending on the modulation scheme. RE are grouped into resource blocks (RBs), each of which spans 0.5ms (one slot) by 180 kHz (12 sub-carriers), Figure 2.7 [11].

The BS uses RBs for frequency-dependent scheduling, by allocating the symbols and sub-carriers within each subframe in units of RBs. The term RB pair is sometimes used for the two consecutive RBs that use the same sub-carriers within a particular subframe. One subtle point is that the DL resource grid does not use the 0 kHz sub-carrier; instead, the RBs on either side use sub-carriers from +15 to +180 kHz and from －15 to －180 kHz. The reason is that the 0 kHz sub-carrier reaches the UEs OFDMA receiver at a frequency of zero, where it can suffer from high levels of noise and interference. Still that sub-carrier on the uplink used, because the SC-FDMA symbols are spread across sub-carriers so are less vulnerable to interference, and because its omission would increase the power variations of the SC-FDMA waveform [11, 14].

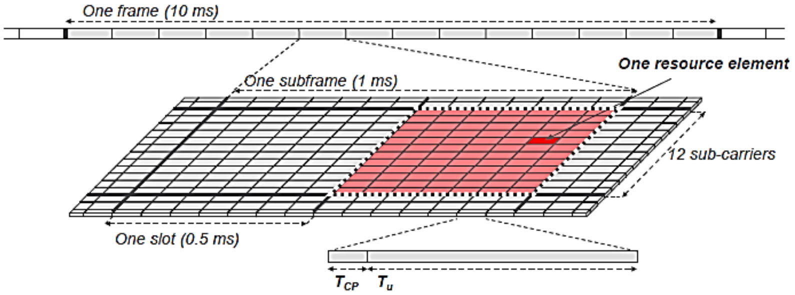


Figure 2.7. Resource grid structure [15]

2.2.8. LTE Radio Resource Management (RRM)

RRM ensure for the efficient usage of radio resources, taking advantage of the available adaptation techniques and to serve the users according to the configured QoS [12]. Several techniques are used as part of RRM; providing Radio Bearer Control (RBC), Radio Admission Control (RAC), Connection Mobility Control (CMC) and Handover Control (HC), Dynamic Resource Allocation (DRA) or Packet Scheduling (PA), Link Adaptation (LA) and Power Allocation (PA) and Inter-Cell Interference Coordination (ICIC) functionalities [16-18]. The following table, Table 2.3 summarizes the techniques used by RRM and their functionalities and descriptions.

Table 2.3 RRM techniques and functionalities [16, 17]

Technique	Function	Description
RBC	Establishment, maintenance and release of radio bearers, configuration of radio resource (RR)	Maintenance of radio bearers of in progress sessions during mobility and release of resources during session termination e.g. HO
RAC	Admit or reject establishment requests for new radio bearers, ensure high radio resource utilization and guarantee proper QoS for in progress sessions	To accept or reject it considers QoS demand, priority level of the new radio bearer
CMC	Management of RR in idle or connected mode during mobility, helps to predefine operator defined policies using neighbor cell load, traffic distribution	In idle mode the cell reselection algorithms predefined for e.g. UE cell selection and in connected mode the mobility of radio connections

HC	Maintaining the radio link of UE in active mode as UE moves within the network	In LTE, HO are hard HO with preparation at the target cell
DRA/PA	Resolves bandwidth contention, selection of radio bearers taking CQI of UEs, buffer status and interference in to account	To satisfy the QoS demand of users while efficiently utilizing the available bandwidth, consider restrictions on some of the available RBs due to ICIC
LA	To determine RB assignment for UE, MCS and power allocation	The selection of MCS always done with a target SINR
PA	To set the transmit power levels until the target SINR reached	The eNodeB distributes its power on the RBs according to the corresponding SINR level

2.3. LTE-Advanced

LTE-A come as the solution to meet the demand and requirement by IMT-Advanced to be real 4G, i.e. fulfilling 1Gbps DL and 500Mbps UL, increasing efficiency in spectrum usage, beyond what LTE can deliver [13, 24 and 31]. The transition from LTE to LTE-A, represents both a physical-layer evolution and a network paradigm revolution [11]. It has similar channel, RRM and other technical qualifications as basic LTE, however, it provides enhanced performance through a variety of features as discussed in the following sections.

2.3.1. Carrier Aggregation (CA)

CA is one of the mainly used and practical features of LTE-A. It is used to increase the bandwidth by combining Component Carries (CC) of same or different frequency bands either in FDD or TDD mode.

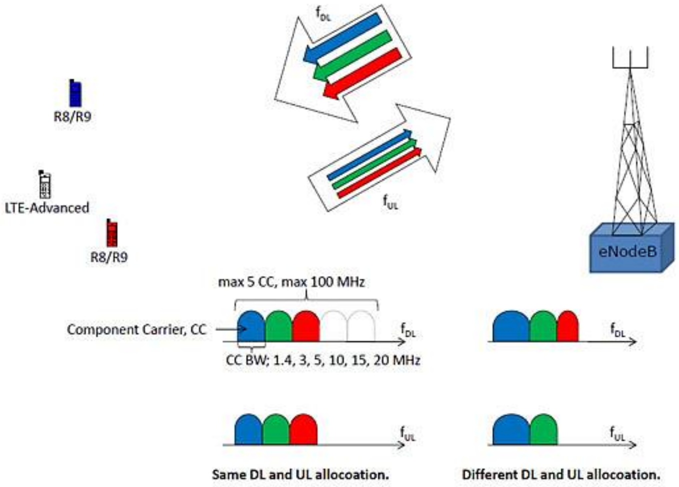


Figure 2.8. CA illustration [31]

Release 8/9 carriers aggregated to guarantee backward compatibility, so that R’8/R’9 UEs utilize any one of the CCs allocated by the eNodeB [30, 31, 33 and 34]. In Release 10, it is specified UEs to aggregate and use allocated two or more CCs in the DL and UL, Figure 2.8 [32, 35]. Each CC can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz and a maximum of five CCs combined to get the maximum aggregated bandwidth of 100MHz, Figure 2.9. According to [17, 30], in FDD mode carrier aggregation the aggregated carriers in DL and UL can be different and UL CCs always equal to or lower than the number of DL CCs. While for TDD mode the number of CCs as well as the bandwidths of each CC will normally be the same [30].

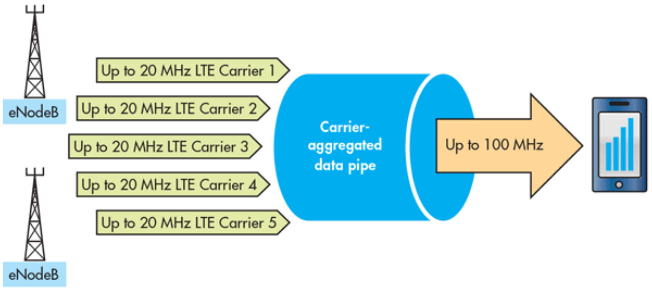


Figure 2.9. Combination of LTE CCs to get higher bandwidth [43]

2.3.1.1. CA Types

Based on CC combinations, CA categorized as intra-band and inter-band. The former is a combination of contiguous and non-contiguous CCs in the same band while the later one is a combination of CCs in different bands. Intra-band CA used if wider than 20MHz is possible in a single band. The easiest way to organize aggregation would be to use contiguous CCs, also called intra-band. Figure 2.10 shows CA types used in LTE-A.

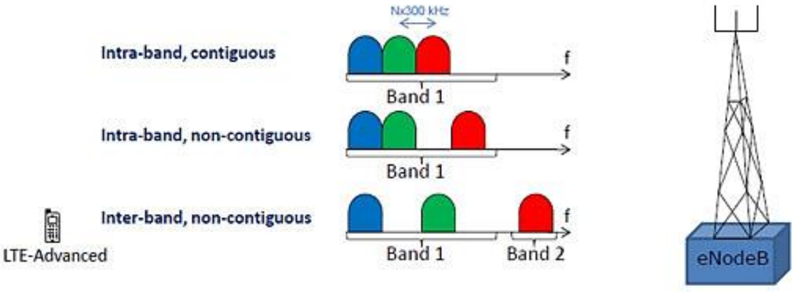


Figure 2.10. CA types [30, 3GPP]

For contiguous CA, the spacing between CCs is required and the spacing between the center frequencies of two contiguous CCs is Nx300kHz, N=integer based on the widest CC in CA configuration. While for non-contiguous cases, the CCs separated by one, or more, frequency gap(s) [30-32]. In Release 10, intra-band carrier aggregation is limited to two CCs of Band 1, while in inter-band CA, it only allows to aggregate bands 1 and 5. In later releases, however, more combinations included. In the implementation of intra-band CA, CCs should be on the same 15 kHz subcarrier raster to allow reception of multiple adjacent CCs using a single FFT (Fast Fourier Transform) instead of an FFT per subcarrier [42]. This property, together with the fact that the frequency-numbering scheme is on a 100 kHz raster, results in the spacing between two component carriers having to be a multiple of 300 kHz, which is the least common denominator of 15 and 100 kHz [33, 34].

2.3.1.2. CA Configuration

CA configuration is a combination of bands, linking with the CA bandwidth class of the UE [34]. The introduction of CA also makes UEs to be called based on their CA bandwidth class, as a result 3GPP has introduced terminology and notation that serve to more clearly express the radio interface configuration [30, 34]. To specify different CA combinations some new definitions used, Aggregated Transmission Bandwidth Configuration (ATBC) and total number of aggregated Physical Resource Blocks (PRB).

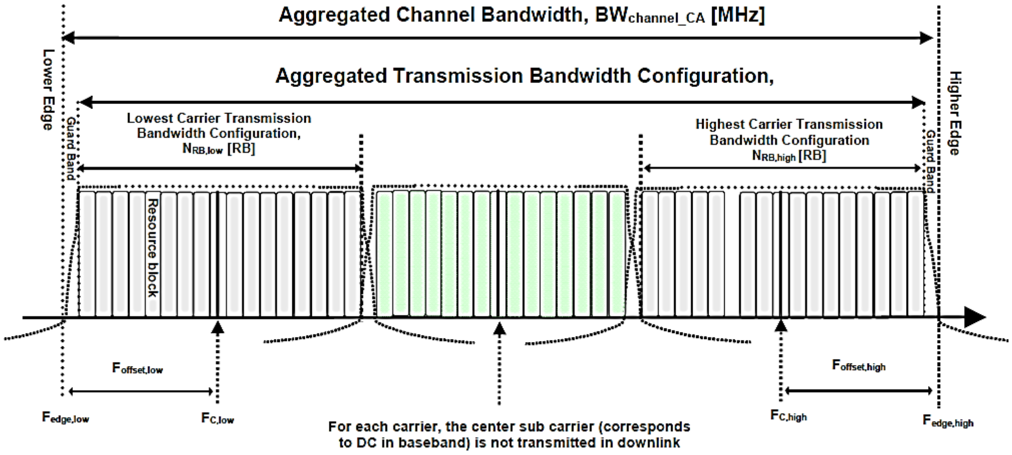


Figure 2.11. Definition of Aggregated channel bandwidth [3GPP R'14]

For intra-band contiguous CA, UE's CA Bandwidth Class is defined according to their number of CCs supported and their ATBC corresponding to Number of aggregated Resource Block

(NRBagg), Figure 2.11. Bandwidth of class A, B, C defined in Release 10 and 11 used in the CA configuration and more classes defined in later release. Table 2.4 shows bandwidth class specified in 3GPP R’14.

Table 2.4 CA bandwidth class [30, 33, 3GPP R’14]

Channel aggregation BW class	Aggregated transmission BW configuration (ATBC)	No. of CCs	Aggregated BW
A	< = 100	1	20MHz
B	< = 100	2	20MHz
C	100 - 200	2	20Mhz – 40MHz
D	200 - 300	3	60MHz
E	300 - 400	4	80MHz
F	400 - 500	5	Later releases
I	700 - 800	8	Later releases

After random access procedure to the Evolved Packet System (ESP) bearer, UE report extra information to the network about its CA capabilities, after. The capabilities notified per frequency band, independently for DL and UL and define the proper CA configuration set to be used. Within the aggregation configuration, the UE can report a combination set, which defines where to allocate the resource blocks. As an example, CA_1C configuration states that the UE can operate on band 1, with two CCs, with a maximum of 200 RB. For the intra-band, combination set is defined by a number of consecutive RBs allocated on each CC whereas for inter-band the combinations rely on the channel occupied bandwidth instead of the number of RBs. In considering CA, other points considered are the involvement of BSs, radio resource and associated channel. When CA is used, a number of serving cells, one for each CC and the coverage of the serving cells may differ, as CCs on different frequency bands will experience different pathless [10, 30, 42]. Primary and secondary serving cells are involved and the RRC connection is only handled by the primary serving cell, served by the Primary CC (DL and UL PCC) and the DL PCC sends NAS information to UE, such as security parameters. In idle mode, the UE listens to system information on the DL PCC. On the UL PCC PUCCH sent. The other CCs are all referred to as Secondary CC (DL and UL SCC), serving the secondary serving cells in which they are added and removed as required, while the PCC is only changed at handover [11, 31].

Figure 2.12 illustrates CA configuration for the inter-band type, with each CC corresponds to a serving cell and each serving cell has different coverage and experience path-loss (rises as frequency increases). Different CCs can be planned to offer different coverage, i.e. different cell size such as, in the figure three CCs serve the black UE, and the white UE is not within the coverage area of the red CC, but the UE served by the rest two CCs, moreover, UEs using the same set of CCs can have different PCC [30, 31 and 33].

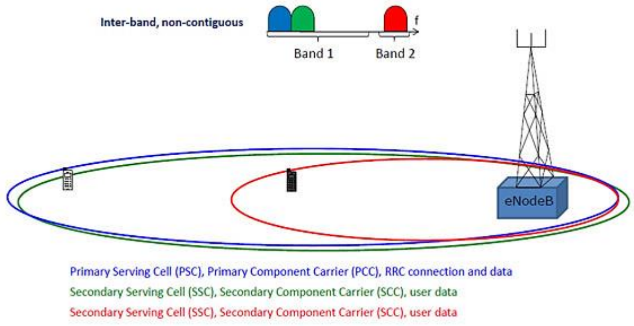


Figure 2.12. Primary and Secondary serving cells [30]

2.3.1.3. Impact of CA in Signaling, MAC and Scheduling

CA prerequisites new RRC messages to be introduced to handle SCC, MAC scheduling to lever CCs that influences MAC and the physical layer protocol [30, 34].

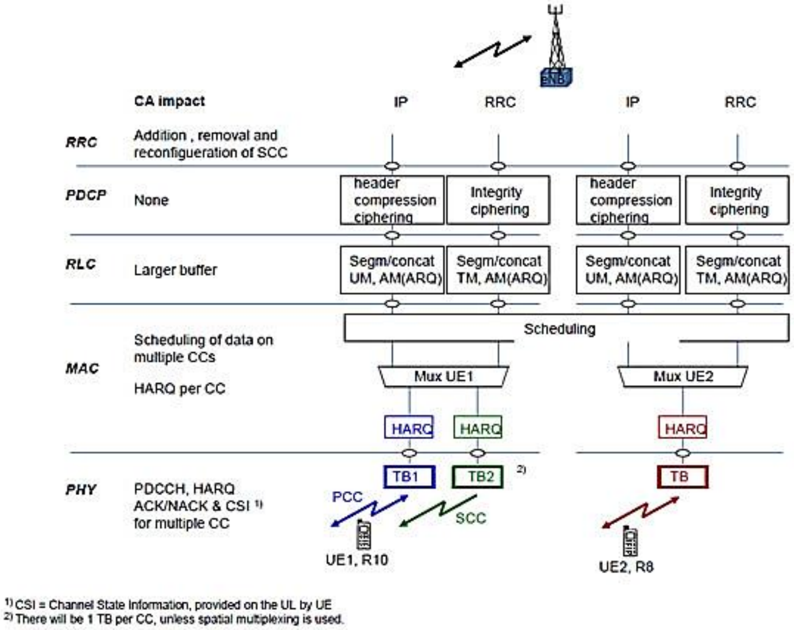


Figure 2.13. Shows change of protocols due to CA [17, 34]

In order to keep R’8/R’9 compatibility the protocol changes will be kept to a minimum as a result the signaling aspect because of CA is only influencing a limited number of protocol layers. Basically, each CC is treated as an R’8 carriers. Major changes on the physical layer are; signaling information about scheduling on CCs must be provided DL as well as HARQ ACK/NACK per CC must be delivered UL and DL, Figure 2.13 [34]. The UE connected to the Primary Cell, will perceive the secondary cells as additional resource to transmit data and NAS procedure, key exchange or mobility carried by the primary cell. For the other layer such as PDCP and RLC layer, CA signaling is completely transparent [34]. From a UE design perspective, a minor aspect of the RLC was changed in comparison to Rel’8, the RLC layer has now to provide higher data rates by having a larger buffer size. The buffer size for each UE category specified in TS 36.306, Table 2.5. From the MAC perspective, the CA simply brings more canals, so that the MAC layer can multiplex the aggregated CCs. Each MAC entity will give to its corresponding CC, own physical layer entity, provide resource mapping, data modulation, HARQ and channel coding [11, 32, 34 and 35].

Table 2.5 UE categories [32, 35]

UE Cat.	Max. L1 data rate DL (Mbit/s)	Max. no. of DL MIMO layers	Max. L1 data rate UL (Mbit/s)	L2 buffer size (KB)	3GPP R.
1	10.3	1	5.2	150	Rel 8
2	51.0	2	25.5	700	
3	102.0	2	51.0	1400	
4	150.8	2	51.0	1900	
5	299.6	4	75.4	3500	
6	301.5	2 or 4	51.0	3300	Rel 10
7	301.5	2 or 4	102.0	3800	
8	2,998.6	8	1,497.8	42200	
9	452.2	2 or 4	51.0	4800	Rel 11
10	452.2	2 or 4	102.0	5200	
11	603.0	2 or 4	51.0	6200	
12	603.0	2 or 4	102.0	6700	
13	391.7	2 or 4	150.8	-	Rel 12
14	3,917	8	9,585	-	

Regarding resource scheduling there are two main choices in the presence of CA; scheduling on the same carrier as the UE granted to the network or using cross-carrier scheduling that is optional feature introduced in Release 10 [30, 34]. Cross-carrier activation is possible through the RRC during the UE capability transfer procedure and it assist to reduce interference in HetNet scenarios with CA. Cross- carrier scheduling is only used to schedule resources on secondary cell without PDCCH. The Carrier Indicator Field (CIF) in the Downlink Control Information (DCI) indicates the carrier responsible for the delivering scheduling information in the context of cross-carrier scheduling. The primary cell cannot be cross-scheduled but through its own PDCCH. Another impact of the cross-scheduling is that the UE is not decoding the PCFICH on the secondary cell anymore, the number OFDM symbols is then unknown at beginning of each sub frame. Hence, PDSCH-Start, ranging from one to four OFDM symbols based on CC bandwidth, allow the signaling of this information to the UE during activation of cross-carrier-scheduling.

2.3.1.4. CA Implementation Scenarios

CA support high data rates over wide bandwidths using varies frequency bands [29]. Intra-band contiguous combines continuous CCs in a single operating band, Figure 2.14 shows CA scenarios. While inter-band CA, aggregate CCs from different frequency bands, as a result it is more complex than intra-band because the multicarrier signal cannot be treated as a single signal and it requires a more advanced transceiver from the UE side.

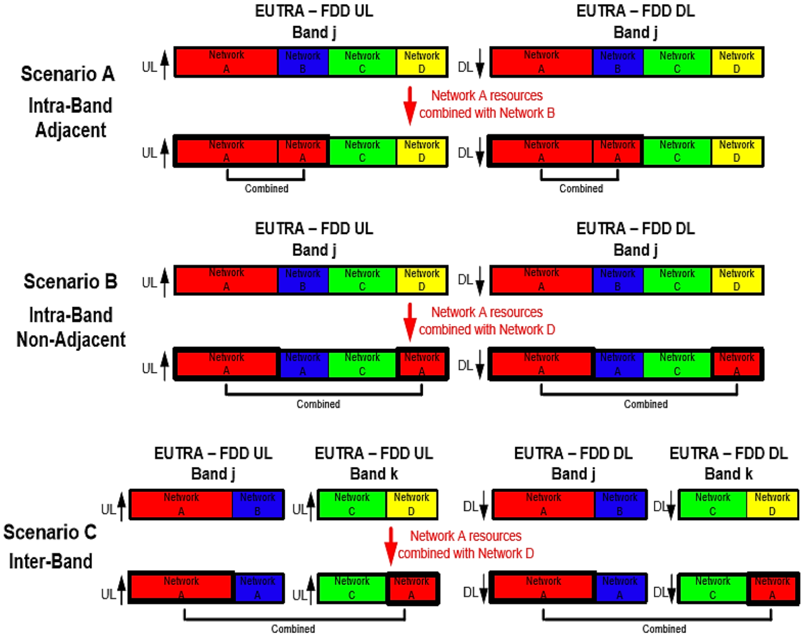


Figure 2.14. CA scenario for LTE-A FDD [33]

Intra-band carrier aggregation implemented in a single band whereas three possible implementations scenarios used for inter-band: (1) *Low-higher*, for coverage advantage for operators owning low band spectrum, so that pairing this with other spectrum maximizes an operator's spectrum assets for coverage and capacity [31]. CA_4A-12A is an example of a low and high band CA case that aggregates two DL CCs from band 4 and 12 to provide up to 30MHz of aggregated bandwidth. In this specific use case, band 12 provides coverage advantages over band 4, and this combination of CA can be used to couple the coverage benefits of band 12 with capacity and higher throughputs of band 4. However, a common concern in this scenario is the coverage and site density mismatch between the low and high bands limits the operation of CA. (2) *Low-lower*, e.g. 700 and 850MHz, helps for operators that own more than one lower frequency bands for coverage and bandwidth enhancement. Have no problems related with different cell sizes, but reduced capacity and throughput. (3) *High-higher*, give high bandwidth while reduced coverage. Thus, requires more BSs to cover target area. In all cases, complex hardware may require from the UE side that increase weight, size, complexity and cost because of more RF units to separate closed radio signals. It also increases cross-modulation and intermodulation, which could occur with multiple transmitters/receivers being operated simultaneously in close proximity.

Moreover, finding a way to use the frequency spectrum more efficiently is important. Performance measurements on live CA deployments indicates that resource usage in aggregated bands is frequently suboptimal, and higher data rates could be achieved by simply overloading a single band [36]. Therefore, consultation with RAN infrastructure vendors, as well as device and chipset manufacturers required when developing CA implementation plans [31].

2.3.2. Enhanced MIMO (eMIMO)

One of the requirements for LTE-A is achieving DL peak spectral efficiency of 30bps/Hz, for these to happen technologies like CA or eMIMO or both required [25-27]. An eMIMO is a technology to improve the spectral energy efficiency, cell edge coverage and channel capacity and acquisition of high dimensional channel state information (CSI). In Release 10, higher order MIMO of up to 8x8, antenna array size of 8 is discussed which doubles the peak data rate compared to Release 8.

2.3.2.1. MIMO Modes in LTE-A

Multi-antenna scheme depends radio environment and number of different Transmission Modes (TM) [26, 27]. Signaling informed to UE through RRC about the transmission mode to use and the UE with high Signal to Interference and Noise Ratio (SINR) benefit from the multi-antenna for high data rate than with low SINR. In the DL, there are nine different transmission modes, where TM1-7 introduced in R’8, TM8 was introduced in R’9 and TM9 was introduced in R’10. In the UL, there are TM1 and TM2, where TM1, the default, was introduced in R’8 and TM2 was introduced in R’10. Using TM9, 8x8 MIMO is supported DL and through the introduction of TM2 UL use of 4x4 MIMO UL can be enabled. It supports both Single User (SU) MIMO and Multi User (MU) MIMO and enables dynamic switching between these two modes, Figure 2.15 [26].

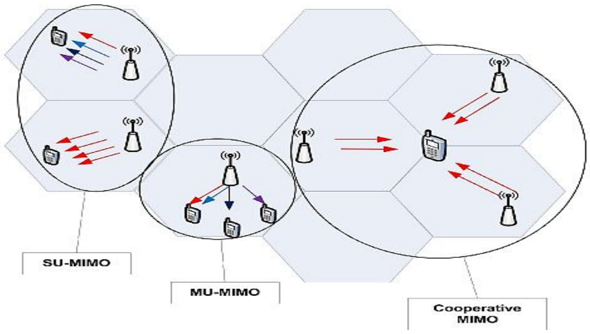


Figure 2.15. MIMO modes in LTE-A [26]

Reference signal used to handle the signal distorted by varies fading types. As a result, it is transmitted together with the desired data and used by the receiver for demodulation of the received signal.

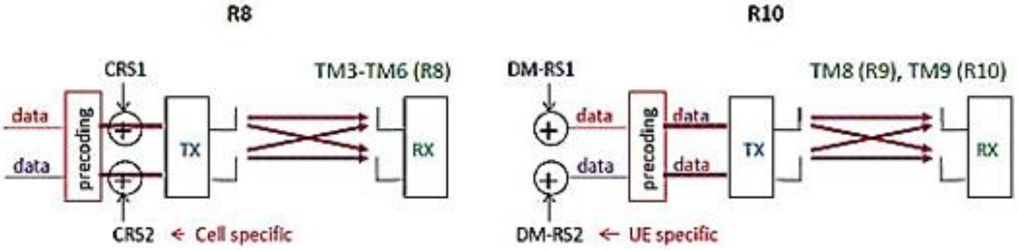


Figure 2.16. MIMO DL with pre-coding and RS for demodulation in R’8 and R’10 [26]

In Release 8, RS is added to the signal after pre-coding, one Cell Specific RS (CRS), cell specific RS per antenna, Figure 2.16. UE decodes and demodulate the information sent by estimating channel influence on the signal using received CRS, used codebook based on pre-coding. Moreover, in R'10, Demodulation Reference Signals (DM-RSs) and UE specific RS are added to the different data streams before pre-coding. Knowledge about the reference signal will provide information about the combined influence of radio channel and pre-coding, no pre-knowledge about the pre-coder is required by the receiver, this case is referred to as non-codebook-based pre-coding [21, 26, 27].

2.3.2.2. LTE-A DL and UL MIMO

The peak spectral efficiency for DL is 30bps/Hz, for this higher order SU-MIMO with multiple antennas is necessary and maximum of 8 layers used in LTE-A. MU-MIMO takes the lead in increasing system capacity and enhanced cell edge throughput and different mitigation techniques to cope with interference. To achieve 15bps/Hz UL peak spectral efficiency, support for SU-MIMO with up to four transmission antennas can be used. In particular, the two-transmission antenna SU-MIMO function is required to satisfy the peak spectral efficiency [26].

2.3.2.3. Radio Frequency Design and Challenge

LTE devices can incorporate up to 8x8 MIMO to enable simultaneous transmission of eight DL and eight UL data streams to increase the overall bitrate, and system capacity. Coupling multiple antennas to the eNodeB to DL is possible, but when comes to compact space of UE, it is difficult to fit multiple antennas. The prime reason for this is placements of antennas and multiple transmission paths that lead to high correlation between signals. The next cause is the integration of Wi-Fi, GPS, and Bluetooth antennas reduce space for MIMO and contributes to sever signal interference. However, advanced pattern diversity technology brings a 2x4 and 4x4 MIMO LTE devices to a reality. It makes to put multiple antennas in close proximity and achieve high isolation and low correlation. In addition, aids to avoid interference for co-located antenna running at the same frequency. To enhance further RF frontend design is pushing forward; two options are possible, although the latter one is practical. The first one is sharing antenna with wireless LAN RF by utilizing WLAN antenna as

RF frontend components. At the cellular side of smart phone, reduces cost as well as physical space. The second approach is co-location of antennas, careful colocation of multiple antennas that have high isolation and low correlation [26 –28]. MIMO implemented with all LTE bands, high performance for higher bands ranging from 1700 to 2700MHz while reduced performance in lower bands. It is capable to aggregate with CA and create quantum leap performance. Also, an alternative solution in cases such that high cost of spectrum.

2.3.3. Heterogonous Network (HetNet)

The traditional macro cell-based deployment is not adequate as more than 50% calls and over 70% of data services occur indoor [39]. Different techniques are used to cope with this constraint such as increasing capacity with a new spectrum, adding multi-antenna techniques and implementing modulation that is more efficient and coding schemes. In addition, densification by adding more sectors per BS used while keeping the homogeneity of the network. However, these methods heal the increasing demand a certain magnitude and incurs network complexity and can be expensive. Although, these measures alone are insufficient in crowded areas and at cell edges where performance can significantly degrade [37]. An alternative approach is to introduce small cells, also called low-power BS, in line with an existing macro eNodeBs to address short-term and long-term challenges and then enhance the network capacity and quality, Figure 2.17.

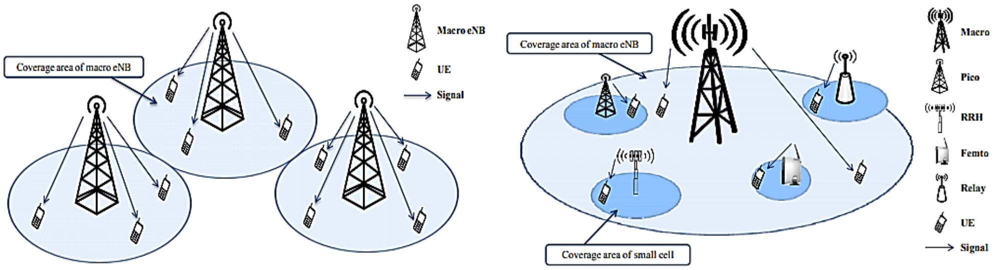


Figure 2.17. Heterogeneous network (Right) Traditional and (Left) HetNet [37]

Small cells used to improve network performance and service quality by offloading traffic from the macro cells within the macro coverage. The business case for a high QoE network that is “always-on, and available anywhere, anytime” is also driving factor towards HetNet evolution. HetNet, defined in the 3GPP LTE-A standard, where performance gains can be achieved through increasing node density, such as Pico, femto, and relay nodes. It brings a complex architectural change, which will affect technology, deployment and monetization and will be an important stepping-stone to 5G [37, 69, and 75]. The following table, Tables 26 and 2.7, lists small cell types, deployment options and specifications and the survey of small cells is summarized in Appendix A, Table A.1.

Table 2.6 Small cell type, feature and application [37-39]

Cell type	Feature				Application	Description
	MIMO	BW (MHz)	Energy (mW)	BH		
Femto	2x2	10	20-250	DSL/ PON	Indoor residential or enterprise known as Closed Subscriber Groups (CSG), used in 3G, 4G & Wi-Fi	Incorporates the functionalities of BSs (BTS, NodeB and eNodeB),
Pico	2x2	20	250	Fiber/ MW	For indoor and outdoor, supports 3G, 4G & Wi-Fi technologies	Supports many users over a range of 200m, offer greater capacity and coverage
Micro/ Metro	4x4	40	10000	Fiber/ MW	Deployed temporarily in anticipation of high-traffic, such as a sporting event, but are also installed as a permanent feature of mobile cellular networks, supports 3G, 4G & Wi-Fi technologies	Extended coverage area and cover 2km maximum

Table 2.7.Summary of Relay node and description [19-21]

Overview	Type	Description	Application
Connected to the Donor eNodeB (DeNodeB) via a radio interface, Un, which is a modification of the E-UTRAN air interface Uu, radio resources are shared between UEs served directly by the DeNodeB and the Relay Nodes, From the UE point of view, RN recognized as BS.	1	simple, low-cost implementation and short processing delays but reduced throughput gains as it amplifies interference and noise with the desired signal that deteriorates SINR	Remote, sparsely populated as well as indoor areas
	2	Radio frequency signals received on the DL from the BS are modulated and decoded and then the encoded and modulated again before being sent to the UE	Indoor/Outdoor
	3	Possess unique Physical Cell ID (PCI) on the physical layer different from that of the BS, as physical layer control signals such as Channel Quality Indicator (CQI) and Hybrid ARQ (HARQ) terminate at the RN	Outdoor

There are also other alternative emerging small cell technologies provided by vendors that enhance coverage with efficient cost. Ericsson (www.ericsson.com) introduced Radio Dot System (RDS) that enables operators to deliver high-performance coverage and capacity in building, underground basement and car parks where conventional BSs cannot be installed. The other product is Hardened Radio Dot (HRD) used in outdoor venues and stadiums, where difficult to cover using macro cells. HRD supports LTE-A features such as 256QAM, D-MIMO and CA.

2.3.3.1. Features of HetNet

HetNet has several features that set them apart from macro networks: 1. *Association and load balancing*, one of the main functions of small cells are to offload UE traffic from the macro and the amount of offloading depends on the criterion by which a UE associated with a BS. DL RSRP used but it cause too much offloading since the transmit power of a macro cell is greater than that of the small cell, therefore, adding a bias to the small cell RSRP is an example of an association method that increases offloading [39]. The interference information is captured in RSRQ based association and hence leads to better load balancing. For highly loaded systems, load balancing will distribute the UE load across all BSs uniformly. This will homogenize the inter-cell interference and lead to a fair distribution of a BSs resources among all its associated UEs. Association can be used based on UE speed, i.e. associating a UE with high velocity to the macro cell for a better performance [39]. 2. *Mobility management*, handover is performed between cells to ensure that a UE is always connected to the best serving cell.

A UE measures the signal strength of its neighboring cells, if it is higher than that of its serving cell plus an offset for a particular time period called the time to trigger (TTT), the UE will report this information to its serving cell and the serving cell then initiates the handover process. In a homogeneous network, the handover parameters such as the handover offset and TTT are common for all cells and all UEs. However, using the same set of handover parameters for all cells/UEs may degrade the mobility performance in HetNet. It is desirable to have a cell-specific handover offset for different classes of small cells. Furthermore, for high-mobility UEs passing through a dense HetNet, the normal handover process between small cells will lead to very frequent changes in the serving cell. This can be solved by associating UE to the macro cell at all times, leading to UE-specific handover parameter optimization. Both cell and UE-specific handover functionalities, therefore, need to be considered for HetNet [39]. 3. *Interference management*, the dense deployment of small cells increases interference, so that the system performance will degrade if not properly managed [36, 40]. For this, Time-domain techniques and their enhancements, eICIC and further eICIC (FeICIC) were proposed in Releases 10 and 11, where a cell can mute some subframes, called Almost Blank Subframes (ABS) and reduce interference to neighboring cells. An eICIC provides improved mitigation by addressing both the traffic and control channels. It addresses interference issues by partitioning and apportioning power, frequency, and time domain resources.

In Release 12, a small cell can perform dynamic activation/deactivation based on its traffic load and interference situation. CoMP technique also aid to mitigate interference by implementing a macro and a small cell cooperation and simultaneously serve a UE. In addition, inter-site CA, specified in 3GPP R’10, avoid interference by allowing UEs to connect to both macro and the small cell and share resources [39, 40]. Concerning Relay node, Multicast-Broadcast Single Frequency Network (MBSFN) frame used to avoid interference. In the In-band relay, the same frequency allocated in the UE-RN and RN-DeNodeB link, which incurs a self-interference on the relay reception and transmission antennas. But in LTE-A, the links are time multiplexed with the help of MBSFN frame, primarily received by the UE only engaged with in the broadcast service. While for the out-band relay the isolation constraint handled by definition in frequency domain but assigning separate frequencies for both links is not efficient and feasible from an operator point of view. Nevertheless, the introduction of CA in R’10 helps to avoid such concern [19].

2.3.4. Coordinated Multi Point (CoMP)

CoMP allow the optimization of transmission and reception from multiple distribution points, either multiple cells or Remote Radio Heads (RRH) in a coordinated way. It will enable joint transmission and/or reception to mobile device and allow devices to select the closest BS. Have impact on power consumption, throughput and allows load balancing and therefore contributes to the mitigation of inter-cell interference [23, 24]. There are two types of CoMP called intra-site or inter-site CoMP, Figure 2.18.

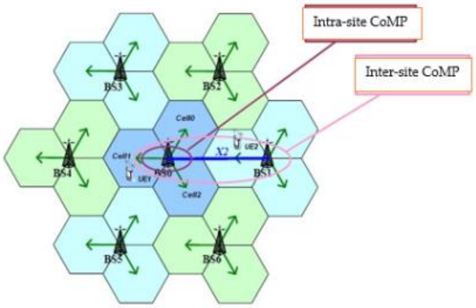
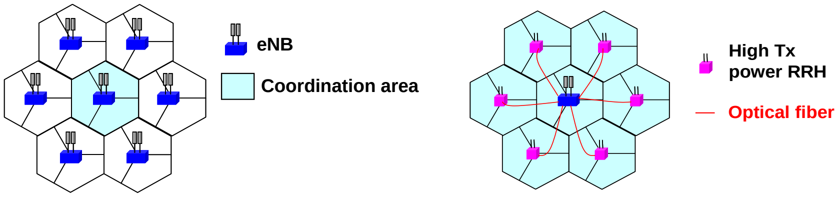


Figure 2.18. Intra and Inter-Site CoMP [22]

The coordination can be simple as in the techniques that focus on interference avoidance or more complex as in the case where the same data is transmitted from multiple cell sites. CoMP standardization by 3GPP is based on four different CoMP scenarios.



(a) (b)

Figure 2.19. Homogenous network with
(a) Intra and Inter-Site CoMP and (b) high transmission power RRHs [22]

The first two scenarios focus on Homogenous network with intra-site CoMP and high transmission power Remote Radio Heads (RRHs), Figure 2.19 (a and b). While the other two, are on HetNet with low power RRHs within the macro cell coverage, where the transmission/reception points created by the RRHs have different cell IDs as the macro cell, Figure 2.20 [22].

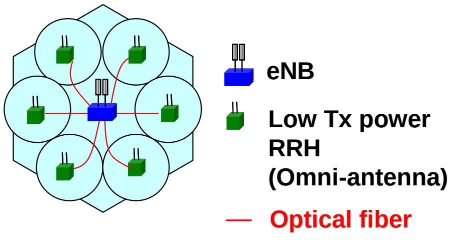


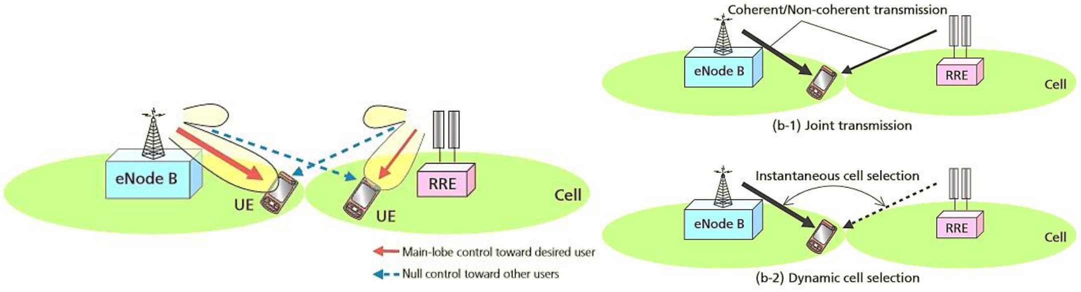
Figure 2.20. Heterogeneous network with low power RRHs within the macro cell coverage [22]

2.3.4.1. Deployment, Transmission and Reception

Two deployment options are involved for CoMP. *Option 1*: a combination of macro/high power RRH and macro/high power RRH CoMP scenario (Scenario 1/2) also called centralized control based on RRH. *Option 2*: a combination of macro and low power RRH CoMP scenario (Scenario 3/4) also called autonomous distributed control based on independent eNodeB configuration [22, 23]. In the first case, multiple RRE connected via an optical fiber and radio resources between cells controlled by eNodeB with a small propagation delay. However, high capacity optical fiber is required and as the number of RRE increases processing load on the central eNodeB increases which limits performance. In the second case, signaling over wired transmission paths is used between eNodeB to coordinate between cells, but a larger propagation delay difference should be assumed due to propagation distance difference. CoMP also categorized as DL and UL CoMP transmission [22, 23].

Further DL CoMP categorized in to two types named Coordinate Beamforming/scheduling (CBS) and Joint processing (JP), Figure 2.21. In CBS, a given sub-frame is transmitted from one cell to a given UE then beamforming and scheduling performed between cells to reduce the interference caused to other cells, while in the latter case, simultaneous data transmission from multiple points to a single UE or multiple UEs involved in a time-frequency resource and dynamic cell selection. Data to a UE is simultaneously transmitted from multiple points, e.g. to improve the received signal quality and/or data throughput for these Joint processing further subcategorized as Non-coherent transmission which use soft combining reception of the OFDM signal and Coherent transmission, which does pre-coding between cells and uses in phase combining at the receiver. In [22], a possibility of hybrid CBS and Joint processing category discussed, some points may transmit data to the target UE according to JP while other points in the cooperating set may perform CBS.

In Joint reception, PUSCH (UL) transmitted by the UE is received jointly at multiple points at a time, e.g., to improve the received signal quality while CBS user scheduling and pre-coding selection decisions are made with coordination among points and data is intended for one point only. The UL CoMP differs from the DL in that, the existence of virtual cell ID (VCID) in the UL. Due to VCID the reception and transmission point are not the same, based on the interference scenario, a device might receive its downlink from the macro cell, where the uplink is received by a small cell, but the UE does not aware of a multi cell reception is occurring.



(a) (b)

Figure 2.21. DL CoMP transmission (a) CBS and (b) JP [22]

2.4. Mobile Backhaul

2.4.1. Introduction

The mobile network is increasingly the preferred choice for end-users wanting to access contents, which usually resides within large, distant web scale data centers [58]. LTE-A bring several enhancements to the radio domain, such as CA and MIMO, eICIC and CoMP, meshing of X2 interface for improved latency and reduce burden to the core network, and HetNet [50]. Such things resulted in massive increases in bandwidth demand across the entire mobile network infrastructure, including the Mobile Backhaul (MBH). Therefore, it is relevant to define the incremental architectural and engineering requirements of the BH network to support its features [48-50]. The MBH network connects RAN air interfaces at cell sites to the inner core network that connects users to content, so it is increasingly a critical part of mobile network. Backhaul is a crucial enabler for mobile operators deploying new high-capacity technologies like LTE-A, as they look for a solution that meets performance requirements [44-52]. Backhaul prominence will rise further with the deployment of small cells, and with the associated increase in the number of cell sites, mostly in challenging urban locations.

2.4.2. Backhaul for HetNet

Backhaul ranges from fiber to microwave (MW) and E-band Point-to-Point (PTP), and to MW Point-to-Multipoint (PMP). The choice depends on the requirement, topology, availability, capability of an operator. In terms of efficiency and keeping KPI requirements such as latency, fiber is the primary target. Whereas PMP is the most cost-effective as it requires fewer radios to meet the backhaul requirements than either microwave or E-band PTP does, and less CAPEX and OPEX cost because of lower equipment and installation costs and fewer links to operate [59]. In contrast, the smaller equipment footprint and the ability to use spectrum licenses that cover areas instead of individual links make PMP easier and faster to deploy in challenging urban environments. In general, a key aspect expected by mobile operators as 4G BH requirements are; reliable low-cost connection, simplify service growth and scale, support both legacy and next generation service and synchronization [59].

2.4.2.1. Fiber

Its unlimited capability such as latency make fiber the prime option to keep pace with the demand for Gbps transmission capacity requirement [45-47]. Moreover, *capacity* for the growing requirements without distance and throughput limitations, *scalability* to easily extended the link through multiplexing wavelength on existing strands or by pulling new strands through existing conduit, *reliability* for superior BH uptime and increased user satisfaction and *redundancy* for critical macro cell backup for the continuing flow of traffic using secondary link, capabilities make fiber prime choice. Operators that own a fiber network will undoubtedly use fiber at many locations [45-47].

However, high cost for investment or lease makes operators to focus on other alternative choices. Once installed, the on-going costs of running fiber links are much lower than wireless, due to the initial cost of traditional cable installation the breakeven point for fiber relative to microwave is somewhere between 18 and 20 years, which is too long to provide an acceptable business case for the mobile operator. It is sometimes, however, new plant required for locations that is difficult to brought fiber to the site. Several techniques in used to completely avoid bandwidth constraints and to render the fiber assets future-proof [49]. Wavelength Division Multiplexing (WDM) combines multiple optical signals by carrying each signal on a different wavelength or color of light. An improvement to WDM, Dense WDM (DWDM) uses close channel spacing to deliver even more throughput per fiber. Modern systems can handle up to 160 signals, each with a bandwidth of 10 Gbps for a total theoretical capacity of 1.6Tbps per fiber, reducing much of the need to add fiber to current networks.

2.4.2.2. Wireless

There is sometimes a case also an operator that own a fiber network may decide to use wireless backhaul for those cells that are far from fiber, or where fiber cannot be easily brought to the small cell [46]. The basic features of different wireless solutions depend on the type of spectrum used. Table 2.8 lists wireless BH solutions with their pros and cons.

Table 2.8 Wireless BH solutions and their pros and cons of bands [45]

Band	Pros and cons
Sub-6 GHz licensed	Sub-6 GHz is the ideal spectrum for small-cell backhaul because it gives operators the flexibility to reach locations that are not within LOS and makes it easier to combine eNodeB and backhaul in a single enclosure. PMP architecture is the most common, but PTP can also be used. The downsides that severely restrict adoption are that available bands in sub-6 GHz spectrum are scarce and expensive, and that they commonly come in narrow channels that have limited capacity, especially when used in a NLOS environment. The capacity limitations are compounded in a PMP architecture, where available capacity is shared among cells in the PMP network and frequency reuse is limited. Compared to a PTP architecture, the operator gets less capacity for the same spectrum within the same area: With PTP the operator can pack many links within the coverage area of one PMP network using the same spectrum. As a result, only operators with sufficient access to the sub6 GHz licensed spectrum can use this solution, and only at the edge of small-cell networks, where capacity requirements are lower.
Microwave PTP/PMP	PTP/PMP Microwave is by far the spectrum band most commonly used for cellular backhaul. Microwave backhaul is a mature solution, with many vendors providing equipment, at a steady decline in price. Yet microwave has very strong competition in the small-cell market because it combines some of the disadvantages of other bands without providing a unique benefit. Unlike sub-6 GHz bands, MW requires LOS. Where there is LOS, a mobile operator is better off using 60 GHz or e-band, because they have smaller antennas, more capacity, and lower spectrum costs. Because MW links can reach more-distant locations, they can be used in rural small-cell deployments or other locations

	where the small cell is far from the aggregation point. For metropolitan locations, the longer radius can become a liability, because it decreases the ability to reuse spectrum (i.e., to use multiple links in the same area, thereby increasing the capacity density, measured in Mbps per square mile). In areas where MW backhaul is used intensively, additional spectrum for small cells may not be available at all target locations. In some bands and countries, regulatory requirements result in antenna sizes that are too large for small cells.
60GHz	This is the unlicensed band that has attracted the highest interest among operators and backhaul vendors. The atmospheric and oxygen attenuation that makes the 60GHz band not well-suited covering long-distance links is beneficial in a small-cell environment, where short range translates into less interference among adjacent links and, hence, greater spectrum reuse. The high frequency also allows for smaller antennas, which are a requirement for small-cell installations. However, LOS requirements make it difficult to integrate the backhaul module within the small cell. No channelization or antenna design requirements increase the flexibility of the solutions in this band, making it possible to reduce the antenna size and widen the beam width. Low-cost equipment is available from an increasing number of vendors and makes it possible to use relay links to overcome LOS limitations.
E-band (70–80GHz)	This licensed band is inexpensive, but in most countries, it is subject to tight regulations dictating specific antenna designs and channelization, which result in bigger antennas compared to the 60 GHz band. Regulatory changes are expected to remove these constraints in some markets and will increase the attractiveness of this band for small cell backhaul. Like the 60 GHz band, e-band is prone to atmospheric attenuation and rain fade, but the effect of oxygen attenuation is much smaller. Still, it is a wide band (10 GHz available in the US) that can transport high traffic volumes, and it is well suited to the short distances that small-cell backhaul requires. It is lightly used, and the narrow LOS beams reduce the potential for interference.

2.4.2.3. BH and Small Cells

A recent survey on small-cell backhaul found backhaul throughput requirements to be mostly around 100Mbps, the figure rise if small cells combine multiple air-interface modules (3G, Wi-Fi) alongside LTE-A [45].

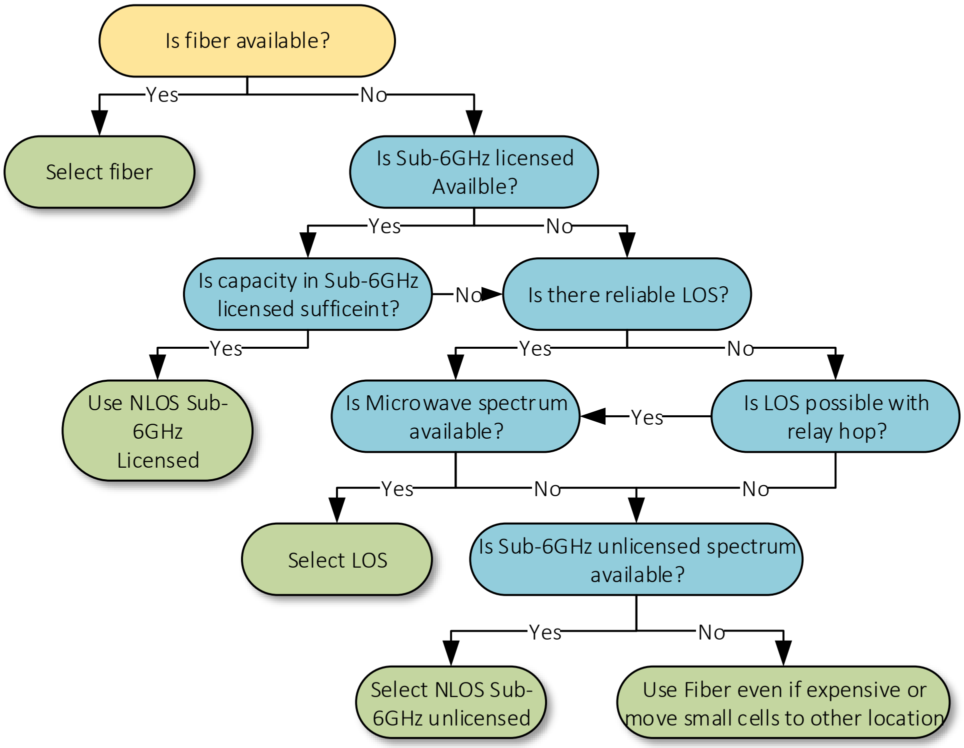


Figure 2.22. Small-cell backhaul decision tree [Redesigned from 45]

There is no single backhaul technology that alone can meet the requirements of small-cell deployments. Fiber is ideal from a performance perspective, whereas wireless alternatives used in case of fiber unavailability and difficulties, for example outdoor deployments or some deployments require LOS communication between the small cell and aggregated macro cell. There are a few high-bandwidths small cell backhaul options to choose from, including microwave, cable modem and fiber-based solutions. Small cells are usually needed in high-density areas, such as venues, hotels, conference centers. The backhaul option that provides a reliable, high-bandwidth connection and also addresses the aforementioned challenges will vary for each deployment scenario. So, the options are, in some cases, more complimentary than competitive [50]. The above figure, Figure 2.22 shows a decision tree for selecting a backhaul solution.

2.4.2.4. Conclusion

Different key parameters considered between fiber and wireless BH choices [44-50]. For example, microwave is cheaper to deploy than fiber and should therefore be when cost is the main concern. However, microwave may not always be the cheaper option, in some cases (e.g. rain) it may necessitate the use of multiple microwave hops to achieve the desired distance at a higher overall cost. Another aspect that needs to be accounted for when building MBH network is power consumption. Bidirectional transmission links consume around 2W, compared to a few tens of Watts for an equivalent outdoor microwave transrecieve system [50]. While this difference per backhaul link may appear to be small, it quickly escalates for the whole network with hundreds of backhaul connections. Overall, the industry consensus is that wireless and fiber will co-exist in MBH, at least over the next several years. There is no single golden rule that will determine when to use fiber and when to use microwave. Instead, all considerations such as cost, required capacity, distance, service availability, future upgrades and regulatory environment need to be considered. However, the growing demand for even higher bandwidth in the access part of the network is likely be followed by the adoption of next-generation LTE-A technology, therefore pushing fiber even deeper into access to satisfy the required backhaul capacities. Table 2.9 summarizes MBH options, their parameters and applications. In addition, maximizing and utilizing the performance of the existing infrastructure will aid to reduce TCO. Developing future proof BH for long term and provide agility and maximize ARPU has to be one of the basic strategies of an operator.

On the other hand, technologies such as Software Defined Network (SDN) and Network Functions Virtualization (NFV) are emerging and play a role in the future MBH together with the already established IP/MPLS and fiber [51, 52]. SDN is a paradigm shift towards simplified networking by abstraction of the forwarding plane to enable improved service structure and an improvement on top of the Network Management System (NMS) and potentially evolves the NMS because the Fault, Configuration, Accounting, Performance and Security (FCAPS) data in SDN architecture could be retrieved from a single controller rather than from several network devices [52, 68].

Table 2.9 MBH comparison [46, 49 and 50]

Type Vs. Parameter	Fiber	Microwave PMP	Microwave PTP	E-band PTP
Capacity (Mbps)	Any capacity required	20–300	20–500	240–2,400
Link distance	Any capacity required	Up to 19.5 km (10.5 GHz), up to 7 km at 26 GHz, and up to 6.4 km at 28 GHz	Up to 50 km	Up to 2 km
Spectrum bands (GHz)	-	10.5, 26, 28	5–80	71–76, 81–86
Bandwidth (MHz)	Unlimited	7–56	3.5–80	Up to 5000
Spectrum rights	-	One spectrum channel supports multiple sites	Limited spectrum availability. Each link requires a separate spectrum lease	Cheaper spectrum than microwave PTP. Each link requires a separate spectrum lease
CAPEX/OPEX tradeoffs	High OPEX, low CAPEX	More CAPEX-intensive solution than leased fiber	Higher OPEX than PMP and E-band due to higher spectrum costs	More CAPEX-intensive solution than leased fiber
Installation costs	Initially high for incumbent operator, for leased depending on lease	Lower cost than for microwave and E-band PTP because less equipment is needed	Lower cost per link, but higher installation costs than PMP as more terminals are required	Higher equipment costs than microwave PTP, comparable installation costs
Application	Where fiber is available, accessible, and cost effective	High cell-density areas	High cell-density areas, but also SU and rural areas where wire line connectivity is not available	High cell-density areas
HetNet suitability	Outdoor/indoor Aggregation and core	Outdoor	Outdoor	Outdoor
Support for X2 mesh	Yes	Yes	Yes	Yes
Latency	⇑	⇓	⇓	⇓
Antenna size	-	⇑	⇑	⇑
Interference potential	Ignored	⇓	⇓	⇓
Frequency reuse	-	⇓	⇔	⇑
Future proof available BW	⇑	⇔	⇔	⇑

⇑ High,
⇓ Low and
⇔ Average

3

Techno-economic Analysis and Modelling

3.1. TEA in Brief

TEA is a method used for evaluating the economic feasibility of multifunctional systems [83, 84]. The nature of the evaluation and modelling is future-oriented, utilizing and combining several methods from the wide field of future-oriented technology analysis (FTA) such as cost-benefit analysis, scenarios, trend analysis, expert opinion, and quantitative modelling. In the context of telecommunications, the term techno-economics was introduced during the European research programme Research into Advanced Communications for Europe (RACE) in 1985-1995. Early techno economic modelling work was done in e.g. the RACE 1014 ATMOSPHERIC and in the RACE 1044 project where alternative scenarios and strategies for evolution towards broadband systems were analyzed [83]. Later in 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 narrowband and broadband services and access networks [83]. Since the late 1990s, many European research projects have used and extended the methodologies and tools created in the early projects.

From the available models, Techno-economic Results from ACTS (TERA), which is used in this thesis, is the most widely used method especially in wireless telecom systems [83, 84]. In general, TEA refers to a set of framework, methods and tools used for evaluating the economic feasibility of complex technical systems. TEA frameworks and methods constitute forecasts for future demand of services provided by a technical system, detailed modelling as well as the costs required to set up and maintain system [83, 84].

3.2. TERA

TERA enables techno-economic evaluations by combining technical, market, economic and costs of key network elements [83]. TERA developed within the European Union Advanced Communications Technologies and Services (ACTS) programme during the period of the fourth framework program of scientific research and development [89].

3.2.1. TERA Framework

The TERA framework for techno-economic, as shown in Figure 3.1, requires market and technology related as well as general economic inputs in order to carry out evaluations [89]. Outputs from the analysis include revenues, costs and investments as well as profits, cash flows, and other economic values. In the TERA framework, the analysis of an investment is always performed for a certain user defined study period. The services to be provided, and the market penetration of these services over the study period must be defined. The revenues for each year are calculated from the combination of yearly market penetration and ARPU information. The network architectures to provide the services must be defined, as well. This requires network planning expertise, and is done mostly outside the TERA framework. A geometric model can be used to estimate the amount of cable, ducts, and civil works required in the access network.

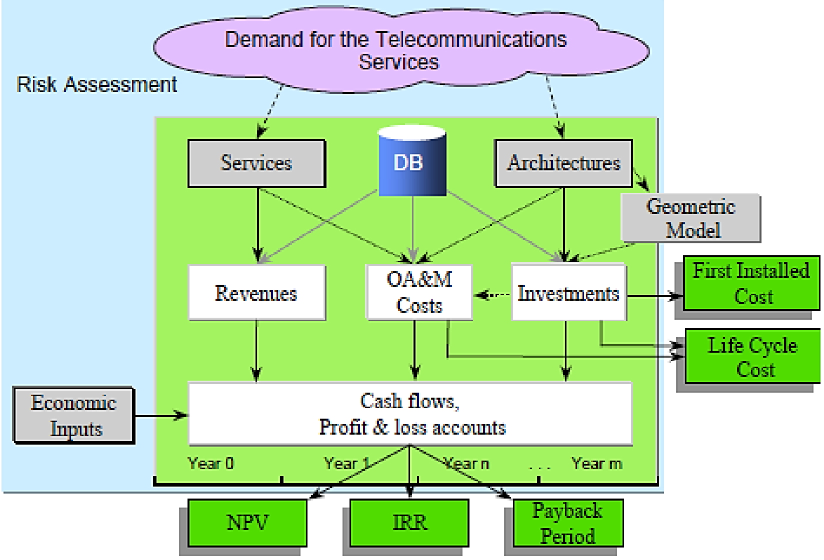


Figure 3.1. TERA framework for TEA [89]

The costs of the network components are calculated using a cost database integrated in the TERA tool. The network architecture and the shopping list together with the cost database give the investments for each year. The investments are usually spread over the study period. The operation, administration, and maintenance costs (OA&M) include the cost of repair parts, the cost of repair work, and the operation and administration costs. The first two of these are automatically calculated by the TERA tool with user-defined parameters, but the last one has to be included in the model manually. The investment costs together with the OA&M costs give the life-cycle costs of the project.

By combining the revenues, investments, OA&M costs, and general economic inputs such as discount rates, the TERA tool calculates profits, cash flows, and standard economic indicators such as NPV, IRR, and payback period. The profits are calculated from the revenues, investments, market share of the technology. The retained cash flows are calculated as the difference between the life-cycle costs and revenues minus taxes. The cash balance shows the cumulative cash flow for each year of the study period. The tool also calculates NPV, IRR, and the payback period of the project.

3.3. Modelling

3.3.1. Cost Modelling

Costs can be generally split between CAPEX and OPEX and two approaches exist for modelling these costs, differing in their starting point for the modelling process [83]. In a top-down approach, the modelling starts by analyzing an existing network infrastructure and based on it a cost is modelled for the new system, while in a bottom-up approach, the forecast demand for the new services is used as a starting point and the required costs are modelled [83]. In techno-economic modelling, the bottom-up and hybrid approaches are preferable and typically used when calculating investments as network element cost varies through time. In this study a hybrid approach used in which the cost of network elements derived from reports literatures, vendors and earlier ethio telecom LTE project while forecasted demand used example to determine the required network elements. Based on the data a cost model illustrated as in Eq. (3.1). Although the cost of backhaul and core is not considered in the cost modelling as the existing network has been under-utilized and has capacity to handle LTE-A traffic.

$$C_T = N_M C_M + N_S C_S + C_{Spectrum} + C_{BH} + C_{Core} + OPEX \tag{3.1}$$

Where, $N_M C_M + N_S C_S + C_{Spectrum} + C_{BH} + C_{Core} = CAPEX$, C_T is total cost, N_M and N_S are number of macro and small cells, C_M, C_S, $C_{Spectrum}$, C_{BH} and C_{core} are the cost related to macro, small cell, spectrum, backhaul and core network respectively and *OPEX* cost to run the network

3.3.2. Revenue Modelling

The number of subscribers, ARPU and market share are the main inputs for calculating the revenues. There are also indirect revenues stemmed from interconnection with other operators, roaming and advertising, which in some cases may even dominate over the direct revenues considered [83]. Eq. (3.2) shows the revenue modelling used in this thesis.

$$\mathrm{R_T} = ARPU * S_P \ * PM_S + \ I_R \tag{3.2}$$

Where, R_T is the generated revenue, S_P is predicted number of subscribers, PM_S is predicted market share of LTE-A and I_R is indirect revenue from for example roaming, sale of SIM, business partners and actors.

3.4. TEA Evaluation

3.4.1. Cash Flow (CF) and Discounted CF (DCF) model

Cash flow is the net amount of cash that is received and disbursed during the study period. Based on the outputs from cash and revenue model, the CF model is drawn as in the Equation (3.3).

$$CF = \sum_{i=1}^{6}(R_T - C_T\,)i \tag{3.3}$$

Where, CF is the cash flow, R_T and C_T revenue and cost models and i is the study period.

Whereas, DCF analysis, in Eq. (3.4), is the process of calculating the present value of an investment's future cash flows in order to arrive at a current fair value estimate for the investment i.e., time value of money [83, 89].

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_i}{(1+r)^i} \tag{3.4}$$

Where, CF is cash flow, r is discount rate and i the study period

3.4.2. NPV, Internal Rate of Return and Payback Period

The NPV of an investment is most favorable to measure profitability and leads to better investment decisions than other criteria [83]. NPV can be calculated, as indicated in Eq. (3.5), taking the difference between the discounted value of the future incomes and the amount of the initial investment (CAPEX). According to the NPV rule, a company should invest in any project with a positive NPV [83].

$$NPV = CAPEX - DCF = CAPEX - \sum_{i=1}^{6} CF_i \,/(1+r)^i \tag{3.5}$$

In addition to NPV, other criteria such as IRR and PP widely used in project valuation. IRR is closely related to the NPV, determined by finding the discount rate that makes NPV = 0. According to the IRR rule, a company should accept investment opportunities offering IRR more than their opportunity cost of capital. Whereas, payback period is the amount of time it takes before the cumulative incomes equal the initial investments and based on the rule, all projects that pay themselves back before a defined cut-off date, i.e. study period, are considered profitable.

4

Scenario Planning and Deployment Options for Addis Ababa

4.1. Scenario Planning

Scenario planning is a tool for exploring, managing situations or uncertainties and disruptiveness of new technologies [5, 53 and 54]. It follows four general processes: (1) *Trend analysis*, (2) *Uncertainty identification,* (3) *Correlation matrix* and (4) *Preparing scenario matrix.* Each process will be explained in the following sub-sections.

4.1.1. Trend Analysis

The contributing factors and trends with challenges for LTE-A are investigated using literatures, related works, standards, expert opinions and vendor reports. Table 4.1 shows a summary of trends and their compilation by the PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis to identify uncertainties that must be assessed and properly managed before further decisions are made.

Table 4.1 Summary of trends (PESTLE [97])

PESTLE analysis	Trends
Political (P)	Availability of spectrum, regulation on site acquisitions, policies for local phone manufacturers, competition policy
Economical (E)	Charging and tariff of services, customizing phones, high CAPEX and OPEX cost, penetration of mobile phones, energy consumption, urbanization, using existing or new sites, indoor coverage, revenue decoupling
Social (S)	User awareness on new technologies, number of connected devices, content creation , internet users shifting from wired to wireless access, growing of apps,
Technological (T)	Technology enhancement, LTE-A features, backhaul link, increased devices, indoor traffic, HetNet, Vendor, power efficient devices, traffic from smart phones increasing, mobile penetration increases, frequency reframing, content providers
Legal (L)	Low to enforce venue owners to install macro and small sites, safety from radiations
Environmental (En)	Green ICT, alternative energy sources, esthetics

4.1.1.1. Key Trends

Trends are factors, which has to be predicted by the development process of the industry [53]. Table 4.2 lists selected trends and their corresponding elaboration of its impact on the LTE-A deployment.

Table 4.2 Selected trends and description

Selected trend name and category	Description
LTE-A features (E, S, T, En)	LTE-A features and deployment preference in terms of technology and demography
HetNet (P, E, T, L, En)	Deployment of HetNet and challenge
Backhaul (E, T, L, En)	The challenge on selecting BH that can handle mounting traffic and demand, flexible and scalable, and cost efficient.
Device availability (E, S, T, L)	Availability and affordability of LTE-A services and supporting devices.
Vendors (P, E, T, En)	Role and management of vendors
Mobile app & service growth (S, T)	The evolution of new services and apps and availability attracting users to data mobile solutions.
Mobile subscribers and traffic growth (S, T)	Number of mobile subscribers as well as data traffic keep increasing
Network efficiency (E, T, En)	Application of environment friendly and power efficient networks
Economic impact (E, S, T)	Mobile broadband impact on end-users and traffic engineering/ SLA for revenue protection

4.1.1.2. Summarized Description for Selected Trends

LTE-A features and deployment preference in terms of technology and demography

During radio frequency planning of LTE-A, different implementation alternatives must be investigated in terms of spectrum, antenna techniques and modulation. According to [8], the most widely used LTE-A feature is CA. In the report, among the available bands 1800MHz takes 57% share followed by 2.6GHz and 800MHz in FDD mode whereas 2.3GHz widely deployed frequency band in TDD mode. In addition, 3GPP TR 36.814 V9.0.0 proposed 450MHz, UHF (698-960MHz), 2.3GHz and C-band (3.4-4.2GHz) bands [58, 59 and 61]. CA enables to pool spectrum resources together within the same band or across different bands to achieve higher bandwidth and capacity in an efficient manner [29, 59 and 66]. Moreover, its flexibility allows providing multiple services over multiple carriers simultaneously for better user experience, for example providing high data rate broadcast program while maintaining unicast data services such as web browsing.

In CA implementation, bands selected based on performance and requirement as different bands have different outcome, for example higher bands provide larger bandwidth whereas lower ones better for coverage requirement. In contrary, higher bands seek more cells than lower bands because of their propagation characteristics. Further enhancement of data rate might require MIMO support. MIMO can implemented with all LTE bands but high performance for higher bands ranging from 1.7 to 2.7GHz while reduced performance in lower bands. Conversely, accommodating high order MIMO in the UL is a challenge as UE size and battery life is a major concern and devices encompassing more antennas are more likely to be physically large devices (e.g. tablets). However, LTE-A provides significant gains with two transmit antennas. Combining MIMO with CA can create significant performance, especially for operators with high cost of spectrum and helps to get high data rate and reduce CAPEX and OPEX cost.

As more benefit for system performance, signal degradation and interference healing, advanced mitigation and enhancement methods also piggybacked with LTE-A like CoMP and eICIC. CoMP is a feature added on 3GPP Release 11, which provides better performance by the coordination of radio resources among BSs to increase SINR in both the UL and DL. Various types of CoMP stated in Chapter 2 section 2.3.4 and the type that could provide the highest system gain is JP with coherent transmission. However, the performance of CoMP depends on traffic load and SINR distributions that are not easy to predict/model, also high volume of CSI information over X2 interface are subject to quantification error, delay and increased ACK/NACK round trip time. It requires specific control and signaling among the master BS and the rest of the cluster BS to exchange CSI and commands with very low latency, time and phase synchronization. Whereas eICIC is important for efficient support of highly variable traffic load as well as increasingly complex network deployment situations, with unbalanced transmit power nodes sharing the same frequency [59].

Deployment of HetNet and its challenge

Indoor traffic growth necessities to deploy on demand, robust and cost-effective small cells as complement or in support of macro cells [73, 96]. Traffic planning requires to consider location, the number of cells to deploy and scalability of the network architecture for increased demand. Nevertheless, the benefit of HetNet bounded with technical, regulatory, cost and vendor related challenges like interference, backhaul, placement and power [64, 73]. Interference highly degrades the systems performance and methods to minimize interference between small cell and macro cell and small cell and small cell has to be prepared. Backhaul is one of the most formidable barriers to small cell implementations as wired options like fiber cost related problems while wireless counterparts has its own set of challenges such as clock timing, jitter control, LOS and interference. Moreover, power source to small cells is also has a significant impact and reason for ongoing cost. In relations with network element management, isolated management of small cells lead to high management cost, so that considering centralized management is crucial. In general, pre-design and pre-caution required when deploy, enhance, maintain and manage small cells to cost-effectively enhance users experience and facilitate seamless hand-over [73, 96].

The challenge on selecting future-proof backhaul and management

Because of the following factors; base station coordination requirement for CA, eICIC and CoMP, meshing of X2 interfaces to avoid unnecessary traffic Ping-Pong and improved latency and minimized network load, the introduction of HetNet and eNodeB demand to communicate with a pool of S-GWs for the purposes of reliability, preparing a MBH that can cope with the ever-increasing demand either with upgrade or replacement is an inevitable [63]. Discussions in [44-52], indicated that scalability, flexibility and simplicity are the three important requirements considered for the backhaul. LTE-A backhaul necessitates SLA performance criteria for availability, packet delay, jitter and packet loss. LTE-A brings further enhancement in spectral efficiency to support extended traffic volume and advanced radio signal processing technique to boost throughput and its features also add engineering complexity to the backhaul. Fiber based backhaul can typically be designed to easily meet this requirement and emerged as the de-facto choice for LTE-A backhaul. Using LoS microwave can also provide similar services, as both options share similar latency characteristics. However, from a microwave link perspective 99.999% availability, i.e. approximate 5 minutes of downtime per year is a requirement. Moreover, security and capacity issues puts MW link alternative doubtful. From the capacity point of view, fiber supports unlimited capacity, conversely, high cost of it makes difficult to use fiber as backhaul link for all deployment scenarios.

Therefore, the MBH link must not be a bottleneck for the increasing capacity and coverage and to the delivery of an optimal QoE for end-users. For the growing number of sites for increasing demand and traffic, mix of macro and small cell for QoS and requirement for standardized and simplified BH to minimize Cost of Ownership (TCO) and OAM respectively. The other strategic factor beside the network infrastructure is management of network elements. Two alternatives exists, either to use the present LTE/3G/2G Operation Support Subsystem (OSS) or separate management system. However, planning to use other capability of LTE-A, called Self Organizing Network (SON) in the long run saves cost. SON encompasses equipment that can sense their surroundings and have necessary intelligence to configure themselves and synchronize with surrounding networks. It will ease the deployment of small cell networks by eliminating manual configuration of equipment at the time of deployment and enable OPEX cost reductions by dynamically optimizing radio network performance during operation.

Availability and affordability of LTE-A services and supporting devices

High tariff, device and inter-network switching cost affects the operator’s upgrade decisions [60]. Therefore, to keep end-user retention and reduce churn rate providing incentives for legacy network users is important. Also, adopting mechanisms for different pricing models than charging higher prices for LTE-A offerings compared to their existing mobile data plans and maintain a higher QoS, for example, “pay-for-what-you-use” pricing models where end-users are charged based on their usage behaviors attracts more users. The leading smart phone manufacturers like Apple, Huawei, Nokia and Samsung are in mass production of LTE-A capable devices. A study of device penetration in Addis Ababa indicates there are devices that can apt with requirements of LTE-A [Chapter 5 Figure 5.6]. However, it is not affordable to most of users in the market. An alternative option can be providing featured LTE-A devices with bundled services or/and supporting local smart phone manufacturers by policies so that ease pain of end-users getting affordable LTE-A devices. Other mechanisms such as lower user terminal costs by reducing import duties or through targeted subsidies, support local internet content in local languages and creating e-government and e-applications.

Role and management of vendors

Vendors deliver network equipment, software, management tools, maintain and train personnel and four general classification of vendors called based on their responsibility [62]. Strategic – are vendors that are high dependence, cost exposure in which organizations need to increase business with, emerging – vendors with small initial presence but can grow over time. Legacy – vendors stayed for a longer period of time, but not strategic and Tactical-vendors that are small in cost and exposure. Trends showed that, complex originations like telecom operators spread Vendor Management (VM) responsibilities and activities throughout their departments. However, organizations that engage in high infrastructure expansion have to develop a disciplined approach to VM for the advantage of gain control over vendors, determine gaps and overlaps [62].

Reduction of risk especially those supporting critical business applications and processes and understand organizational skills to manage vendors and where they exist and identify gaps and ensure the right personnel, with the right skills and leverage vendor management best practices across the organization. Finally, the operator that relay on vendors have to take precaution in decisions during technology selection and agreement, i.e. following and checking requirement in comply with specification.

Number of mobile subscribers as well as data traffic keep on increasing

The number of mobile subscribers increasing from time to time. According to [55, 74], world wide mobile broadband subscription will reach 9Billion by 2022, which were 7.5Bilion in 2016, and 5Billion of it will be LTE/LTE-A subscribers. In the stated period the total traffic generated will reach 71EB, which were 8.8EB in 2016, while the generated traffic per smartphone reaches 12GB per month [54, 55 and 58]. In [55], it is presented that the role of emerging markets, like Ethiopia, is high in Sub-Saharan Africa and it places Ethiopia among the top five countries in the world who add net mobile subscribers of 3Million, in the fourth quarter of 2017. From the data obtained from ethio telecom, it is observed that the number of mobile subscribers have reached 61.81Million (>50% penetration) of which 243Thousend are LTE subscribers. In addition, the revenue generated from this sector takes 87% of share over other services provided by ethio telecom [3]. In [57], it is indicated that broadband connection could help to transform a country's economy development and improve employment growth if effective policies and guideline are set for policy makers, regulators and other stakeholders. Moreover, mobile broadband could help to transform a country's economy development and improve employment growth if effective policies and guideline are set for policy makers, regulators and other stakeholders [5, 57].

Application of environment friendly and power efficient networks

Densification cause concerns of power consumption and influence on the environment. According to International Telecommunication Union-Standardization (ITU-T) sectors' Y.3021, among objectives in developing future networks, having environment aware networks is basic for reduced CAPEX and OPEX cost and extend lifetime of an equipment. Considering the contribution of ICT to reduce the undesirable impact on the environment also other major aspect. Its implementation often categorized into "Green by ICT" and "Green ICT", which has interpreted as green by future networks and selecting and applying green technologies for networks [56]. In both implementations energy consumption of network elements and its impact on the environment significantly reduced. Standardization bodies suggest techniques that will aid in reducing energy consumption. Smart antenna systems such as MIMO can support higher data rates under the same transmit power, frequency and bit-error-rate and then gain of high spectral efficiency and SINR. Other mechanisms like energy efficient BSs, energy consumption-based routing and traffic engineering, energy aware network planning and shifting the traffic during peak time can save more energy. Besides, emerging technologies like C-RAN (Cloud/Centralized RAN) and SON are encouraging features for management of resources as well as promoting efficiency in power, cost and interference reduction. C-RAN assists in energy saving and RRM controlling by pooling BBUs in selected master eNodeB and then backhauling it to RRH as network access point in HetNet.

Traffic engineering and SLA for revenue protection

The decoupling between traffic growth and revenue generated from it will be the challenge for network operators [29]. As the network intelligence has shifted from the core network to the edge and access even to devices, operators move in making huge investment and being act as bit provider results in decreasing revenue. Therefore, service providers need to figure out new ways to generate additional revenues by implementing traffic engineering and converting bit pipes to smart pipes and empower SLA to end users and bandwidth allocation to content providers. Differentiated QoS/QoE of mobile service helps to guarantee bandwidth efficiency than allocating bandwidth for all of the mobile services, for example services such as video streaming [60].

Progressive vs. full rollout of LTE-A to the market

Covering the whole target area by LTE-A demands high CAPEX and OPEX cost as technology's adoption comes through time and leads to wasting resources unnecessarily. While progressive rollout of LTE-A to hot-spots helps the operator to manage the network, cost, traffic, in contrast it resulted in degraded QoS as UE moves between LTE-A and non-LTE-A networks will be a reason for user frustration and increased churn rate. In this scenario, full implementation of the network will be compulsory. However, the decision depend on tradeoffs like between cost vs. number of users, user's responsiveness and acceptance rate, phone availability and related reasons. Therefore, careful investigation of the above scenarios with the target technology features can determine the rollout constraints.

4.1.2. Selected Uncertainties

From the selected trends, the uncertainties in Table 4.3 are chosen for further analysis and a correlation matrix developed based on Shoemakers scenario planning methods. Correlation matrix is a tool used to identify interrelationships between uncertainties [53].

Table 4.3 Selected uncertainties

Uncertainty	Description
U1	Which deployment options and LTE-A features are best practical and feasible for ethio telecom? *Full/complete or Progressive*
U2	Will LTE-A feature compatible devices both local and imported available in affordable price?
U3	How to implement cell type/HetNet to handle data traffic and tackle related challenges? And How to manage the indoor and outdoor user and traffic? Small cell and band selection as in-band or out-band,
U4	Which backhaul link feasible to handle the growing subscriber and traffic? *Fiber or wireless or existing or new*
U5	Do strategies; data price plan featured phones, awareness creation, vendor management, and role of content providers influences the organization and end-users and then promote users as well as traffic growth?
U6	Will end-users adopt to LTE-A quickly?
U7	Thinking of CA, which implementation scenario, i.e. using new frequency band or refarming or using intra-band and inter-band CA, is cost effective and answers the required demand? *Refarming or getting new or intra-band or inter-band*

It is then a prerequisite to check the interrelation between uncertainties, to see the impact of one uncertainty on another so that critical, scenarios identified. It is performed as [53], for example in Table 4.4 a “yes” answer of an uncertainty for U1 will increase the chance of a “yes” answer for the U2. If the chance goes up, the correlation between U1 and U2 marked as “+” to indicate positive, if chances go down marked as “-“. Symbols, “0” and “?” indicates the two uncertainties relationship is independent and indeterminate respectively. It is possible to construct different scenarios matrices from the independent uncertainties. Finally, U1 and U3 selected to construct final scenario matrix, while others support analysis of selected scenarios.

Table 4.4 Correlation matrix

	U1	U2	U3	U4	U5	U6	U7
U1	×	+	0	+	+	+	+
U2	×	×	+	+	0	?	0
U3	×	×	×	+	0	+	?
U4	×	×	×	×	+	+	?
U5	×	×	×	×	×	+	?
U6	×	×	×	×	×	×	-
U7	×	×	×	×	×	×	×

4.1.3. Scenario Matrix

The following key uncertainties, discussed below, are selected as a key for the scenario matrix and further investigated for the techno-economic analysis.

a. Deployment option:

Trends show that majority of LTE-A deployment are using CA, followed by combination of CA, MIMO and high order modulation to acquire high data rate and increase overall network performance. Moreover, the choice to deploy LTE-A progressively or in full is the important aspect to consider in terms of resource, CAPEX and OPEX cost. Decision in choosing of features and deployment options, relay on the capacity, resource and vendors who provide the technologies. In terms of deployment, progressive option will ease early pains for operator related with expenditures and device cost. However, it will result degraded QoS as user’s moves between the LTE-A covered and non-covered areas. On the other hand, full deployment avoids coverage constraint and satisfy end-users demand, but it will require high CAPEX and OPEX cost. Overall, in deploying LTE-A ethio telecom has to plan efficient and effective ways that reduces capital and operational cost, utilize the resources, i.e. spectrum, BSs, BH and core network, plan strategies that will promote MBB usage and follow a tariff model that attracts more users and generate revenue from it.

b. Small cell type and band selection:

It is pointed out that, in cellular networks more than 50% calls and over 70% of data services occur indoors [Section 3.3]. Performance related factors, such as penetration loss, prohibit signals to address indoor users that relay on traditional macro cell-based deployments. Different techniques were adopted to tackle the difficulties; increasing capacity with new radio spectrum, adding multi-antenna techniques and implementing efficient modulation and coding schemes. Also densification can be used by adding more sectors per BS or deploying more macro BSs. Nevertheless, these measures alone are insufficient in the most crowded environments and at cell edges where performance can significantly degrade. Moreover, some approaches are difficult and expensive. An alternative approach is using diversification of cells by introducing low power small cells to existing macro BSs, known as HetNet. Its reduced power consumption, installation, CAPEX/OPEX cost than defined methods makes operators to change paradigm and then enhance the network capacity, coverage and quality using small cells.

Small cells operate in similar fashion with macro cell and uses same resource except the coverage area and capacity. Regarding resource spectrum allocation for small cells is crucial and have to be managed to avoid interference. Two types of spectrum assignment are possible, in-band - shares same band with the macro cell and out-band - a dedicated frequency assigned to small cells. In-band requires reduced investment cost, but interference degrades the quality of service that needs advanced interference management techniques such as eICIC. While out-band increases the overall system efficiency and capacity with high investment cost. In general, it is indispensable to deploy a robust, cost-effective LTE-A using macro or small cells depending on requirement and concerns in relation to backhaul, controlling/monitoring systems, handover and vendor has to be addressed.

The two uncertainties are basis for the selection of scenarios and the rest of uncertainties used for detailed explanation. Finally, the resulted plausible scenarios (Figure 4.2) that will be uncertain in the LTE-A implementation are obtained and discussed in the following section:

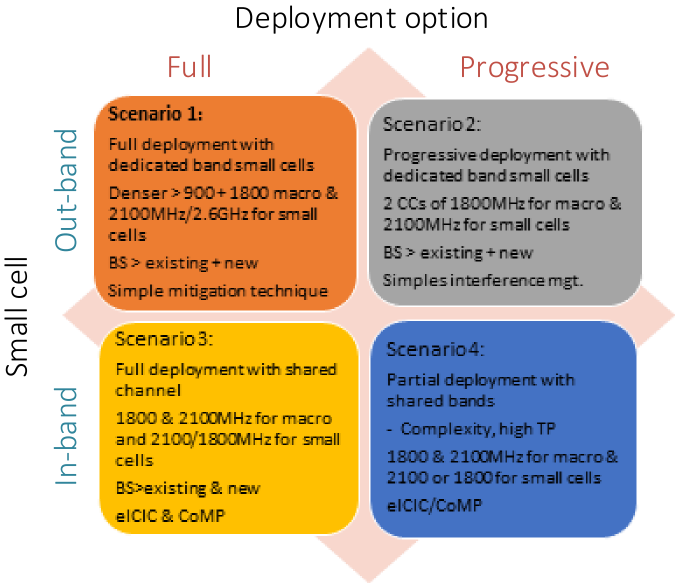


Figure 4.1. Scenario matrix

4.2. Deployment Option for Addis Ababa

From the scenario matrix, Figure 4.1, the following scenarios are selected as the LTE-A deployment option for Addis Ababa. Carrier aggregation and small cells selected for LTE-A deployment based on the discussed trends, performance and cost. The carrier aggregation combination performed by refarming the existing unused band slots and based on 3GPP R’14. The following tables indicates the aggregation of bands for macro and small cells.

Table 4.5 CA configuration and BW combination set defined for band 3 and 8 [3GPP R’14]

CA Config.	UL CA Config	Band	1.4 (MHz)	3 (MHz)	5 (MHz)	10 (MHz)	15 (MHz)	20 (MHz)	Max.agg. BW (MHz)	BW combination set
CA_3A_8A	CA_3A_8A	3				Yes	Yes	Yes	30	0
		8			Yes	Yes				
		3				Yes			20	1
		8			Yes	Yes				
		3			Yes	Yes	Yes	Yes	30	2
		8		Yes	Yes	Yes				
		3			Yes	Yes	Yes	Yes	30	3
		8			Yes	Yes				
CA_3A_3A_8A	CA_3A_8A	3	Table 4.8						50	0
		8			Yes	Yes				
		3	Table 4.8						40	1
		8			Yes	Yes				
CA_3C_8A	CA_3A_8A, CA_3C	3	CA_3C with 2 Contiguous CCs with 40MHz						50	0
		8		Yes	Yes	Yes				

Table 4.6 CA configuration and BW combination sets for non-contiguous CCs of 1800MHz [3GPP R’14]

CA c Config.	UL CA Config.	Channel BW for carrier (MHz)	Channel BW for carrier (MHz)	Max. aggregated BW (MHz)	BW combination set
CA_3A_3A	-	5,10,15,20	5,10,15,20	40	0
		5.10	5,10,15,20	30	1
		5	3	10	2
		3,5	5		

Table 4.7 CA configuration and BW combination sets for contiguous CCs of 2100MHz for small cells [3GPP R’14]

CA Config.	UL CA Config.	Channel BW for carrier (MHz)	Channel BW for carrier (MHz)	Max. aggregated BW (MHz)	BW combination set
CA_1C	-	5,10,15,20	5	25	0
		5	5,10,15,20		

Table 4.8 CA configuration and BW combination set defined for band 1 and 3 [3GPP R'14]

CA Config.	UL CA config.	Band	1.4 (MHz)	3 (MHz)	5 (MHz)	10 (MHz)	15 (MHz)	20 (MHz)	Max.agg. BW (MHz)	BW combination set
CA_1A_3A	CA_1A_3A	1			Yes	Yes	Yes	Yes	40	0
		3			Yes	Yes	Yes	Yes		
		1			Yes	Yes	Yes	Yes	40	1
		3		Yes	Yes	Yes	Yes	Yes		
CA_1A_3A_3A	-	1			Yes	Yes	Yes	Yes	60	0
		3	CA_3A_3A 40MHz agg. BW using non-contiguous CCs							
CA_1A_3C	CA_1A_3A, CA_3C	1			Yes	Yes	Yes	Yes	60	0
		3	Using CA_3C 40MHz obtained using contiguous CCs							

Table 4.9 CA configuration and BW combination set defined intra-band contiguous CCs of band 3[3GPP R'14]

CA configuration	UL CA configuration	Channel BW for carrier (MHz)	Channel BW for carrier (MHz)	Max. aggregated BW (MHz)	BW combination set
CA_3C	CA_3C	5,10,15	20	40	0
		20	5,10,15,20		
CA_3B	-	5	3	10	0
		3,5	5		

From the tables and available resource, maximum of 60MHz aggregated bandwidth obtained using inter-band CA of 3 component carriers from band 1 and 3 and as minimum as 10MHz using inter-band carrier aggregation, Table 4.8 and 4.6 and 4.9 respectively. However, using Intra-band carrier aggregation is preferable if the operator has required bandwidth for LTE-A and in parallel eludes network and UE complexity, as UEs has to decode, modulate three or more non-contiguous CCs, Table 4.7. By refarming the existing spectrum, 40MHz bandwidth obtained using intra-band carrier aggregation and component carriers of 1800MHz, Table 4.6. On the other hand, a combination of band 3 and 8 provide 50MHz aggregated bandwidth. Considering higher throughput requirement for LTE-A a combination of higher bandwidth taken for the succeeding scenarios using band 3 and 8 for macro while band 1 and 7 for small cells.

4.2.1. Scenario 1

Full deployment with small cells using out band carriers

According to [3], Addis Ababa's demography categorized as dense-urban (DU), urban (U) and sub-urban (SU). DU/U areas identified as crowded with high traffic and SU sparsely populated areas. For these areas the implementation of macro and small cells is based on coverage, capacity, throughput, network complexity and cost which are the determinant factor for LTE-A deployment. Concerning carrier aggregation the existing unutilized band slots refarmed and it can be possible to obtain aggregated 50MHz bandwidth by combining the three frequencies, i.e. 900, 1800 and 2100MHz, Chapter 6 section 6.4 and Table 4.5-4.9. Different bands assigned for the macro and small cell for the purpose of mitigating interference beside high network performance. In addition, bands combined using bandwidth and demography. Dividing small cells in to layer is important to allocate resources based demand, reduce interference and spectrum efficiency.

Relying on the above discussions and Table 4.5-4.9, deployment option that best suit for full deployment of LTE-A is to use 900MHz and 1800MHz for denser and CCs of 1800MHz for densest macro cell and allocate 2100MHz for small scale and high band frequency, e.g. 2.6GHz, for dense small cell requirements, Figure 4.2 (a) and (b).

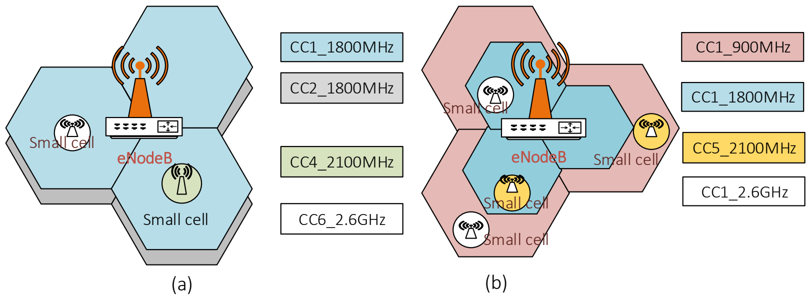


Figure 4.2. LTE-A deployment option: (a) Using two CCs of band 3 for macro and band 1/7 for small cells, (b) using band 3 and 8 for macro and band 1/7 for small cells

For SU areas 1800MHz used for macro coverage and 2100MHz for hotspot to enhance data rate. Figure 4.3 shows deployment option for SU using 1800MHz for coverage in macro level and 2100MHz for the RRH.

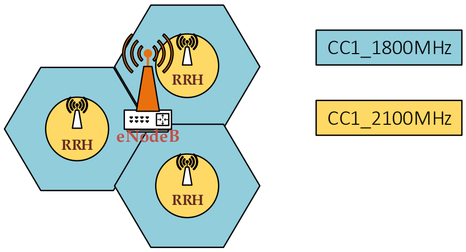


Figure 4.3. LTE-A deployment for SU

4.2.2. Scenario 2

Progressive deployment with out-band small cells

Covering the whole city may not be feasible because of high investment cost. The substitute deployment approach is to deploy LTE-A progressively starting from DU and proceed to other areas. Taking network complexity on UE and BSs in to consideration, assuming small scale small cell requirement, relying on contiguous CCs will be beneficial to address the current market demand for DU/U. Achievable aggregated bandwidth for macro and small cell summarized in Table 4.6, 4.7 and 4.8. *Therefore, assuming higher bandwidth, for these scenario contiguous CCs of 1800MHz assumed for macro cells. Whereas, component carriers of 2100MHz and 2.6GHz assumed to be used for small cells, Figure 4.4.*

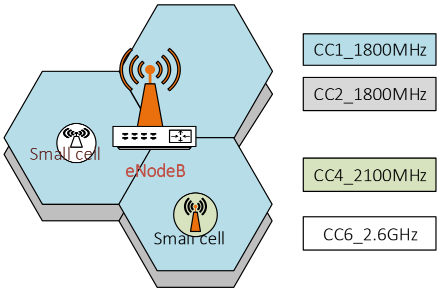


Figure 4.4. Progressive LTE-A deployment: Non-contiguous intra-band CA using 2 CCs of band 3 and contiguous CCs of band 1 for small cells and

4.2.3. Scenario 3

Full deployment with small cells using in band carriers

In the option of implementing LTE-A in full range in which the small cells sharing the same band as the macro cell, there is a trade-off in providing higher throughput with reduced interference and cost. Taking performance of macro and small cells, demography and interference in to considerations the following viable option selected for ethio telecom for full deployment of LTE-A with in-band small cells for DU/U and SU areas. *For denser DU/U areas using CCs of 1800MHz for macro and small cell whereas assigning 1800 and 2100MHz for macro cells and 2100MHz for small cells with interference mitigation techniques for less dense areas, Figure 4.5 (b) and (c) respectively.*

In SU areas with lower data and traffic demand than DU/U, choosing bands that will provide coverage and throughput is advantageous. *Assuming shared channel between macro and* *small cells, 1800MHz for macro coverage and CCs of 1800MHz for hot spot areas, Figure 4.6.* In the future, the macro cell can use either CC of 1800 or 2100. For the two demographies, intra-system interference management techniques required such as eICIC and CoMP and for the inter-system interference inter-system coordination used.

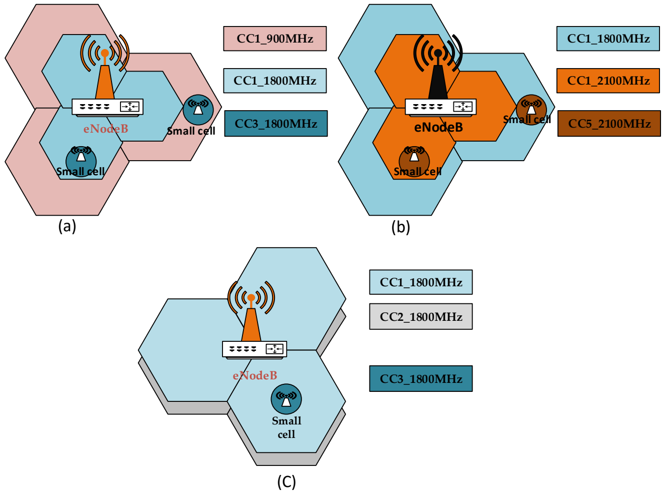


Figure 4.5. LTE-A deployment: (a) Band 8 and 3 for macro and band 3 for small cells (b) Band 3 and 1 for macro and CC of 1800/2100MHz for small cells and (c) two CCs of 1800MHz for macro and small cells

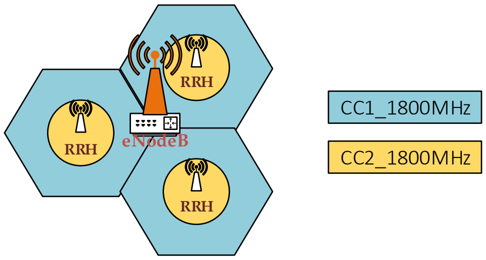


Figure 4.6. LTE-A deployment for SU

4.2.4. Scenario 4

Progressive LTE-A deployment with in-band small cells

For progressive LTE-A deployment with in-band small cells for DU/U areas, a combination of component carriers of 1800MHz used assuming performance, reduced UE and network complexity and cost. *For densest and denser areas two component carriers, CC1 and CC2 used for micro cell and while either of the available CCs of band 3 and band 7 assigned for small cells, Table 4.6 and Figure 4.7 (a) and (b) respectively*.

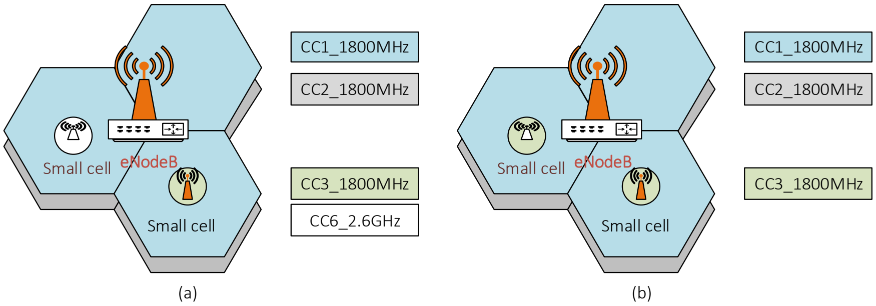


Figure 4.7. Progressive LTE-A deployment: (a) CCs of band 3 for macro and band 3/7 for small cells (b) CCs of band 3 for macro and small cells

To reduce the interference and provide quality of service for end-users enhanced mitigation techniques, eICIC and CoMP used which require additional investment and operational cost.

5

Applied TEA Framework and Tool

5.1. Modified TEA Framework

The original TERA framework/model is modified for this thesis, as shown in Figure 5.1, to contain parameters that will enhance the performance of the network. The efficiency of a telecom can be pre-designed during technology selection as well as operating the network that will directly decrease the CAPEX and OPEX cost and indirectly upturn revenue.

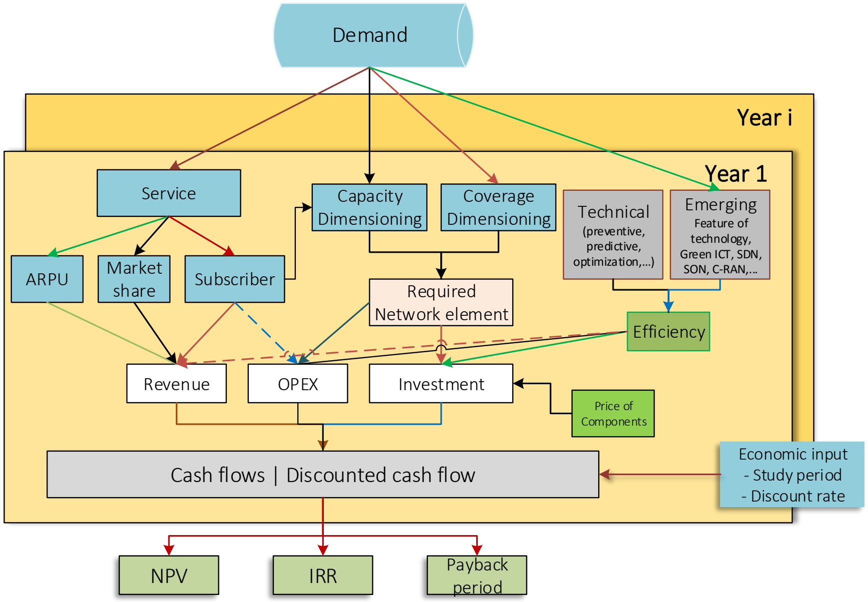


Figure 5.1. Modified TERA framework for TEA

5.1.1. Efficiency Parameters in Brief

In the modified framework technical (maintain, renew and optimize) parameters, like preventive and predictive maintenances and emerging or new technologies and features that can aid in increasing overall system efficiency considered.

5.1.1.1. Technical

The components assumed in this category related with costs arise after the operation of a given technology, i.e., OPEX. OPEX cost is one of the determining factor in analyzing the viability of a technology. Currently most of the maintenance procedures functional after the service interrupted and complaints at hand. This is a major problem that will significantly degrade the image of the service provider and a reason for high OPEX cost and revenue loss.

So that, using available mechanisms such as predictive, proactive/preventive maintenances by identifying critical network elements (NE) and using standards and state-of-the-art technologies and methodologies are mandatory. For example, in [90], demonstrated that by integrating infrared thermography module in the identified NE can effectively predict thermal defect in electrical components and protect from network failure.

In addition, proactive maintenance using database containing logs of systems alarm to provide better solution, deep analysis of the root cause of failure and regular optimization procedures are crucial measures to consider , Figure 5.2.

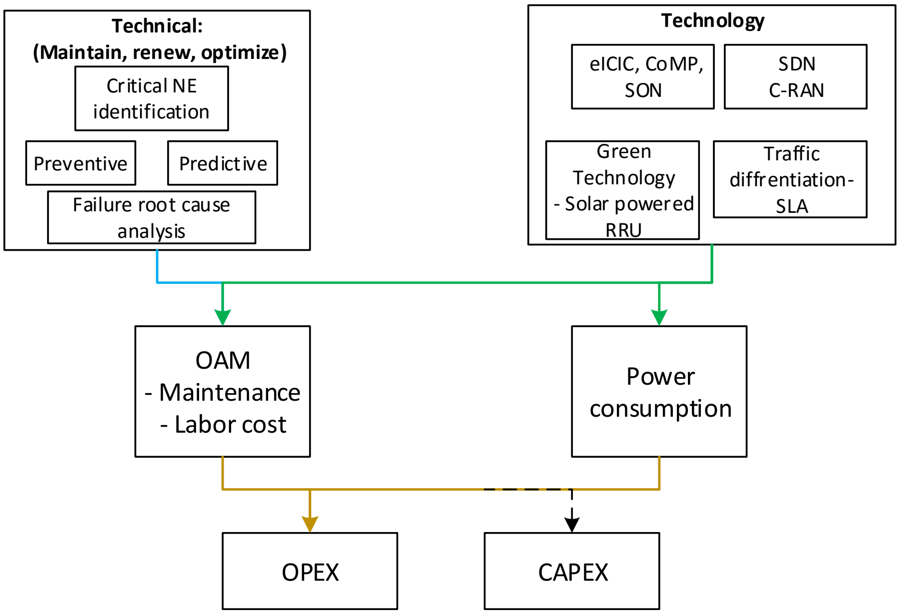


Figure 5.2. Cost reduction mechanisms

5.1.1.2. Technology

The consideration to new and emerging technologies is other milestone to further enhance the efficiency of a network, aid in cost reduction and income increment. Beside selected technology feature and its implementation, for example application of Green RRU and centralized RAN are advantageous to decrease CAPEX and OPEX cost. Moreover, additional features of LTE-A such as CoMP, eICIC and SON also helps in efficient network performance and better management of mobile network equipment. Moreover, parameters like SLA incorporates definitions of provided services that provide obligated to deliver for end-users, such as resolution time. SLA establish user's expectation with regard to performance, QoS and the operator can apply traffic differentiation by giving priority for key services and technologies such as video streaming and HD audio. Besides keeping a high QoE consistently required, the operator can manage the traffic by avoiding unnecessary traffic over-flooding the network and reduce related operational costs. In addition, by implementing efficient digitized management of resources, the operator can improve the resolution time and avoid wastage of resources.

5.2. Developed Tool and Inputs

Based on input/output parameters of the TERA and modified model, a new TEA tool developed for this thesis, Figure 5.3.

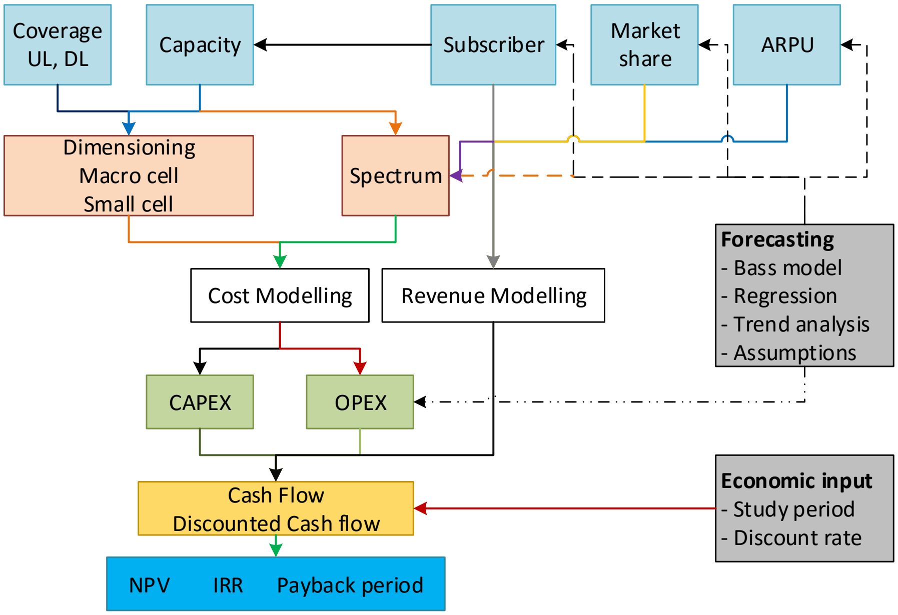


Figure 5.3. A flowchart of TEA tool developed for this thesis

5.2.1. Tool Description

The TE analysis of the LTE-A deployment performed for a certain defined study period, six years used for this research. The services to be provided, market penetration, target subscribers of these services over the study period and availability of LTE-A capable devices also defined. The revenues for each year are calculated from the combination of yearly market share, subscriber and ARPU. The network elements to provide the services defined based on network dimensioning and the costs of the network components are calculated using sources from literatures, vendors and previous ethio telecom LTE project. The OPEX cost results from the operation, administration, and maintenance costs (OA&M) include the cost of operation and administration and costs related with running the network such as power consumption, computed. In the analysis a discounting rate of 10% used and based on the newly developed TEA tool outputs such as profits (Eq. (3.2)), cost (Eq. (3.1)), cash flows (Eq. (3.3)), and standard economic indicators such as DCF (Eq. (3.4)), NPV (Eq. (3.5)), IRR, and payback period generated calculated using the associated equations in brackets.

5.2.2. TEA Inputs

5.2.2.1 Market Analysis

(i). Monthly Data Plan

LTE-A provides better user experience than previous mobile generations, as a result mobile based apps and services emerging every time that require high network capacity and speed. According to [98], to stream a low-quality audio with 96kbps it requires 0.72MB per minute. Whereas it requires 2.4MB to stream 320kbps high quality audio. In addition, it requires 0.3GB, 0.9GB and 7.2GB to stream 320p low quality, HD 720p and UHD 4K video respectively [88]. The following table, Table 5.1, shows data plan versus apps and services.

Table 5.1 Data plan vs. apps and services [88, whistleOut.com]

Apps and services	3GB	10GB	15GB	At least 20GB
Email	✓	✓	✓	✓
Web browsing	✓	✓	✓	✓
Facebook	✓	✓	✓	✓
Music streaming	✓	✓	✓	✓
Online gamming	✓	✓	✓	✓
YouTube	✓	✓	✓	✓
Streaming video	✓	✓	✓	✓
Downloading movies and games	✓	✓	✓	✓

Green= good, Yellow= caution and Red= need more data

In [98], it is indicated that different services providers like YouTube, Facebook uses different bitrate depending on the media resolution and bandwidth. For example, a 4.5Mbps 1080p HD movie for 10 minutes over fast internet connection require 34MB data [88]. T-Mobile illustrated and suggest a data plan of 30GB per month/user to access online streaming video, social media, and etc. The following table, Table 5.2 shows average smart phone data usage to browse different applications and services. Overall, a single user can stream online video, use social media, download apps, surf web and sent and receive emails. The current, data plan for ethio telecom for LTE network is 20GB/month/user for average users [3]. Relying on growing demand, the above estimates, assumption and discussion, a data plan of 30GB is assumed and used for capacity dimensioning for LTE-A deployment.

Table 5.2 Smart phone data usage

Apps/services	Required data			
Source/Operator	Ting.com	AT&T	US_cellular	Telstra
email	350KB/email	300KB/email	350KB/email	0.5MB/email
Photo	2MB/photo	5MB/photo	4MB/photo	0.5MB/email
Social	250KB/post	5MB/post	250KB/post	250KB/post
Browsing	180KB/page	250KB/page	180KB/page	1.5MB/page
App download	4MB/app	5MB/app	4MB/app	35MB/app
Music streaming	1MB/min	2MB/min	1MB/min	2.5MB/min
Game play	1MB/min	200KB/min	1MB/min	35MB/min
Video streaming	16.5MB/min	97.5MB/min	16.5MB/min	3.75GB/movie

(ii). LTE-A Subscribers Forecast

For the two scenarios, the number of subscribers forecasted for six years based on Bass model. Bass model is the best-known model for a full description of the beginning and extensions of new service. It provides a conceptually appealing and mathematically elegant structure to explain how a new technology or product diffuses through a target population of end-users. It well explains the market predicting a system for the product or service types having a diffusion type characteristic such as mobile telecom [95]. The number of future LTE-A users will depend on the population potential, growth rate innovation (p) and imitation (q) coefficients and estimated according to the following equation, Eq. (5.1).

$$N(t) = M * \frac{1 - e^{-t(p+q)}}{1 + \frac{q}{p}\, e^{-t(p+q)}} \tag{5.1}$$

Where, *M* = is the market capacity, previous LTE and 3G subscriber assumption by [3] presumed, *p* > 0 is the probability of initial purchase of LASIM (LTE-A SIM) at the beginning of the service life cycle and is related to the size of the initial adoption, *q* > 0 refers to the size of the group of possible future adopters and *N (t)* is the number of subscriber at time *t* (1 to 6 years).

In this research, M is assumed based on Table 5.3, with growth margin of 15%, 10% and 2% for DU, U and SU respectively, for both scenarios. While average value of 0.03 and 0.38 taken for p and q respectively. Using equation 5.1 the results of forecasted subscribers for the study period for the two scenarios summarized in Table 5.4 and Figure 5.4.

Table 5.3 Subscriber forecast assumptions [3]

Demography	Area (km^2)	Population	User/km^2			Scenario	
						One	Two
Dense urban	70.46	901,893	12,800		Area(km2)	240.82	779.95
Urban	170.36	838,395	4,921		Population	1,740,288	2,103,571
Sub urban	539.13	363,283	674				
Total	779.95	2,103,571					

Table 5.4 Subscriber forecasted for six years

Year	2010 E.C	2011 E.C	2012 E.C	2013 E.C	2014 E.C	2015 E.C	2016 E.C
N(t) Scenario 1	47,274	175,212	441,916	852,950	1,263,364	1,529,004	1,656,502
N(t) Scenario 2	57,143	211,787	534,166	1,031,003	1,527,090	1,848,182	2,002,295

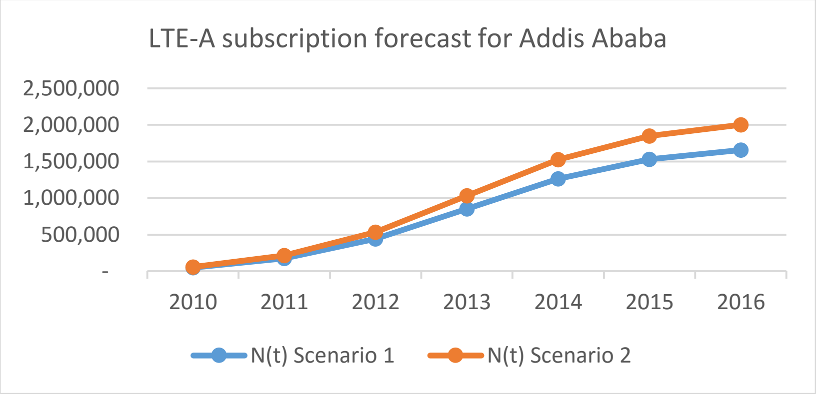


Figure 5.4. LTE-A subscriber forecast for six years

(iii). ARPU

Next, taking the profit generated and 85% mobile market share assumption and subscriber growth, the ARPU calculated for the previous ten years and forecasted for the coming six years using exponential regression [3]. The result indicates that the subscription as well as ARPU keep on increasing, Figure 5.5.

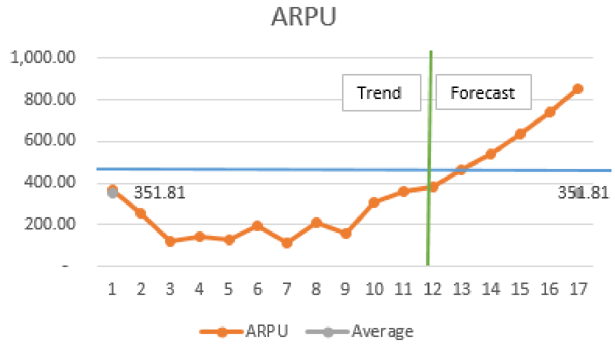


Figure 5.5. ARPU trend and forecast

(iv). Smart Phone Penetration

LTE-A capable device analysis in Addis Ababa indicates that smart phone availability and penetration rate is increasing and the market is advancing in to multi-device era in which smartphone users are likely to own a tablet, mobile Wi-Fi router or other device [3]. Even though the outcome after LTE-A deployment from the user side is unpredictable and depends on the deployment option engaged, ethio telecom must expand the customer base by adding new value-added services, flexible data tariff, other mechanisms to attract more users and then increase ARPU.

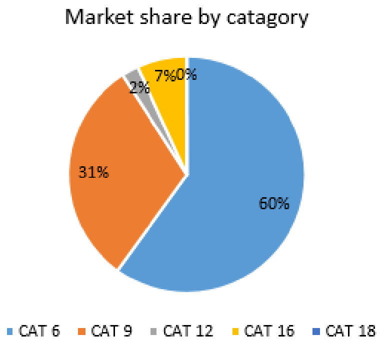


Figure 5.6. LTE-A capable device availability [3, Table 2.5]

(v). Market Share

LTE-A is new to the market, and it will be difficult to quantitatively put the market share, therefore, forecasted results in; publications, white paper and reports on the subject matter used for these thesis work. In [4 and 9], it is mentioned that LTE-A will take 50% of the global mobile market share. The same report pointed out that, the developing countries, especially Sub-Saharan Africa will achieve higher rate of ARPU with growing MBB ultimatum through LTE/LTE-A. In these regions the number of mobile subscription and data demand increasing exponentially and according to [55], Ethiopia called as an emerging market for mobile network with higher mobile subscriber growth. Sources from ethio telecom also show that the mobile penetration reaches 60%, which strengths the MBB and subscription demand escalation [3]. In [4, 8], the market share of LTE-A in 2017 in Sub-Saharan Africa was 4% and projected that it will reach 12% and 29% in 2020 and 2025 respectively.

5.2.2.2. CAPEX and OPEX cost

Network dimensioning is carried out to determine the CAPEX and OPEX of network equipment required to offer the planned services to the end users, Chapter 6. The costs driven based on recent literatures, vendor reports and data driven assumptions.

(i). CAPEX

After the required number of eNodeBs known by capacity and coverage dimensioning [Chapter 6], the next step is to determine the cost related to network components. According to [65, 85 and 86], the total CAPEX of three sector new MaBS with CA is 130k£ (equivalent with 4,215.90k Birr, i.e. exchange rate of 1£ (Euro) = 32.43Birr [87]). In addition, for the upgrade of the existing site, i.e. 329 LTE BSs, 30k £ (972.90k Birr) taken for CAPEX. For small cells like MiBS and PiBS 50% and 15% of MaBS respectively. In [120], for site with 4G LTE a CAPEX cost of 15K GBP (equivalent with 545.55kBirr, i.e. 1GBP = 36.37Birr) for MaBS. Whereas for site with no LTE network it is assumed 58.90kGBP (2,142.19KBirr) for deploying multicarrier BS and civil works and for small cells including equipment and civil work a total CAPEX cost of 15.8k GBP (574.65k Birr) taken. Further in [86] the total CAPEX cost to deploy LTE-A given as; $147k (4,116k Birr, 1$=28 Birr) for macro cell and in [86] a maximum of $100k (2800k Birr) and $10k (280k Birr) required for macro and small cells. Table 7.3 summarizes the CPEX cost. For this research average value assumed and 3,318.52k Birr and 759.23k Birr is taken as CAPEX cost for new site and upgrading existing LTE site respectively. For outdoor and indoor small cells 20 and 10% of the macro cell CAPEX assumed for the TEA.

(ii).OPEX

The operational cost related with maintaining, running and OA&M given as 648.6k Birr for new site and 324.3k Birr for upgrade in [65, 85]. In [86], 1.8k GBP (58.73k Birr) and 3.9k GBP

(127.26k Birr) with erosion factor of 5% per year taken for upgrading and new site respectively. In [86], $29.55k (827.4k Birr) taken as OPEX cost for new site with 3 CCs. For the research average values taken, i.e. 534.42kBirr for new and 191.52k Birr for upgraded sites. To determine the cost of small cell similar approach is used as CAPEX cost, 20% of OPEX of macro for outdoor and 10% for indoor. Since operation is a continuous process, the OPEX is not a single time cost as CAPEX. For the study an erosion factor of 5% used for the study period for the OPEX. Also, other factors assumed that can further decrease the OPEX cost that can also strengthen the erosion factor assumption, Section 5.1.1.

(iii). Spectrum Valuation

Increasingly, both industry and governments are viewing spectrum in economic terms, as an input to the production of telecommunications services [78]. However, it raises questions on how to value it among government, regulators and policy makers. Technical and economic factors involve in valuation process. Spectrum has different characteristics, called intrinsic or unchanged characteristics such as propagation, bandwidth, range and extrinsic or variables that can affect value of spectrum such as environment, number of users, etc. [78].

A government’s approach to spectrum regulation, its market structure and its investment regulations can influence the perceived value of a spectrum license. Technology advances, meanwhile, are driving more demand, and regulators are striving to realize the full economic potential of spectrum, and to keep pace with market changes. There are two accepted spectrum valuation methods, which are opportunity cost and econometrics [79]. But also, there are more approaches to price a spectrum. The following table, Table 5.5, summarizes spectrum valuation approaches and parameters used.

In the environment of slowed technology market adoption and dominant incumbent operator it will be difficult to predict the value of spectrum for the future. In Ethiopia adoption to new technologies is slow because of tariff, phone availability and affordability and awareness. Moreover, the impact of MBB in economy not fully understood and measure taken to avoid the mentioned reasons are slow. According to [81], mobile contributed $32B in Sub-Saharan Africa. On the other hand, any laws or rules that inhibit or put too high price on investment, importation of equipment or repatriation of profits could negatively influence the potential for bidding on spectrum opportunity [80]. To avoid the gap and promote broadband growth regulators uses incentives pricing and set-aside for new entrants. For Ethiopia econometric valuation method will be appropriate for regulators for future while for the current market assuming new entrants the AIP will help to promote the MBB growth.

Table 5.5 Spectrum valuation approaches [79]

Approach	Description	Input parameters
Income approach	Estimates value from a commercial perspective	Total revenue, CAPEX, OPEX & investment risk cost
Economic wide approach	Assesses the value of spectrum in terms of its contribution to the national economy	Economy at micro (individual, households), meso (industries, service sector) and macro (country)
Benchmarking approach	Estimates the value of spectrum to be auctioned based on past prices with the country and in other countries	Value of a company, technology using the spectrum,
Opportunity cost approach	Estimation of value based on differences in using and not using the spectrum	Technical: congestion, Infrastructure owned and technology selection by the operator Economical: Spectrum vs. cost reduction, DCF or time value of money
Econometric approach	Integrates mathematics, statistics and economic theory to value spectrum	Past data, supply and demand, number of spectrum slots, duration of license, GDP, number of mobile phone users, education level of people, ARPU

It will be astute for ethio telecom owing new spectrums that can be used for future expansions and ease costs related to spectrum. In this thesis, 2.6GHz or other bands is used in selected small cells and the impact on the TEA is reflected using the model as in Equation (5.2). For the techno-economic evaluation of this thesis work, the following spectrum valuation method is used for the additional spectrum demand [80]:

$$S_P = \frac{(\propto B_N)}{\beta S_A} * \ B_P \ (Birr/MHz) \tag{5.2}$$

Where, S_P and B_P are price of spectrum and BS, B_N total BSs, S_A allocated spectrum amount and $\beta$and $\propto$ are coefficients. The value is paid during investment and renewal for the spectrum 10% of the spectrum each year (6 years study period).

6

LTE-A Radio Network Dimensioning

The LTE-A planning is not different from the general planning of mobile networks. It is classified into nominal planning (rough estimate against coverage in area of interest, using link budget), detailed planning, soft launch and optimization (tuning to meet KPI based on the real field measurement and network statistics) [69]. The result of the planning will be dependent on QoS (target quality), capacity to be offered, coverage, deployment time and the budget of the operator. The major difference between LTE-A planning with other wireless network planning is mainly technologies like OFDM, SC-FDM, increased PRB and bandwidth because of CA. A rough estimate of the required number of eNodeBs is obtained using coverage dimensioning. Then assessment of eNodeB rely on capacity calculations follows to complete the dimensioning process. If the coverage estimates for the given configuration, fulfills the capacity requirements, then there is no addition to the previous plan. On the other hand, suitable number of cell sites is added to achieve the capacity targets.

6.1. Capacity Dimensioning

The capacity of the LTE-A is dependent on the modulation scheme, coding, available bandwidth, and required data plan per user. The efficient use of the radio resources in LTE-A is enhanced by using adaptive modulation and coding scheme, such that the user near the BS utilize higher modulation order, 16QAM, 64QAM and even 256QAM used, while less orders at, like QPSK [68]. Capacity dimensioning is the estimate of the resources needed for supporting a specified offered traffic with a certain level of QoS that helps in determining the number of the sites required to cover a certain area. Different parameters taken for the estimation such as market size, potential subscribers which depends on the number, size and market share, Figure 6.1. In addition, cell capacity, subscriber density and subscriber traffic profile are the main requirements for capacity dimensioning, Chapter 5 Section 5.2.2.2. Cell capacity in LTE-A is impacted by several factors such as interference level, packet scheduler implementation and supported. Other parameters such as BH traffic ratio, assumed based on reports and literatures. From the 24hour per day 3 hours are the busiest, therefore, 9% BH traffic ratio is used [91]. From the whole subscribers handled by the BSs only 15% active subscribers connected to RRC [3]. However, the dimensioning is performed based on peak capacity. The capacity based on the number of sites is compared with that of the coverage and maximum of the two results selected as the required number of eNodeBs for LTE-A.

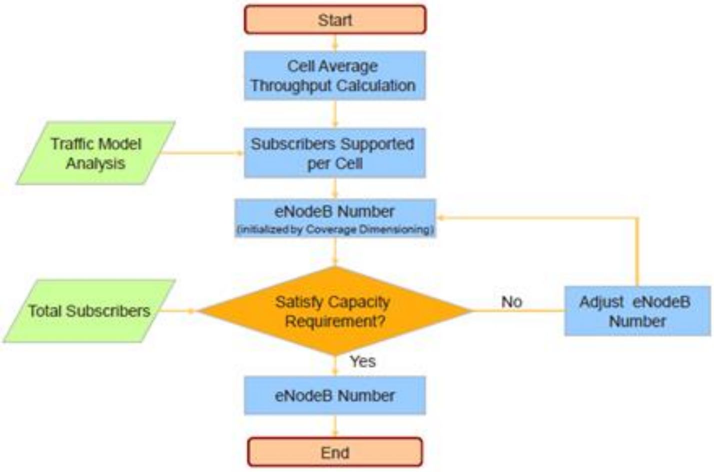


Figure 6.1. LTE-A capacity dimensioning flow chart [68]

6.1.3. Capacity Driven eNodeBs

Capacity driven eNodeB requirement is computed using the following equations. The total number of subscribers taken from chapter 5, Section 5.2.2.2 and the number of users per eNodeB calculated using Equations (6.2) and (6.3).

The number of subscribers per eNodeB is given by:

$$\#\text{eNodeB}_{\text{capacity}} = \frac{Total\ subscribers}{No.of\ subscriber\ per\ eNodeB} \quad (6.1)$$

No. of subscriber per base station (#):

$$S_{\text{eNodeB}} = Max.eNodeB\ throughput * \frac{1000}{BHT} \quad (6.2)$$

BH throughput/subscriber (kbps):

$$BH_T = \frac{Dataplan(GB)*8*10^6}{30*BH_{Traffic}} * \left(\frac{1}{3600}\right) \quad (6.3)$$

For the selected scenarios, 600Mbps eNodeB throughput and aggregated 40MHz system bandwidth with 4x4MIMO taken. In addition, the assumed monthly data plan of

30GB/month/user used to and based on the Eq. (6.3) the BH_T is found that 200kbps, Table 6.1. Grounding on the above inputs and equations the required capacity driven number of base stations calculated and summarized in Table 6.1 for each scenarios.

Table 6.1 Capacity dimensioning for scenario 1 and 2

Parameter	Input/output	Value	Scenario 2	Scenario 1
Data requirement/month/user (GB)	30	a		
Days/month	30	b		
Traffic ratio of BH to whole day (%)	9%	c		
BH throughput per subscriber (kbps)	200	d		
eNodeB throughput (Agg.40M & 4x4 MIMO) (Mbps)	600	e		
Maximum subscriber (#) (e*1000/d)		g	3000	
Maximum subscriber per sector (g/3)		h	1000	
Total subscriber taken (#)		i	1,740,288	2,103,571
eNodeB required (i/g)		j	580	701
RRC active ratio	15%	k		
Max RRC connected user supported (k*g)		l	450	
Max RRC connected user supported/sector (l/3)		m	150	

6.2. Coverage Dimensioning

The coverage planning of LTE-A is predicted using path loss, to produce an estimate of the coverage radius of eNodeB at the same time allow some overlapping to avoid coverage holes and it is mainly technology dependent [68].

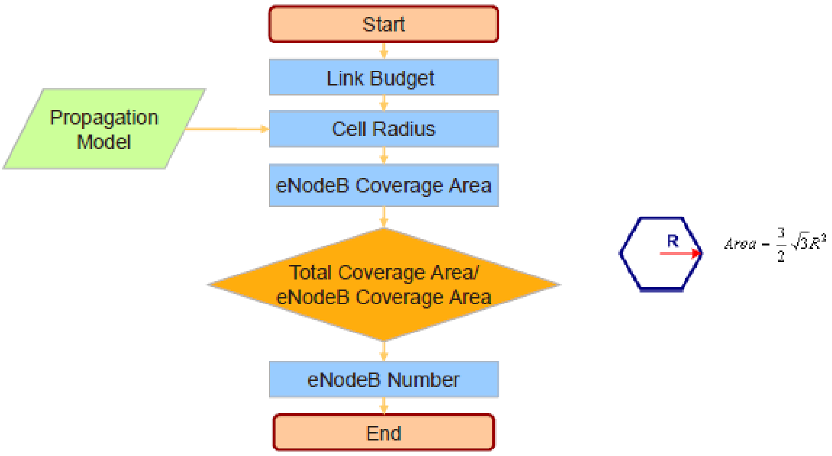


Figure 6.2. LTE-A coverage dimensioning flow chart [68]

Figure 6.2 shows the coverage dimensioning flow chat. The target of the LTE-A dimensioning is to estimate the required site density and site configurations for the area of interest. LTE-A dimensioning process starts with the radio link budget calculations, to determine the maximum path loss depending upon the propagation models used. The estimated cell size, obtained in this step, leads to the maximum allowed size of the cells. Separate link budget calculations are performed for DU, U and SU for the selected scenarios. In addition, excel based link budget tool used for coverage dimensioning while COST-231 Hata applied as a propagation model in this thesis.

6.2.1. Radio Link Budget

The link budget calculations estimate the maximum allowed signal attenuation between the UE and the eNodeB antenna [69]. The maximum path loss allows the maximum cell range to be estimated with a suitable propagation model. The cell range gives the number of BSs required to cover the target geographical area. The following table, Table 6.2, shows summary of LTE-A Radio Link Budget used in this research.

Table 6.2 LTE-A DL and UL radio link budget

DL Link budget (PDSCH)	Value	Index	UL Link budget (PUSCH)	Value
eNodeB - UE			*UE – eNodeB*	
eNodeB transmitter characteristics			*UE transmitter characteristics*	
Number of PRBs	50		Number of PRBs	10
DL data rate (Mbps)	8		DL data rate (Mbps)	2
eNodeB Tx power (dBm)	46	a	UE Tx power (dBm)	23
eNodeB antenna gain (dBi)	18	b	UE antenna gain (dBi)	0
eNodeB cable loss (dB)	2	c	eNodeB cable loss (dB)	0
EIRP (dBm)	62	d = a+b-c	EIRP (dBm)	23
			Tx power per PRB (dBm)	13
UE receiver characteristics			*eNodeB receiver characteristics*	
UE noise figure (dB)	7		eNodeB noise figure (dB)	2
Thermal noise (dB)	-104.43		Thermal noise per PRB (dBm)	-121.42
Receiver noise floor (dBm)	-97.43		Receiver noise floor (dBm)	-119.42
Required SINR (dB)	-2.87		Required SINR (dB)	1.9
Receiver sensitivity (dBm)	-100.3		Receiver sensitivity per PRB (dBm)	-117.52
CCH overhead (dB)	1		Rx antenna gain (dBi)	18
Rx antenna gain (dB)	1		ENodeB antenna cable loss (dB)	2
Body loss (dB)	0		Shadowing loss (dB)	7

Coverage probability (%)	90		Interference margin (dB)	2
Shadowing loss (dB)	8.75		Indoor penetration loss (dB)	20
Interference margin (dB)	4			
Indoor penetration loss (dB)	20			
Allowed propagation loss (dB)	129.55		Allowed propagation loss (dB)	127.52

6.2.2 Propagation Model

A propagation model describes the average signal propagation, and it converts the maximum allowed propagation loss to the maximum cell range [70]. It depends on: demography, distance, frequency, atmospheric conditions and indoor/outdoor. Common examples are free space, Walfish–Ikegami, Okumura–Hata, Longley–Rice, Lee and Young's models [69]. The application of models depends on the frequency in use, in this research band 3 and 8 are used for the selected scenarios. The suitable propagation model for this thesis is then using COST 231-Hata or modified Hata model and it is described below [61, 68 and 94]:

$$\text{PL}= -46.3-33.9\log(f)-13.82\log(hBS)-a(hUE)-[44.9-6.55\log(hBS)]\log(d)-Co \qquad (6.4)$$

The *blue* and *red* colors represent the path loss constant and path loss exponent respectively and $a(hUE)$ is UE antenna gain function and defined for urban (Eq. (6.5)) and sub-urban (Eq. (6.6)) areas as the following:

$$a(hUE)=3.2(log11.75hUE)^2-4.97, f\geq 400MHz \qquad (6.5)$$

$$a(hUE)=1.1(logf-0.7)hUE-(1.56logf-0.8) \qquad (6.6)$$

Where, *f* = carrier aggregation in MHz, *hBS* BS antenna height in meters, *hUE* UE antenna height in meters, *d* is the cell radius in km and the term *Co* (0dB for SU and 3dB for DU/U) are used to account for different trains [94].

6.2.3. Output Power

Transmitter power is one of the main factors that impact the link budget [68]. For the link budget 46dBm and 23dBm transmission power for eNodeB and UE respectively, used.

6.2.4. Cell Edge User Throughput

Based on [91], a minimum internet speed is recommended for online streaming videos from known content providers like Netflix, iTunes, Amazon and YouTube [Chapter 5, Table 5.1]. The minimum required speed at cell edge is assumed 8 and 2Mbps for DL and UL respectively.

6.2.5. Receiver Sensitivity

The eNodeB receiver sensitivity is the signal level/threshold at which the RF signal can be detected with a certain quality. This threshold refers to the antenna connector and should consider the further demodulation and the required output signal quality. The receiver sensitivity depends on the following factors: Data rate targeted at cell edge, target quality, Hybrid Automatic Repeat reQuest (HARQ), i.e., block error rate (BLER), maximum number of retransmissions, radio environment conditions (multipath channel, mobile speed), and Noise figure (NF) of the eNodeB receiver. The receiver sensitivity per subcarrier is calculated as [69]:

$$\mathrm{Rx}_{\mathrm{sensitivity}} = SINR + NF + NP + 10\log(15000) \tag{6.7}$$

Where, $Rx_{sensitivity}$ is receiver sensitivity, $SINR$ is the threshold of the receiver that can demodulate the signal and it is related to the MCS for the UL and DL, respectively, the BLER target, MIMO gain, and HARQ setting.

The SINR values are vendor specific and depend on the receiver design [70]. NF for LTE/LTE-A it is between 6 and 8dB and NP (− 174 dBm/Hz) is the density of the thermal white noise power, which is estimated as:

$$\mathrm{NP} = \log(290 * 1.38^{-23} * 103) \tag{6.8}$$

6.2.6. Interference margin (IM)

The interference margin is encountered in the link budget due the possibility of noise rise according to the load level [69]. Unlike the UMTS system, LTE (A) has no intra-cell interference because of the OFDM subcarriers’ orthogonality. Therefore, the UL RB load can reach 100%, depending on the UL eNodeB scheduler mechanism and subscriber’s distribution. However, inter-cell interference should be considered in the UL and DL. IM is calculated considering other-cell loading, target SINR, and minimum achievable SINR. It for the increase in the terminal noise level caused by the interference from other users. For the UL and due to the change in scenario as per TTI basis and non-deterministic distribution of users, it is recommended to estimate the interference margin using an actual dynamic simulation. While for the DL, IM can be computed analytically as the relation between signals received with and without interference and can be estimated as follows:

$$\mathrm{IM}_{\mathrm{DL}}= -10\log(1 - Load_{DL} I_N 10^{0.1SINR_{PDSCH}}) \tag{6.9}$$

Where, IM_{DL} is DL interference margin, $Load_{DL}$ is the DL load, I_N is the adjacent cells interference factor, and $SINR_{PDSCH}$ is the required SINR for PDSCH detection.

6.2.7. Coverage Driven eNodeBs

Using the maximum allowed propagation loss from Table 6.2, coverage driven BS demand is calculated. For hexagonal cell and urban city, the site covered by each eNodeB calculated as follows:

$$\text{Site Area} = 1.5*\sqrt{3} * R^2 \tag{6.10}$$

Where, R = R_{DL} and R_{UL} cell rage in the DL and UL.

According to [3], Addis Ababa's demography categorized as DU, U and SU. They encompasses 70.46, 170.36 km^2 (240.82km^2) and 539.13 km^2 respectively, which makes a total of 779.95 km^2. In this thesis, densest (DU) and denser (U) areas assumed to take 40% and 60% of 240.82km^2 respectively. The number of coverage driven site is then calculated as:

$$\#\mathrm{eNodeB}_{\mathrm{coverage}} = \frac{Total\ area\ (km^2)}{Site\ area\ (km^2)} \tag{6.11}$$

6.3. Small Cell Dimensioning

Mobile broadband data is highly localized as the majority of current traffic is generated indoors and in hotspots [70, 71, Chapter 3: Section 3.3]. Moreover, according to [72, 75] 80% of mobile usage occurs in building. It, therefore makes sense to deploy an overlay of small cells in those regions of the macro coverage area which generates heavy data demand [70, 71 and 97]. Small cells offload data from the macro coverage area and improve frequency reuse. Additionally, they can also offer higher capacity than the macro as they can better adapt to the spatial-temporal variations in traffic by dynamic interference management techniques, such as cross-carrier scheduling, CoMP and eICIC. Providing high QoS, using only MaBS is not best practice in the environment of high data demand as high bandwidth demanding apps and services best served for UEs near the BS [72].

So, to increase QoS densification of cells as HetNet required. However, beside the benefit gain placement of impact the system efficiency and adds complexity to the network. In addition, it necessitates an ideal backhaul link. For example, for high data traffic it will need 100-200 Mbps link capacity per cell and if the traffic aggregated to MaBS the requirement extends to 1Gbps per site. A demand, capacity and cost conditions determine the number of Indoor and outdoor small cell. In instances less dense areas, only a single or few small cells sparsely deployed [3GPP TR 36.932]. Whereas, denser locations necessities denser small cells. Moreover, to determine the required number of SCs cost, energy efficiency, node capacity (users/node) and interference taken in to consideration.

6.3.1. Indoor Small Cells

In the study seven hot spot areas are identified and organized in clusters based on the geographic area, Table 6.3. To select the area, existing LTE KPI report and building density used as key parameter [3]. According to [82], in Legehar and the surrounding area, there are 20 buildings that are identified as crowded and business areas.

Table 6.3 Hotspot selection

Cluster	Cluster name	Area
1	Bole	Bole, Olympia, Airport, Gerji, Bole Michael, Welo sefer
2	Legehar	Legehar, Addis Ababa Stadium, Mexico, Kazan chis, Ledeta
3	Megenagna	Megenagna, 22, G.sholla, CMC
4	Sarbet	Sarbet, Old Airport, Bisrate Gabriel, Mekanisa
5	Menen	Menen, 4, 5 and 6 Kilo, Kebena
6	Piasa	Piasa, Ras Mekonnen,
7	Merkato	Merkato, Somale tera, Abinet

Uniform number of buildings assumed for the rest of areas in all clusters. In addition, in Addis Ababa, it is observed that most building that is used for commercial purpose not fully used, i.e. shops, malls used up to four floors and not all buildings are hotspots. In the study 40 users per floor per day assumed uniformly. In addition, the demand is forecasted for the study period. In [70], it is indicated that small cells serve 32-64 users per cell, Annex A Table A.1. For efficient performance, however, 32 users per cell recommended. Accordingly, the required number of small cells determined based on the following equations.

$$S_{Indoor} = \frac{Number\ of\ subscribers(N_S)}{Small\ cell\ capacity} \tag{6.12}$$

N_S calculated as:

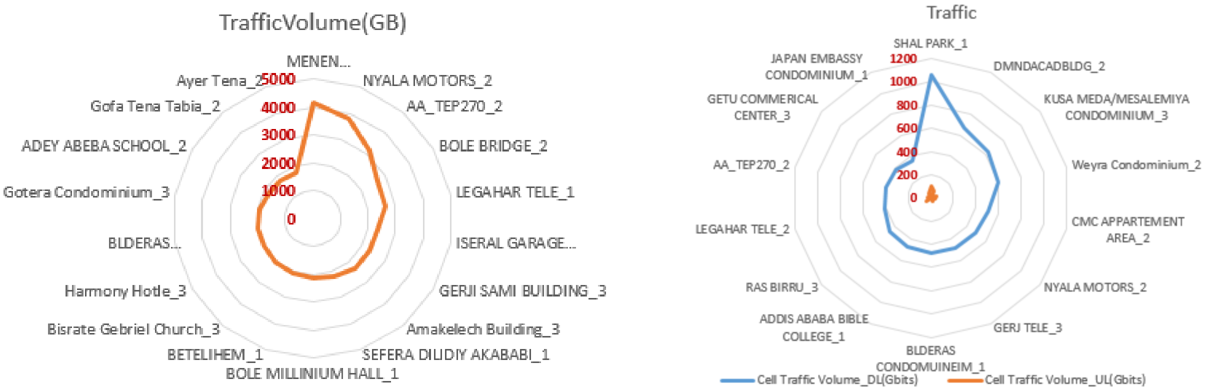
$$N_S = B_C * U * f * C_A \tag{6.13}$$

Where, S_{Indoor} is indoor small cell, N_S is number of baseline subscribers, B_C buildings per cluster, U users, f is floor and C_A cluster area.

A straight line forecasted method used to forecast the number of users for the study period. Considering urbanization, city growth, growth of apps and services a constant growth rate of 10% also assumed, Table 6.4.

Table 6.4 Predicted indoor users

	Baseline	2011 E.C	2012 E.C	2013 E.C	2014 E.C	2015 E.C	2016 E.C
Growth rate		10%	10%	10%	10%	10%	10%
Users							
Scenario one	22,400	24,640	27,104	29,814	32,796	36,075	39,683
Scenario two	12,800	14,080	15,488	17,037	18,740	20,615	22,676



(a) (b)

Figure 6.3. LTE data traffic (a) 2017 KPI (b) 2018 KPI

For scenario one all clusters are taken whereas for scenario two 4 clusters, i.e. Bole, Legehar, Megenagna and Sarbet selected. These areas considered as densest locations based on the KPI report of the existing LTE network Figure 6.3. Finally, relying on the inputs and Eq. (6.12) and (6.13), the corresponding number of small cells for scenario one and two are 1240 and 709.

6.3.2. Outdoor Small Cells

With optimal placement among concentrated traffic hotspots, capacity gains upwards of 400% are achievable using only 4 metro outdoor SCs per macro cells, Table 6.5. Placing small cells too close to macro cell center causes them to compete and reduce effectiveness. In all cases, proper placement benefits to achieve the greatest ROI [77].

Table 6.5 Impact of placement on effectiveness of metro cells (4 metro per macro) [77]

MeBS distance from MaBS	% gain in median user throughput
200m	2%
400m	70%
700m	467%

Additionally, dedicated carrier preferred for SCs in the outdoor, as it avoids interference with macro cell and support metro cells to cover wider area. It also assists to absorb a larger amount of traffic off the macro network and greatly improving TCO and reduces CAPEX cost [78]. Relying on these argument and 3GPP technical recommendations of outdoor small cells, 2 metro cells per macro cell assumed [3GPP TR 36.932].

Figure 6.4. Small cell placement at hotspot

The area under consideration are: The Light Relay Transport (LRT), which has a total length of 31.6Km with 39 stations. According to Ethiopian Railway Corporation, in 2016 the LRT transports 113, 500 passengers on average. The Bole International airport is the other focus area. According to Ethiopian Airlines, it is the busiest airport in Africa designed to serve 5 million and plan 22 million passengers per year at the end of 2018. The other hot spot area that has to be considered is stadiums and public places. It will be effective if public venues equipped with SCs in supplement to macro cells. Overall, these areas are crowded with users and placing SCs support for better QoE, to alleviate the load on macro cell and congestion so that it provides better performance for users and generate more revenue. Figure 6.4, shows possible placement of small cells.

6.4. Spectrum Dimensioning

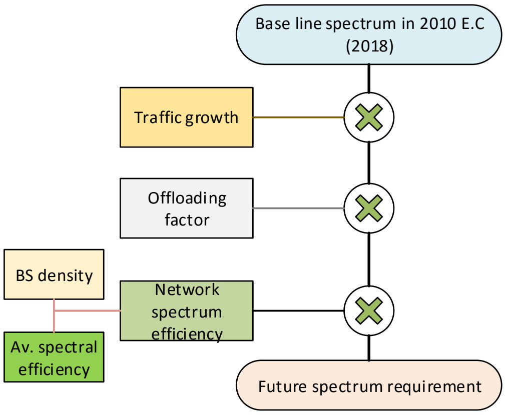
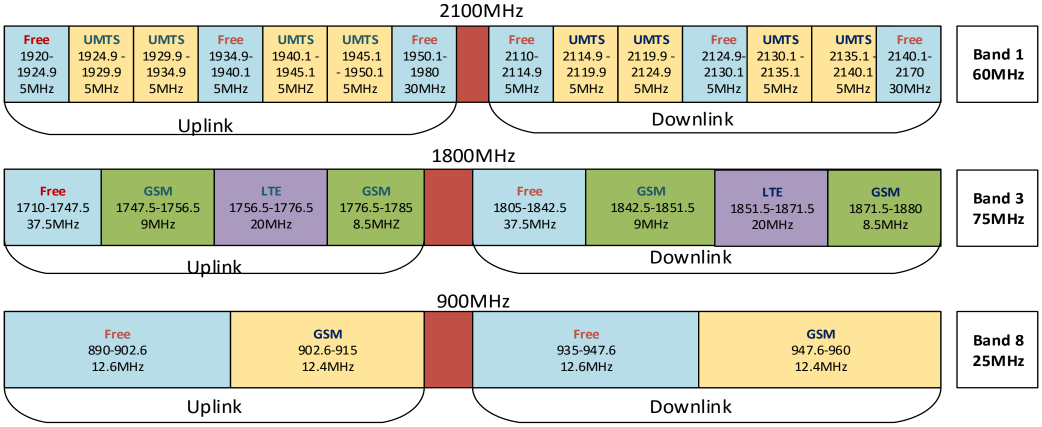


Figure 6.5. Future spectrum prediction [79]

ITU recommends operators to predict the spectrum demand and equipped with for their future expansions. The methodology, in Figure 6.5, adopted from ITU to predict future spectrum requirement for ethio telecom for the macro and small cells. The spectrum holdings of ethio telecom in 2G, 3G and LTE mobile networks and available slots that can be refarmed for LTE-A are summarized in Figure 6.6. From the available spectrum, the utilized bandwidth (S_U) is 71MHz and that will be refarmed for LTE-A, S_{UN} is 89MHz.



2100MHz

Free 1920-1924.9 5MHz	UMTS 1924.9 - 1929.9 5MHz	UMTS 1929.9 - 1934.9 5MHz	Free 1934.9-1940.1 5MHz	UMTS 1940.1 - 1945.1 5MHZ	UMTS 1945.1 - 1950.1 5MHz	Free 1950.1-1980 30MHz		Free 2110-2114.9 5MHz	UMTS 2114.9 - 2119.9 5MHz	UMTS 2119.9 - 2124.9 5MHz	Free 2124.9-2130.1 5MHz	UMTS 2130.1 - 2135.1 5MHz	UMTS 2135.1 - 2140.1 5MHz	Free 2140.1-2170 30MHz	**Band 1 60MHz**
Uplink								Downlink							

1800MHz

Free 1710-1747.5 37.5MHz	GSM 1747.5-1756.5 9MHz	LTE 1756.5-1776.5 20MHz	GSM 1776.5-1785 8.5MHZ		Free 1805-1842.5 37.5MHz	GSM 1842.5-1851.5 9MHz	LTE 1851.5-1871.5 20MHz	GSM 1871.5-1880 8.5MHz	**Band 3 75MHz**
Uplink					Downlink				

900MHz

Free 890-902.6 12.6MHz	GSM 902.6-915 12.4MHz		Free 935-947.6 12.6MHz	GSM 947.6-960 12.4MHz	**Band 8 25MHz**
Uplink			Downlink		

Figure 6.6. ethio telecom frequency usage [3]

A forecast by [8, 55, 74], the sub-Saharan region used for traffic growth. While the offloading factor ranges between 0 and 1. The spectral efficiency (bps/Hz/cell) depends on technology used and LTE-A has high spectral efficiency up to 30bps/Hz [80, 81]. However, spectral efficiency calculated is calculated based on Eq. (6.12) and the result indicted that taking the mentioned inputs the spectral efficiency is 22.5bps/Hz.

$$\eta = P.R_{av}.\frac{G}{BW} \qquad (6.12)$$

Where, η spectral efficiency in bps/Hz/cell, P peak data rate, R_{av} MCS, G is gain by MIMO and CA and *BW* channel bandwidth, *P* = 600Mbps, $R_{av} = 64\text{QAM} > 2/3$, G=2 (2 for CA) and BW = 40MHz

To check whether the existing spectrum support LTE-A or not, i.e. the amount of spectrum required, Equation (6.13) is used [80, 81].

$$BW_R = Cell_C(Mbps)/SE\left(\frac{\frac{bps}{Hz}}{cell}\right) \qquad (6.13)$$

Where, BW_R is required bandwidth, $Cell_C$ is cell capacity (calculated based on Eq. (6.14) and (6.15)) and *SE* is spectral efficiency.

$$Cell_C = S * \left(8192(\frac{Mb}{GB})\right) * \frac{D_P\left(\frac{\frac{GB}{sub}}{month}\right)}{\left(Sites*3sector*3600(\frac{s}{hr})*30(\frac{day}{month})\right)} * D \qquad (6.14)$$

$$D = \frac{9\%(BH\ share)}{50\%(Maxload)} * \frac{50\%}{15\%} \qquad (6.15)$$

Where, *S* is the subscriber assumed in scenario one and two, D_P data plan and *D* is distribution. *D* is based on BH share, maximum load in which 50% of the traffic is carried by 15% of the cells.

Then based on Eq. (6.13 – 6.15), the required spectrum for scenario one is 72.22MHz while for scenario two is 72.21MHz, which indicates that the existing free spectrum, i.e., S_{UN} = 89MHz is enough the macro cells for the next 6 years (study period).

7

Results and Discussion

The succeeding section go through deployment, dimensioning, market analysis and techno-economic evaluation results and discusses the observation on the results obtained.

7.1. Results

7.1.1. Deployment Option

After organizing the scenarios, a deployment preference is selected based on the available resources, such as spectrum, existing BSs and backhaul for the macro and small cell. Depending on the discussions of the previous chapters a deployment option is identified for each scenarios. For the LTE-A implementation CA and HetNet are selected taking performance and cost in to consideration. Possible CA configurations realized relying on the existing ethio telecom frequency holdings, i.e. refarming, and new plan for small cells [Chapter 6, Section 6.5] and in comply with 3GPP R’14 specifications. Tables 7.1 and 7.2 illustrate allowable CA configurations and its application.

Table 7.1 CA configuration for macro and small cell assignment

CA configuration	UL CA Configuration	Max.agg.BW (MHz)	Max. Config. for ethio telecom	Usage
CA_3C	CA_3C	40	25	MC
CA_3A_3A	-	40	40	“
CA_3C_8A, CA_3A_8A, CA_3A_3A_8A	CA_3A_8A, CA_3C	50/30/50	35/30/50	MC/SC
CA_1A_3A_8A, CA_1A_3A_3A_8A, CA_1A_3C_8A	CA_1A_3A, CA_1A_8A, CA_3A_8A, CA_3C	50/70/70	50/70/70	MC
CA_1C	CA_1C	40	25	SC
CA_1A_8A	CA_1A_8A	30	30	“
CA_1A_3A,CA_1A_3A_3A, CA_1A_3C	CA_1A_3A, CA_3C	40/60/60	40/60/45	“
CA_3A_7A,CA_3A_3A_7A, CA_3A_3A_7A_7A, CA_3A_7A_7A, CA_3A_7B, CA_3A_7C, CA_3C_7A, CA_3C_7C	CA_3A_7A, CA_7C, CA_3C	40/60/80/60/40/60/60/80	40/60/80/60/40/60/45/65	“

Table 7.2 Selected CA configuration for the deployment options

Demography	Selected CA configuration		Achievable BW (MHz)	
	Macro cell	Small cell	Macro	Small
DU	1800 CCs	CCs of 2100 or CCs of 2.6GHz	35-40	25-100
U	CCs of 900 and 1800MHz	CCS of 2100 or CCs of 2.6GHz	30-50	25-100
SU	1800MHz	CCs of 2100	20	25

7.1.1.1. Full LTE-A Deployment with Out-band Small Cells

In this deployment scenario covering the whole Addis Ababa exploiting CA and HetNet examined. The network layout designated in Chapter 4 Section 4.2.1 Figures 4.2 and 4.3 relying on the applied bands propagation characteristics. Bands for CA tabbed targeting capacity, coverage, bandwidth gained, demography and cost. CCs of band 3, i.e. intra-band CA allocated for the DU [Figure 4.2 (a)] to achieve high bandwidth with less network complexity.

In addition, to circumvent performance related problems such as coverage mismatch and attain better indoor coverage than other higher bands. Whereas for out-band indoor and outdoor small cells, band 1 and 7 utilized as illustrated in Tables 7.1 and 7.2, to address the indoor and outdoor demand and traffic. For urban areas with assumed lower traffic and building density than DU the combination of low-high CA combination applied for the coverage and throughput advantage. Therefore, CCs of 900 and 1800MHz, i.e. inter-band CA employed for the macro cell and band 1 and 7 used for small cells, Figure 7.1 (b). While 1800MHz assumed to be used for the macro cell while in selected hotspot places band 1 applied for small cells in SU case, Figure 4.3.

7.1.1.2. Progressive LTE-A Deployment with Out-band Small Cells

The focal point for progressive deployment is, deploying LTE-A to address the high demand on DU and U locations. In doing so, device availability and penetration rate, degree of adoption, simplicity (UE and NE) and cost implications taken in to consideration. The existing LTE and free slots of 1800MHz utilized, so that CCs of it can be assigned for the macro and CCs of 2100MHz or 2.6GHz used for small cells depending on the demand, Tables 7.1 and 7.2. The highlighted deployment alternative shown in Chapter 4, Section 4.2.2 Figure 4.4.

7.1.2. Dimensioning

7.1.2.1. Capacity and Coverage Dimensioning

In this section, results obtained in the LTE-A radio network dimensioning process summarized. Based on the discussions on Chapter 6, Section 6.1 the capacity driven eNodeB requirement for each scenario is determined and the number of eNodeBs required for first and second scenario are 701 and 580 respectively. While concerning coverage dimensioning, the cell range for the two scenarios derived relying on the APL result of the link budget. Accordingly, the cell range of scenario 2 for R_{DL} and R_{UL} is 0.61 and 0.53 respectively. Thereafter, build upon Eq. (6.10), site area for DL and UL found that 0.95 and 0.73 km^2 respectively and situated on Eq. (6.11), the coverage driven eNodeBs for DL are 253 while 328 for UL. The final BSs requirement is max (DL, UL), that is *328*. Similarly, for scenario 1, and using Eq. (6.10), the cell range for R_{DL} is 0.43 and R_{UL} is 0.37 for DU and U areas, the resulted site area for DL and UL are 0.47 and 0.37 km^2 respectively. And for the SU area R_{DL} is 1.31 and R_{UL} is 1.15, the result for cell area becomes 4.46 and 3.43 km^2 for DL and UL respectively. Based on Eq. (6.11), the coverage driven eNodeBs for this scenario are performed separately for dense DU/U (240.82km^2) and SU (539.13km^2). The corresponding eNodeBs for DL are 202 for DU/U and for the SU is 121 (539.13/4) with total *323* eNodeBs for DL, while for UL 262 for DU/U area and 157 (539.13/3) for SU areas respectively, with a total of *420* eNodeBs. The final BSs requirement to cover the whole Addis Ababa, i.e. max (DL, UL) is *420*. Overall, the dimensioning result indicated that, it is capacity limited and the required BSs rely on number of eNodeBs found by capacity dimensioning, Table 7.3.

Table 7.3 Summary of results of coverage and capacity dimensioning

Scenario	Capacity	Coverage
Full	701	420
progressive	580	328

7.1.2.2. Small Cell Dimensioning

In Chapter 6 Section 6.3, a small cell dimensioning for the indoor and outdoor areas performed. To determine the required number of indoor cells, hot spot area identification performed using Addis Ababa LTE traffic, building densities and standards. Whereas, for the outdoor scenario related works and 3GPP TR 36.932 recommendations used. The following table, Table 7.4 summarizes the number of indoor and outdoor SCs needed for the selected scenarios.

Table 7.4 SCs for Full and Progressive deployments

Scenario	Outdoor SC	Indoor SC
Full	200	1240
progressive	100	709

7.1.2.3. Spectrum Dimensioning

The required bandwidth for the deployment of LTE-A in either full deployment or progressive deployment with out-of-band Heterogeneous Network for the study period calculated. Then based on Equations (6.12 – 6.15), the required spectrum for scenario one is 72.22MHz while it is 72.21MHz for scenario two. The result indicates that the existing unutilized bandwidth, i.e. S_{UN} = 89MHz is sufficient for the next 6 years (study period) for the deployment of LTE-A for either cases.

7.1.3. Market Analysis

Monthly data plan, candidate subscriber, ARPU, and market share of LTE-A determined relying on data driven analysis, forecasting, reports and assumptions. Taking existing ethio telecom data plan and advancement of data intensive apps and services a monthly data plan of 30GB/month/user assumed, Table 5.1. Likewise, LTE-A subscribers for the study period forecasted using bass model for the viable deployment options and ARPU estimated taking previous subscriber and revenue evolution of ethio telecom and applying exponential regression, Table 5.3, 5.4, Figure 5.4 and Figure 5.5, respectively.

7.1.4. Techno-economic Evaluation

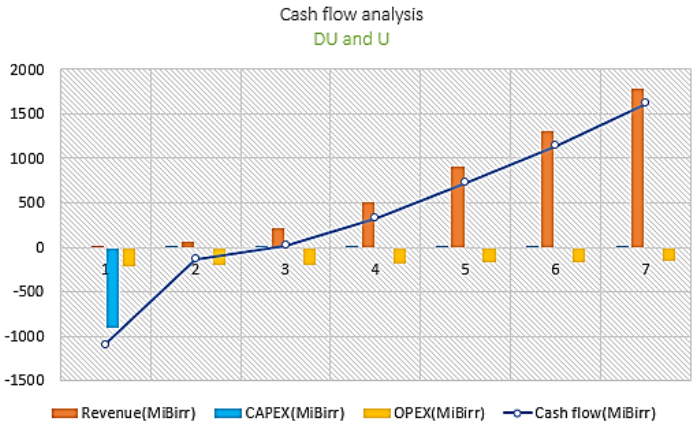
The existing 329 LTE BSs upgraded whereas new sites added for the first scenario. In terms of spectrum, no cost for additional band assumed since the unutilized bandwidth from the existing network used. The CAPEX and OPEX costs, revenue, market analysis used in the TE evaluation is based on inputs discussed on Chapter 5.Then the output of techno-economic evaluation is performed for the two scenarios, as discussed below, using key TE evaluation parameters like NPV, CF, DCF and PP.

7.1.4.1. Full LTE-A Deployment with Out-band Small Cells

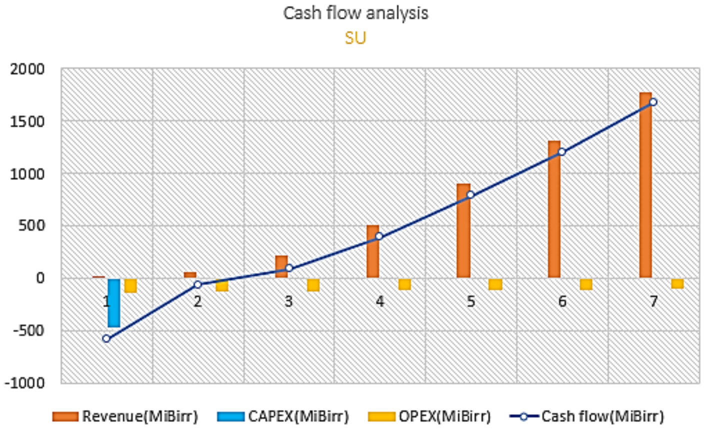
The CF, DCF analysis of scenario one relying on total cost and revenue summarized on Table 7.5. The succeeding figures, Figures 7.1 and 7.2 also illustrates results of evaluation further from demography, coverage and capacity point of view respectively. In addition, the corresponding NPV and payback period outcomes shown in Table 7.6.

Table 7.5 Cash flow analysis for scenario one

Year	Baseline	2011 E.C	2012 E.C	2013 E.C	2014 E.C	2015 E.C	2016 E.C
Revenue(MiBirr)	16.63	68.27	214.12	510.37	902.07	1,309.31	1,776.19
CAPEX(MiBirr)	(2,207.33)	-	-	-	-	-	-
OPEX(MiBirr)	(454.47)	(432.06)	(410.77)	(390.55)	(371.34)	(353.09)	(335.75)
Cash flow(MiBirr)	(2,645.16)	(363.79)	(196.65)	119.82	530.73	956.22	1,440.44
Cumulative CF	(2,645.16)	(3,008.95)	(3,205.60)	(3,085.78)	(2,555.05)	(1,598.83)	(158.39)
DCF	(2,645.16)	(330.71)	(162.52)	90.02	362.50	593.74	813.09

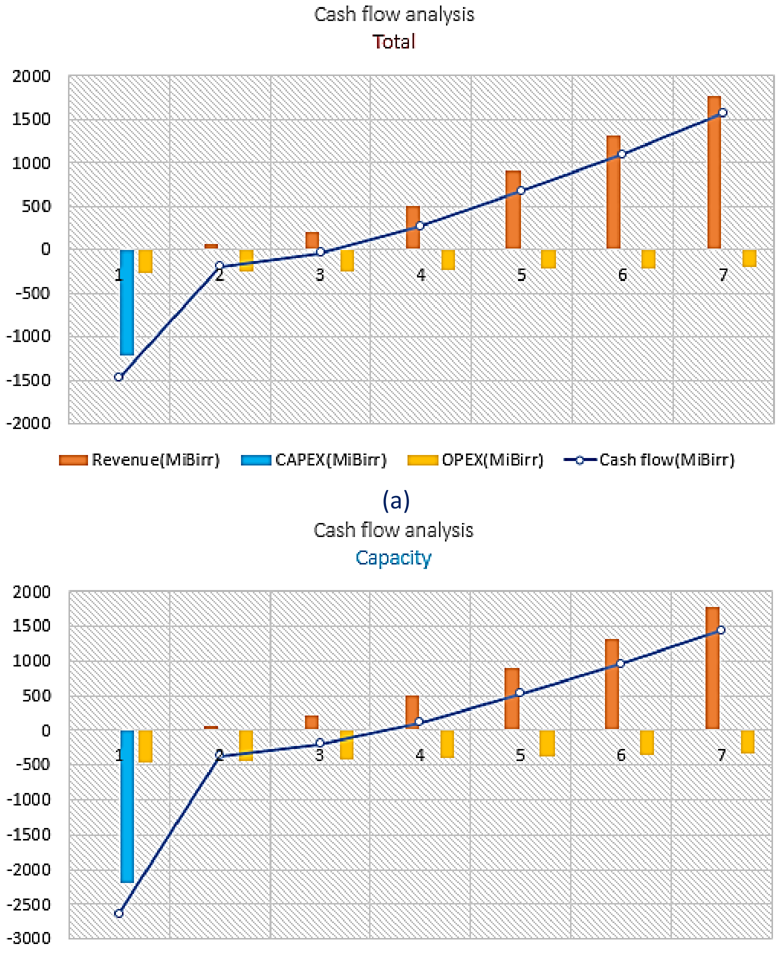


(a)



(b)

Figure 7.1. Cash flow analysis (a) DU and U and (b) SU



(a)

(b)

Figure 7.2. Cash flow analysis for scenario one (a) Coverage and (b) Capacity

Table 7.6 Summary of TEA for scenario one

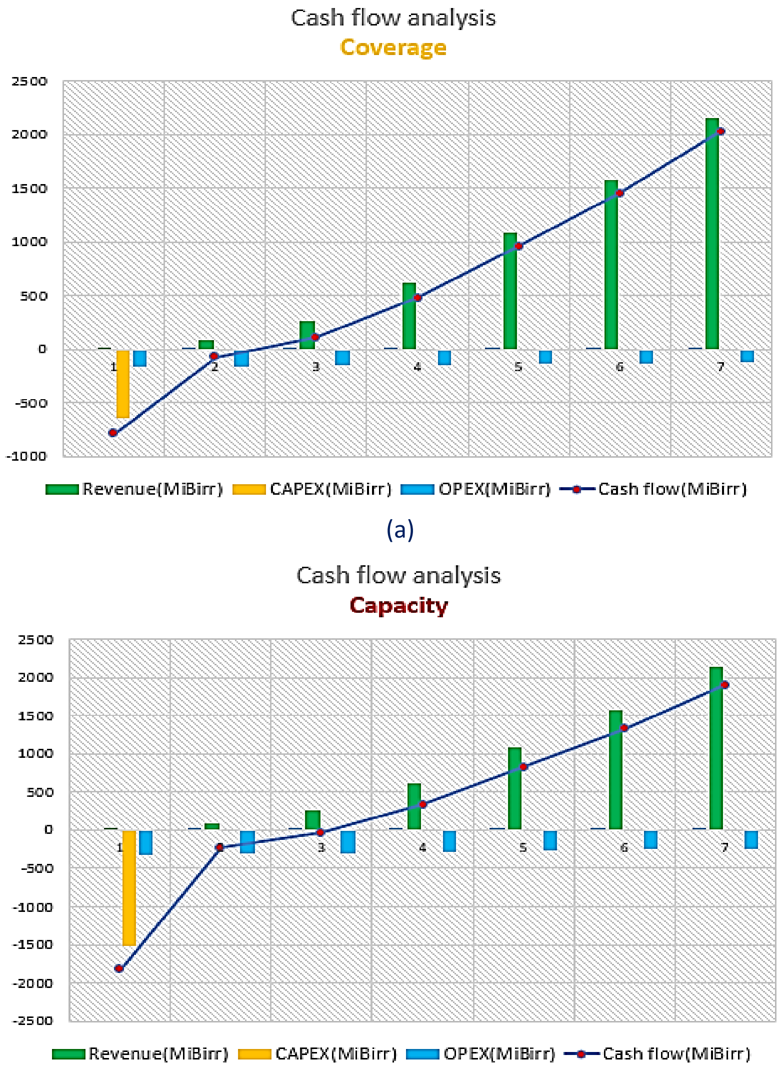
Deployment	Dimensioning	NPV	Payback period (year)
DU and U	Coverage	1,162.47	4.13
SU		1,975.89	3.19
DU, U and SU		565.52	4.68
DU, U and SU	Capacity	(1,277.80)	-

7.1.4.2. Progressive LTE-A Deployment with Out-band Small Cells

Similarly, the techno-economic evaluation results of CF, DCF for this scenario summarized in the subsequent table and figure, Table 7.7 and Figure 7.3, respectively, in terms of coverage and capacity point of view. Whereas, Table 7.8 summarizes the NPV and payback period.

Table 7.7 Cash flow analysis for scenario two

Year	Baseline	2011 E.C	2012 E.C	2013 E.C	2014 E.C	2015 E.C	2016 E.C
Revenue(MiBirr)	20.10	82.53	258.82	616.90	1,090.37	1,582.63	2,146.97
CAPEX(MiBirr)	(640.71)	-	-	-	-	-	-
OPEX(MiBirr)	(165.65)	(157.46)	(149.67)	(142.28)	(135.25)	(128.58)	(122.23)
Cash flow(MiBirr)	(786.26)	(74.93)	109.15	474.63	955.12	1,454.05	2,024.74
Comulative CF	(786.26)	(861.19)	(752.04)	(277.41)	677.71	2,131.76	4,156.50
DCF	(786.26)	(68.12)	90.21	356.60	652.36	902.85	1,142.91



(a)

(b)

Figure 7.3. Cash flow analysis of scenario two (a) Coverage and (b) Capacity

Table 7.8 Summary of TEA for scenario two

Deployment	Dimensioning	NPV	Payback period (year)
DU and U	Coverage	2,290.55	3.29
DU and U	Capacity	644.02	4.70

7.2. Discussion

Services that necessity high network capacity as well as technology evolving and demanding high expenditure. There is always a tradeoff between QoS and cost, though, efficient panning helps to properly manage resources and save unnecessary wastage. In scenario planning, list of possible LTE-A deployment options revealed and two of them identified as viable deployment scenario of LTE-A for Addis Ababa. Subsequently, go through coverage, capacity, small cell and spectrum dimensioning and techno-economically investigated for the feasibility taking prescribed inputs and applying the modified TERA framework and developed TEA tool.

In full deployment with out-band small cells, the NPV and payback period, Table 7.6, indicated that LTE-A is feasible in DU, U and SU areas in coverage perspective as illustrated in Figures 7.1 and 7.2. The NPV result shows positive for the indicated demographies, Tables 7.1 and 7.2, with 4.13 and 3.19 PP for DU/U and SU respectively. Since the scenario is capacity limited and the NPV and PP results indicated that it is not feasible in the defined study period in this context.

In progressive deployment with out-band small cells, the NPV and payback period, Table 7.8, indicated that LTE-A is feasible in DU and U areas both in coverage and capacity perspective. The NPV and PP for coverage and capacity is 2,290.55 and 644.02 and 3.29 and 4.70 respectively. In general, the TE evaluation result showed that progressive deployment of LTE-A is practical and feasible deployment option of LTE-A for Addis Ababa.

8

Conclusion and Future Work

8.1. Conclusion

The research discusses and analyze the trend on the evolution of mobile data demand and traffic growth and its impact on existing network infrastructures. The analysis result indicate that the current infrastructure cannot cope with the ever-growing end-user demand and an efficient network that is capable of providing coverage, capacity and throughput qualification is mandatory. The research also themed with describing the cellular technology evolution giving focus on LTE-A and its features.

Employing systematic literature reviews, standards, reports, expert opinions and stat-of-the-art, a scenario is planned to pinpoint realistic LTE-A deployment options for Addis Ababa. Positioning on the result macro, small cell and spectrum dimensioning performed to drive needful NE for CAPEX and OPEX analysis. In the study, the status and applicability of existing resources, such as spectrum, base station and backhaul for LTE-A identified. It then concluded that the backhaul has the capacity to handle LTE-A while LTE base stations can be upgraded and new sites added depending on the scenarios. Concerning spectrum, a six years demand forecasted and the possibility of reusing the unutilized bandwidth verified. However, new bands can be involved for small cells in limited circumstances, such as dense urban indoor areas.

As technologies complexity varies, selecting the right feature requires a strategic decision. In study the possible trends identified and organized using PESTLE analysis, uncertainties for the local context investigated and viable deployment preferences identified for Addis Ababa using scenario planning. Following, LTE-A radio dimensioning for the viable options and TEA applied to evaluate the technical and economic feasibility. Out of the available TEA frameworks, TERA framework chosen as a result of its practicality in the evaluation of wireless communication systems. The framework is modified to enclose parameters that will reduce cost and escalate revenue. Afterwards, relying on the input parameters a new TEA tool developed that can automatically decide the feasibility of LTE-A. It takes technical, i.e.

dimensioning and market, i.e. ARPU, subscriber, data plan and market share inputs to calculate the CAPEX and OPEX cost. In addition, taking economic inputs, i.e. study period and discount rate, the tool provides CF, DCF, NPV and payback period result to conclude the viability of the LTE-A deployment.

Lastly, from the aforementioned scenarios; scenario one is not feasible within the six year study period while it is found that scenario two is a viable LTE-A deployment option. In general, it is an inevitable thing that mobile data demand and traffic increasing in the coming years in Ethiopia, specifically in Addis Ababa and a technology that can handle this demand required. It is also important to identify proper planning and scientific analysis method to evaluate technology viability in technical and economic measures.

8.2. Future Work

This research investigates viable deployment option of LTE-A for Addis Ababa to accommodate mobile data demand. It can be a research area if one performs detail analysis of all TERA framework deliverables, refine the modified framework and TEA results. Investigating the feasibility of LTE-A further by adding voice, VoLTE, and its impact on the LTE-A dimensioning and TEA results is another area for future work. It is also possible to analyze and investigate the LTE-A radio network dimensioning using planning tools, such as WinProp and Atoll and simulation tools like Matlab to investigate network dimensioning results and the influence of small cells on macro cell and overall impact on the system performance. Developing Graphical User Interface (GUI) for the modified TE analysis method could be a very good project work so that the tool will be very usable for other related TE studies.

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Appendix A

Table A.1 Small cell vendors, functionalities and specifications

Vendor	Product name	Usage	Data rate (Mbps)		BW (MHz)	Operating bands	Mode	Tech.	MIMO	Modu.	Output power	Release	BH	Other features
			DL	UL										
Bai cells	Neutral Cell Indoor Multi FDD/TDD Small Cell	Indoor	150	75	Up to 20	1,2,3,4,5,7,8, 12,13,17,20 & 28, 34,38,40,41, 42 & 48	FDD/ TDD	4G Wi-Fi	2x2	QPSK, 16QAM, 64QAM	24dBm, +-2dB	10	Wireless	
AirSpan	AirHarmony 1000	outdoor	300*	100*	Up to 20	28,38,40,41 & 42	FDD/ TDD	4G	2x2	Up to 64QAM	+37dBm	Current & new	Fiber/ wireless	eICIC, ABS, Embedded SON
AirSpan	AirDensity access	Indoor	150	50	Up to 20	3,7 & 40	FDD/ TDD	4G	2x2	Up to 64QAM	+23dBm	10	Wireless	
AirSpan	AirDensity Relay BH		450	50	60 with CA	1,8,41 &42	FDD/ TDD	4G	4x4	Up to 64QAM		10	Wireless	
AirSpan	AirHarmony 4000/4200/4400	Outdoor	450*	150*	2x20 with CA	3,26,28,40,41 & 42	FDD/ TDD	4G	2x2 4x2	Up to 64QAM	+43dBm	10, 11, 12 & more	Fiber	eICIC, ABS, Embedded SON
AirSpan	AirPole 1000/1200/1300/2100	Outdoor	300	100	Up to 20	3,41 & 48	FDD/ TDD	4G	4x4	Up to 64QAM	4x26dBm	10	Wireless	
AirSpan	AirSynergy 2000	Outdoor	300*	100*	Up to 20	2,3,4,7,9,10,12, 17,20,25,38,40, 41,42 & 43	FDD/ TDD	4G	2X2	Up to 64QAM	+30dBm	8,9 & 10	Wireless	eICIC, ABS, Embedded SON, SDR
AirSpan	AirUnity 540/544/545/546	Indoor	150	50	Up to 20	41 & 25	FDD/ TDD	4G	2X2	Up to 64QAM	+23dBm	10	Wireless	
AirSpan	AirVelocity	Indoor	150	50	Up to 20	3,7,40 & 66	FDD/ TDD	4G	2X2	Up to 64QAM	+26dBm	10	Wireless	
Qucell	Enterprise LTE Small Cell	Indoor	150*	50*	Up to 20	All	FDD	4G	2x2	-	-	9/10	Fiber	VoLTE, CSFB,SON
Ericsson	Radio Dot System	indoor	400(4G)+ 42(3G)+	100 11	Up to 80	Full range	FDD/ TDD	3G 4G	-	Up to 256QAM	+17dBm	-	Fiber	
Nokia	Flexi Zone	Outdoor#	300		-	1,2,3,4,25,40, 41,	FDD/ TDD	3G 4G	2X2	-	-	-	Fiber/ wireless	Multi-vendor
ZTE	Small cell - BS8912	Indoor/outdoor	150	50	Up to 20	1,3 and 7	FDD	4G	2X2	-	-	-	Fiber/copper	
ZTE	Femt0-BS8102	Indoor	150	50	Up to 20	1,3 and 7	FDD	4G	2X2	-	-	-	Fiber/copper	

(*) Assumption

(+) 400/100Mbps is with 2x20MHz for 4G and 42/11Mbps is with 4x5MHz bandwidth for 3G

(#) outdoor micro cell with up to 5km and 840 active users