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

Assessment and Optimization of Infrastructure and Radio Resource Utilization efficiency for LTE/LTE-A Cellular Networks, the Case of Ethio telecom

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

December 2024
Addis Ababa, Ethiopia

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Thesis Report: ***Assessment and Optimization of Infrastructure and Radio Resource Utilization efficiency for LTE/LTE-A Cellular Networks, Case of Ethio telecom***

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Declaration

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

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

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Abstract

Customers' quick requests for a variety of primary (basic and required, such as call, SMS/MMS, and data) and secondary (luxury and business class enterprises, such as high BW quality video accessing, video and camera surveillance, and online systematic monitoring & accessing) services via mobile networks necessitate thoughtful, timely responses from suppliers. The existence of many standards makes it difficult for 3G mobile networks to roam and cooperate with other mobile networks. However, LTE is a global standard that provides global mobility and service portability without binding customers to companies' proprietary hardware. Moreover, LTE is primarily a synthesis of multiple previous technologies rather than a completely unique standard. Since LTE/LTE-A/LTE-A pro is the most recent and enhanced service, it can currently satisfy consumer requests for high-speed data, low latency, bandwidth efficiency, multimedia broadcast and unicast, and high-quality cellular broadband services with affordable prices and revenue structures. This will be achieved by utilizing key technologies including orthogonal frequency-division multiplexing (OFDM), RF analysis and carrier aggregation, adaptive modulations, multiple-input multiple-output (MIMO), Hetnets and CoMP, and others. For instance, MIMO technology can significantly increase channel and spectrum efficiency. The physical layer channel includes modulation, cyclic prefix, frequency, bandwidth, and coding rate, all of which contribute to the high throughput. To increase spectral efficiency, the system uses OFDMA as an access mechanism in the downlink and Single Carrier Frequency Division Multiplexing (SC-FDMA) in the uplink. The Sphere Decoding (SD) detector, QR decomposition with M-algorithm maximum likelihood detector (QRM-MLD), Maximum Likelihood (ML) detector, Zero-Forcing (ZF) detector, and Minimum Mean Square Error (MMSE) detector are the superior signal detection methods that are employed. The ideal signal detector has a higher bit-error-rate (BER) in a correlated MIMO-OFDM scenario. even if the suppliers are testing and researching possible future R&D optimizations and service enhancements. In order to upgrade to LTE-4.5G and LTE-5G and offer opulent services like high BW, high QOS, low cost and jitter, error-free, and customer-acceptable, operators and service providers are now innovating, analyzing, and optimizing their LTE/LTE-A systems. As a result, consumers are sharing the globe and enjoying the newest innovations. Furthermore, engineers and technologists are researching and presenting their results and breakthroughs from theses, research, and seminars. In addition to discussing the evaluations, visualizations, and/or analyses utilizing various research techniques and algorithms to trace the availability, this thesis can also discuss LTE/LTE-A in the context of the aforementioned situations. After that, it will make a determination regarding the analysis. Based on the analysis, it is feasible to optimize the structural infrastructures and available resources to improve quick, dependable, and accessible services like SMS/MMS, calls, high bandwidth data, cheap cost, very little jitter, and delay with flawless system integrations. In the framework, market analysis and LTE-Advanced radio network link budget dimensioning are conducted using the COST-231 Hata model; existing LTE traffic, standard, and demographic studies are conducted for macro and small cells, respectively. Additionally, the required system bandwidth is estimated and computed correctly.

As a result, it will offer critiques, suggestions, and conversations regarding the outcome, followed by reports and presentations of the thesis. Based on this thesis study, it will be feasible to conduct a detailed survey, observations, and optimizations of the efficiency of LTE/LTE-A infrastructures and the consumption of radio resources in Ethiopian telecom cellular mobile networks. Additionally, it will analyze the optimizations of LTE/LTE-A upgrades to LTE-A pro and LTE-5G innovations. In addition, this thesis will demonstrate how LTE/LTE-A resource optimizations can serve as technical references and support as well as a means of disseminating engineering research and findings.

Keywords: — LTE, LTE-advanced, BW, OFDM, SC-FDMA, QOS, E-UTRAN, Resource Allocation, Delay, Jitter, SMS/MMS, Efficient Communications.
— Radio Resource Management (RRM), radio access technology (RAT), and heterogeneous wireless networks(HetNets).

Acknowledgment

Foremost, I would like to express my sincere gratitude to my advisor Yalemzewd Negash(PhD) for the continuous support of my MS.c thesis, for the motivation, enthusiasm and immense knowledge. His directions helped me all the time of the thesis and writing of this thesis. Besides to my advisor, I would also like to thank my thesis committee: Dr.Yehenew Wonde and Dr. Murad Ridwan for their encouragements, hard questions and insightful comments that helped me in strengthen my thesis. Similarly, I would like to say thank you for Dr. Ing. Dereje Hailemariam and Dr. Biniam Berhanu for your cooperation.

And my gratitude to the ethio Telecom Company, friends and experts in ethio Telecom, and also goes to my friends for giving me support and vital information.

Last but not the least; I would like to thank my family for your glamorous, patience and generous directional support.

Finally, all thank is due GOD, the most merciful, beneficent and the most gracious, who provided me with strength and ability to accomplish my work.

Dedication

To my families for their encouragement and continued support.

1.0 List of contents

2.0List of Symbols and Acronyms

Symbols

$F_{s,0}$	Nominal sampling frequency (with *OSR* = 1)
BW_{occ}	Occupied channel bandwidth
dB	*Decibels*
dBc	*Decibels relative to the Carrier*
di	*LO delay to the i-th cell*
f0	*BB signal frequency*
fc	*Carrier frequency*
Fs	*Sampling frequency*
Fs,0	*Nominal sampling frequency (with OSR = 1)*
ILSB	*Current corresponding to one LSB*
j	*Imaginary unit*
Lr	*Symbol roll off length*
n0	*Time shift (in samples)*
Nbits	*Number of bits*
NCP	*Cyclic Prefix size (samples)*
NCP,0	*Nominal Cyclic Prefix size (with OSR = 1)*
NFFT	*FFT size (samples)*
NFFT,0	*Nominal FFT size (with OSR = 1)*
NRB	*Number of Resource Blocks*
ns	*Slot index*
Nsc	*Number of occupied subcarriers*
Nslots	*Number of slots*
Nsymb	*Number of SC-FDMA symbols per slot*
NZC	*Length of the Zadoff-Chu sequence*
TCP	*Cyclic Prefix duration*
TFFT	*Useful symbol duration*
TLO	*Local Oscillator period*
Ts	*Sampling period*
VDD	*Supply voltage*
xBB(t)	*Baseband signal*
xRF (t)	*RF signal*

Acronyms

4G	Fourth Generation
5G	Fifth generation
BS	Base Station
HetNets	Heterogeneous network
QOS	Quality of service
AAA	Authentication authorization and administrations
RNC	Radio network controller
NGN	Next generation network
FDD	Frequency division duplex
TDD	Time division duplex)
RRM	Radio resource management
CRN	Cellular Radio Network
MIMO	Multi input multi output

CoMP	Coordinated Multi point
DWDM	Dense wave division multiplexing
LTE	Long Term Evolution
CWDM	Course wave division multiplexing
PRB	Physical Resource Block
OFDM	Orthogonal frequency division multiplexing
SC-FDMA	Single carrier frequency division multiplexing access
SINR	Signal to interference plus Noise Ratio
SNR	Signal to noise ratio
VAS	Value Added Services
RRM	Radio Resource Management
SP	Service providers
ATN	Aeronautical telecommunication network
RTN	Radio transmission network
3GPP	Third Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
ACK	Acknowledgment (in ARQ protocols)
ARQ	Automatic Repeat request
BS	Base Station
EDGE	Enhanced Data rates for GSM Evolution
eNB	Evolved Universal Terrestrial Radio Access Network Node B
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
HARQ	Hybrid ARQ
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
ITU	International Telecommunication Union
IMT-A	International Mobile Telecommunications Advanced
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
NACK	Negative Acknowledgment (in ARQ protocols)
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-to-Average Power Ratio
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
QPSK	Quadrature Phase-Shift Keying
RN	Relay Node
SC-FDMA	Single Carrier FDMA
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UTRAN	Universal Terrestrial Radio Access Network
UMTS	Universal Mobile Telecommunications System
ACLR	Adjacent Channel Leakage Ratio
AM-AM	Amplitude-Amplitude Modulation
AM-PM	Amplitude-Phase Modulation

BB	Baseband
BPSK	Binary Phase Shift Keying
BW	Channel bandwidth
CA	Carrier Aggregation
CC	Carrier Component
CIM	Counter-intermodulation
CMOS	Complementary Metal-Oxide Semiconductor
CW	Continuous Wave
DAC	Digital-to-Analog Converter
DDRM	Direct Digital-to-RF Modulator
DFT	Discrete Fourier Transform
DMRS	Demodulation Reference Signal
DNL	Differential Nonlinearity
DSP	Digital Signal Processing
EVM	Error Vector Magnitude
FDD	Frequency-Division Duplexing
FDMA	Frequency-Division Multiple Access
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
GPS	Global Positioning System
I	In-phase
IC	Integrated Circuit
ICI	Inter Carrier Interference

CHAPTER ONE

ITRODUCTIONS TO LTE, LTE-ADVANCED, NR AND NGN OPTIMIZATIONS

1.1 The history, development, and driving forces behind cellular network technology

1.1.1 Development of cellular and mobile technologies

The evolution of cellular and mobile technologies began with the introduction of **first-generation (1G)** systems in the early 1980s, marking the advent of mobile communication. These analog systems functioned much like traditional analog radios but suffered from limited capacity due to large cell tower sizes and inefficient spectrum usage. Mobile devices of this era were bulky, expensive, and primarily designed for business users [11].

The **1990s** saw the arrival of **second-generation (2G)** digital mobile communication, which brought about smaller, more affordable devices and better spectrum efficiency. Initially focused on voice communication, 2G later expanded to support instant messaging via **Short Message Service (SMS)**. **GSM**, the most widely adopted 2G system, was initially a Pan-European standard but quickly gained global recognition.

Building on 2G, the introduction of **2.5G**, or **General Packet Radio Service (GPRS)**, marked a shift to packet-switched networks, enabling simultaneous voice and data transmission. Further enhancements like **Enhanced Data Rates for GSM Evolution (EDGE)** improved performance, laying the foundation for the next generation.

By the **2000s**, **third-generation (3G)** networks emerged to address growing data demands driven by the Internet. Unlike 2G's **Frequency Division Multiple Access (FDMA)** and **Time Division Multiple Access (TDMA)**, 3G employed **Wideband Code Division Multiple Access (WCDMA)**, achieving higher data rates and better spectrum efficiency. The primary 3G standard, **Universal Mobile Telecommunication System (UMTS)**, evolved from GSM by overhauling the air interface while largely retaining the core network infrastructure.

To further improve data capabilities, **3.5G technologies** such as **High-Speed Downlink Packet Access (HSDPA)** and **High-Speed Uplink Packet Access (HSUPA)**—collectively referred to as **High-Speed Packet Access (HSPA)**—were developed [1, 2, 11]. These advancements set the stage for the introduction of **Long-Term Evolution (LTE)** by **3GPP**, which revolutionized both network architecture and the air interface, enabling faster and more efficient communication.

1.1.2 Back ground

Evolution of Mobile Networks

Second Generation (2G) and Third Generation (3G) mobile networks were initially designed to meet growing demands for wireless voice and data services. However, they faced challenges in scaling effectively to accommodate the rapid increase in usage. To address these limitations, the **Third Generation Partnership Project (3GPP)** introduced **Long-Term Evolution (LTE)**, a technology aimed at significantly improving network performance and efficiency.

LTE, built on the foundations of **GSM** and **UMTS**, offers substantial enhancements, such as:

- Increased service capacity.
- Optimized resource usage.
- Reduced deployment and operational costs.
- Flexible implementation models.

These advantages have led to widespread adoption by leading mobile network operators globally.

LTE and the Transition to 4G

Initially, LTE did not fully satisfy the **4G technical specifications** set by the **International Telecommunication Union (ITU)**. Nevertheless, it was classified as 4G for marketing purposes due to its substantial improvements over 3G technologies. **LTE Advanced**, however, fully complies with ITU-R standards, meeting all requirements for 4G classification.

Key LTE features include:

- **High Data Transfer Rates**: Capable of supporting services like HD video streaming at up to **100 Mbps** for mobile users and high-capacity applications exceeding **20 Mbps**.
- **Efficient Bandwidth Utilization**: Maximizing spectrum use to support more users simultaneously.
- **Low Latency**: Ensuring fast responses for applications like gaming and real-time video conferencing.
- **Multimedia Service Support**: Delivers unicast and broadcast modes for diverse multimedia applications.

Overcoming 3G Challenges with LTE

3G standards' variation created difficulties in seamless roaming and operational consistency across different networks. LTE resolves these issues by:

- Establishing a **global standard**, removing reliance on proprietary hardware.
- Supporting **worldwide mobility** and **service portability**, ensuring consistent user experiences across regions.

Unlike an entirely new technology, LTE builds upon earlier systems, integrating advancements that enhance performance while maintaining backward compatibility.

LTE Technology Features

LTE incorporates several key features at its **physical layer**, which contribute to improved performance:

- **Uplink**: Uses **Single Carrier Frequency Division Multiplexing (SC-FDMA)** for higher spectral efficiency.
- **Downlink**: Employs **Orthogonal Frequency Division Multiplexing (OFDMA)** to minimize interference and boost throughput.
- **Advanced Parameters**: Frequency, bandwidth, modulation, cyclic prefix, and coding rate are carefully optimized to maximize throughput and quality of service (QoS).

Stakeholders and Continuous Advancement

The success of LTE relies on the commitment of various stakeholders, including:

- **Customers**: Demand for better connectivity and advanced services.
- **Service Providers**: Driving network upgrades and innovation.
- **Operators**: Ensuring efficient deployment and optimization.

Continuous **research and development** efforts target ongoing enhancements, from

4G LTE to **5G** and even **6G** technologies, with a focus on delivering cost-effective, high-capacity, and broad-coverage solutions.

LTE Deployment in Ethiopia

Ethiopian Telecom has implemented **LTE**, **LTE Advanced**, and **LTE 5G NR (New Radio)** through phased rollouts, achieving high customer satisfaction. This thesis investigates strategies to optimize resource utilization in these networks, using Ethiopian Telecom's cellular infrastructure as a case study.

Conclusion

LTE represents a major leap forward in mobile communication technology, addressing the limitations of earlier networks while laying the foundation for future advancements. By leveraging GSM and UMTS technologies and introducing innovations like SC-FDMA and OFDMA, LTE delivers exceptional performance in terms of speed, efficiency, and scalability. Ethiopian Telecom's adoption of LTE technologies demonstrates their commitment to providing world-class connectivity and meeting the demands of modern wireless communication.

1.1.3 Motivation

For many years, mobile telecommunications revolved around voice calls, with data services playing a minor role. However, as technology advanced, data traffic steadily surpassed voice traffic. By 2010, congestion in 2G and 3G networks emphasized the urgent need for increased network capacity and efficiency. The development of **LTE (Long-Term Evolution)** was motivated by three critical factors:

1. Core Network Optimization

- **Traditional Dual Networks**:
    - 2G and 3G networks maintained separate **circuit-switched domains** for voice and **packet-switched domains** for data.
- **VoIP Integration**:
    - LTE introduced **Voice over IP (VoIP)**, enabling voice and data to operate over a single **packet-switched domain**.
- **Cost Benefits**:
    - Consolidation reduced both **Capital Expenditures (CAPEX)** and **Operational Expenditures (OPEX)**, making LTE a cost-efficient solution for operators.

2. Latency Reduction

- **Challenges in 3G Networks**:
    - Applications on 3G networks faced high latency (~100 ms), which was unsuitable for real-time services like voice communication and interactive applications (e.g., gaming).
- **LTE Solution**:

  - LTE significantly reduces **end-to-end latency**, enabling seamless real-time interactions and enhanced user experiences.

3. Complexity Management and Performance Demands

- **Backward Compatibility**:
  - LTE supports earlier technologies like **UMTS/HSPA** and **GSM/EDGE**, introducing complexity in network design.
- **Rising Expectations**:
  - As demand for higher speeds, better performance, and increased throughput grows, LTE addresses these needs through optimized **spectrum usage** and advanced techniques:
    - **Spatial Diversity**: Improves performance without requiring additional time or bandwidth.
    - **Frequency and Time Diversity**: Mitigates multipath fading to enhance reliability.

Key Technologies in LTE

1. **Orthogonal Frequency Division Multiplexing (OFDM)**:
   - Converts high-speed data streams into multiple **lower-rate transmissions** across orthogonal subchannels.
   - Maximizes spectral efficiency by overlapping subcarriers in the frequency domain.
2. **Multiple Input Multiple Output (MIMO)**:
   - Employs multiple antennas at the transmitter and receiver to improve **channel capacity** and **spectrum efficiency**.
   - MIMO balances trade-offs between performance and system complexity, particularly as the number of antennas increases and higher transmission speeds are introduced.
3. **MIMO Signal Detection Methods**:
   - **Techniques**: Zero-Forcing (ZF), Minimum Mean Square Error (MMSE), and Maximum Likelihood (ML).
   - **Comparison**: While **ML** offers the best performance, its complexity poses challenges for practical implementation.

Advancements in RF Design

- Modern radio frequency (RF) circuits are moving toward **digital implementations**, reducing reliance on analog components.
- Technologies like **Direct-digital RF modulators (DDRM)** and **RF Digital-to-Analog Converters (RF-DAC)** enable cost-effective and scalable **all-digital transceivers**.
- However, ongoing research remains focused on hardware prototypes rather than theoretical analysis.

LTE-A Enhancements

The global adoption of **LTE-A (LTE Advanced)** is driven by its superior capabilities:

1. **Features of LTE-A**:
   - **Carrier Aggregation (CA)**: Increases bandwidth by combining multiple carriers.
   - **Coordinated Multipoint (CoMP)**: Reduces interference and improves signal quality.
   - **Heterogeneous Networks (HetNet)**: Enhances coverage with a mix of macro, micro, and small cells.
2. **Performance**:
   - LTE-A delivers up to **three times the speed** of LTE.
   - Reduces energy consumption and environmental impact.
3. **Benefits**:
   - Higher data rates and improved spectral efficiency.
   - Fewer dropped connections and greater resilience to interference.

Motivation in the Ethiopian Context

1. **Rising Mobile Data Traffic**:
   - Mobile data usage in Ethiopia is growing rapidly, prompting **Ethiopian Telecom** to deploy LTE in select areas.
2. **Economic Impact**:
   - Enhanced connectivity is expected to boost GDP, create jobs, and improve access to social services like healthcare and education.
3. **Infrastructure Challenges**:
   - Existing networks in Addis Ababa are insufficient to meet future market and economic demands.
   - Scalable and robust solutions are required to address increasing subscriber growth and data consumption.
4. **Role of LTE-A**:
   - With superior performance, LTE-A is well-positioned to handle these challenges.
   - Operators must conduct **pre-deployment analyses** to evaluate technology feasibility and manage costs effectively.

Techno-Economic Analysis (TEA)

- **Purpose**:
  - Helps operators like **Ethiopian Telecom** design cost-effective LTE-A rollout strategies.
  - Optimizes investment by identifying essential network features and aligning with market needs.
- **Outcome**:
  - Ensures economic viability while meeting the technological demands of a growing market.

Conclusion

The motivation for LTE stems from the need to overcome the limitations of earlier technologies and meet the rising demands for high-speed, low-latency mobile networks. LTE-A's advanced features, coupled with scalable deployment strategies, provide a path forward for operators like Ethiopian Telecom to support economic growth and improve quality of life through robust telecommunications infrastructure.

Literature review

This section consolidates insights from various studies that explore the potential, challenges, and future prospects of LTE-A deployment, emphasizing different perspectives from operators and researchers.

Techno-Economic Aspects (TEA) of LTE-A Deployment

The study in [6] examines the techno-economic aspects of LTE-A deployment, highlighting factors critical to its success:

1. **Integrated Modeling:** Combines population density and geographical data.
2. **Service Demand:** Considers service penetration and usage growth.
3. **Pricing Strategies:** Includes data plan promotions to drive adoption.
4. **Network Design:** Optimized for both coverage and capacity.
5. **Cost Forecasts:** Differentiates between capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX includes expenses for spectrum, LTE eNodeBs, and Mobility Management Entities (MMEs), while OPEX covers site rentals, maintenance, leased lines, and energy costs.

The analysis projects profitability within six years and concludes that LTE-A effectively balances the growing demand for speed, capacity, and spectrum flexibility with manageable costs.

Investment Strategies for LTE-A Deployment

The "Build it and they will come" strategy is critiqued in [7], emphasizing the need for targeted investments to maximize user adoption. The study identifies two critical areas for successful 4G migration:

1. **Pricing:** Leveraging improved Quality of Service (QoS) to justify higher prices, subsidizing devices, and reducing data costs compared to 3G.
2. **User Education:** Communicating the benefits of 4G effectively to drive migration.

These strategies underscore the importance of aligning market offerings with user expectations and economic conditions.

Carrier Aggregation (CA) in LTE-A

Carrier Aggregation is pivotal in addressing rising data demands. The study in [10] focuses on:

1. **Frequency Bands:** Dual-band usage, e.g., 700 MHz and 2600 MHz.
2. **Configurations:** Single-carrier, contiguous component carrier (CC), and inter-band CC.
3. **Network Optimization:** Enhancements through new or existing base stations.

The TEA evaluates market conditions, user costs, and equipment investments, concluding that LTE-A with CA outperforms single-carrier systems, making it ideal for high-demand mobile broadband (MBB) applications.

Channel Estimation in LTE Wireless Networks

Research in [5] and [6] investigates channel estimation for LTE systems:

- **Techniques:** Least Squares (LS) and Linear Minimum Mean Square Error (LMMSE) methods are evaluated for single-input single-output (SISO) configurations.
- **Interpolation Methods:** Linear, spline, and p-chip techniques affect LMMSE performance. Simulations demonstrate that both modulation schemes (QPSK, 16QAM) and interpolation methods impact accuracy, especially under mobile conditions.
- **Findings:** LS and Maximum Likelihood (ML) estimation excel in high Signal-to-Noise Ratio (SNR) environments, while MMSE performs better at low SNRs.

MIMO Systems and Inter-Carrier Interference (ICI)

In 2x2 MIMO LTE systems, [7] explores channel length's impact on LS and LMMSE estimation, emphasizing equalization to improve SNR. Other studies focus on reducing ICI in Orthogonal Frequency Division Multiplexing (OFDM) systems:

- **Self-Cancellation Techniques:** Proposed by Seyedi and Saulnier [14], pairing self-cancellation with frequency offset estimation reduces ICI efficiently while maintaining computational simplicity.
- **Pulse-Shaping Techniques:** Cheng et al. [8] suggest alternating pulse-shaping windows to improve Bit Error Rate (BER) at the cost of higher computational complexity.

Further, Kumar et al. [6] introduce time-domain equalization with window functions, enhancing the Signal-to-ICI Ratio, though higher-order windows remain unexplored.

Advanced Techniques for ICI Reduction

Zhao & Haggman [16] propose self-cancellation approaches that enhance BER and reduce ICI, but at the cost of transmission rate and bandwidth efficiency. Nyquist windowing, as discussed in [17], suppresses side lobe effects to improve carrier frequency offset resilience. However, computational intensity in MMSE optimization remains a challenge.

This body of research highlights LTE-A’s potential to address growing data demands while emphasizing the need for strategic investments, advanced channel estimation techniques, and innovative methods for ICI mitigation. These insights are instrumental in understanding LTE-A's role in the future of mobile broadband networks.

1.2 Thesis out line

The research is organized into five chapters as follows:

Chapter One: Introduction

This chapter introduces LTE and the advancements in LTE-Advanced (LTE-A). It includes the following:

- **Background:** Overview of LTE and LTE-A developments.
- **Motivation:** Rationale for the research.
- **Problem Statement:** Identification of key issues in LTE and LTE-A networks.
- **Objectives:** Goals the research aims to achieve.
- **Methodologies:** Approaches and methods used in the study.
- **Expected Contributions:** Anticipated impact and significance of the research findings.
- **Scope and Limitations:** Boundaries and constraints of the study.
- **Literature Review:** Synthesis of relevant studies and foundational knowledge.

Chapter Two: Technical Optimizations of LTE and LTE-Advanced

This chapter delves into the technical strategies for optimizing LTE and LTE-A networks. Topics include advancements in:

- Network architecture.
- Radio interface technologies.
- Resource management and spectral efficiency improvements.

Chapter Three: Deployment Trends and Scenarios

This chapter examines current deployment trends for LTE-A, addressing:

- **Uncertainties:** Factors that could influence LTE-A implementation.
- **Deployment Strategies:** Development of practical and feasible deployment scenarios.

Chapter Four: Results and Discussions

This chapter presents the findings of the research, including:

- **Optimization Results:** Analysis and interpretation of the outcomes.
- **Discussions:** Critical evaluation of the findings in relation to existing studies.
- **Conclusions:** Summary of key takeaways from the research.
- **Future Work:** Suggestions for further exploration and innovation.
- **Recommendations:** Practical guidance for stakeholders and operators.

Chapter Five: Library Resources and Supplementary Materials

The final chapter provides supporting resources, including:

- Bibliographic references.
- Appendices and supplementary documentation.

This structure ensures a comprehensive exploration of the topic, from foundational concepts to practical applications and future directions.

1.3 Statement of the problem

Telecommunication companies continue to invest heavily in mobile technologies to improve services for their users. Despite these efforts, these technologies are often deployed without sufficient investigation or thorough techno-economic analysis. This oversight leads to performance inefficiencies, such as interference, limited capacity, and underutilization of resources, particularly in 3G and LTE networks. These issues compromise Quality of Service (QoS), reduce user satisfaction, result in resource wastage, limit revenue growth for operators, and increase both capital expenditure (CAPEX) and operational expenditure (OPEX). The negative impact extends beyond users to national development, as mobile broadband is a key driver of individual and economic progress. This is particularly relevant to Ethiopia's Growth and Transformation Plan (GTP), which heavily depends on a robust telecom sector, emphasizing the need for a comprehensive techno-economic evaluation of emerging mobile technologies.

The introduction of LTE-A offers a promising solution to meet the growing demand for advanced mobile services. However, there are uncertainties surrounding its features, costs, resource requirements, user adoption rates, and the availability of compatible devices. Simply deploying LTE-A is not enough to guarantee its acceptance or technical viability. Additionally, there is a lack of clarity regarding which LTE-A features are best suited to the local context. Therefore, designing practical deployment scenarios and conducting a detailed techno-economic feasibility analysis are essential.

Core Challenges

The primary challenges can be outlined as follows:

- **Demand for LTE/LTE-A (4G) and NGNs:** There is a pressing need to deliver efficient broadband services for applications such as voice, MMS, video streaming, and conferencing. These demands must cater to both residential and enterprise customers.
- **Capacity, Coverage, and QoS Issues:** These challenges arise due to the incomplete deployment of cellular networks and inadequate ICT infrastructure by telecom operators.
- **Resource Optimization in LTE/LTE-A:** Achieving maximum resource utilization and effective optimization is critical for supporting high-throughput services ranging from 300 Mbps to over 1 Gbps. Vendors and R&D teams from telecom operators are actively seeking solutions to these optimization challenges.

Research Aim

This thesis seeks to address these challenges by developing detailed optimization strategies for LTE-A deployment. The focus is on achieving technical efficiency and economic feasibility while ensuring alignment with local needs and conditions.

1.4 Objective

1.4.1 General objective

The primary objective of this thesis is to analyze and optimize resource utilization in LTE/LTE-A cellular networks. The goal is to maximize bandwidth or data throughput to minimize costs while enabling the effective delivery of the latest services.

1.4.2 Specific objectives

To achieve the general objective, the following specific objectives have been outlined:

- **Study and Describe Technological Aspects of LTE/LTE-A:** Develop a comprehensive understanding of the technologies underpinning LTE/LTE-A systems.
- **Analyze the Infrastructure Architecture of LTE/LTE-A:** Examine the structural components of LTE/LTE-A, including:
  - Core network.
  - Value-Added Services (VAS) and Intelligent Networks (IN).
  - Transmission networks (e.g., microwave, coaxial, and fiber).
  - Multimedia networks.
  - Radio networks.
- **Address Resource Components in LTE/LTE-A:** Identify and assess the various resource elements within LTE/LTE-A cellular networks.
- **Analyze Resource Utilization in LTE/LTE-A:** Investigate the current utilization patterns and effectiveness of resources in LTE/LTE-A systems.
- **Optimize Resource Utilization:** Propose and implement optimization strategies to enhance resource utilization for improved service durability and efficiency.

1.5 Methodology

Overview of Methods

This thesis adopts a comprehensive and multifaceted approach to validate its hypothesis, leveraging a combination of descriptive and analytical techniques, statistical models, and techno-economic analysis (TEA). Below is an overview of the methods employed:

1. Data Collection and Sources

- **Primary Resources**:
    - **Standards and Specifications**:
        - **3GPP Documentation**: Focus on **3GPP TS 36.101 Release 14** to ensure compliance with LTE-A standards.
        - **ITU Publications**: Reference for forecasting spectrum requirements.
    - **Ethio Telecom Documentation**: Analysis of reports and data, particularly on the **2600 MHz**, **1800 MHz**, and **800 MHz spectrum bands**.
- **Secondary Resources**:
    - **Academic Literature**: Studies and journals on LTE-A technology from IEEE and related publications.
    - **Vendor Reports**: Insights into industry best practices and real-world LTE-A deployments.
    - **TEA-Centered Dissertations**: Informed the techno-economic analysis aspect of the study.

2. Analytical Methods

1. **Spectrum Performance Analysis**:
    - **Bands Evaluated**:
        - 2600 MHz, 1800 MHz, and 800 MHz bands.
    - **Goals**:
        - Develop optimal LTE-A deployment strategies tailored for Addis Ababa.
        - Assess feasibility and throughput.
2. **Coverage Dimensioning**:
    - **Model Used**:
        - **COST-231 Hata Model**: Applied to estimate signal coverage in various deployment scenarios.
    - **Tools**:
        - **Excel-Based Link Budget**: Evaluates coverage capabilities and resource requirements.
3. **Capacity Dimensioning**:
    - Inputs include:
        - Subscriber forecasts.

        - Cell capacity and data plans.
    - **Output**:
        - Infrastructure planning to support projected LTE-A traffic.
4. **Indoor and Outdoor Small Cell Requirements**:
    - Based on:
        - Existing LTE traffic.
        - Product surveys and demographic data.
        - Projected subscriber growth.
5. **Spectrum Forecasting**:
    - **Method**: ITU-T forecasting method.
    - Purpose: Estimate spectrum requirements based on projected growth and technological needs.

3. Market Analysis

1. **Target Market Assessment**:
    - Identified **subscriber demographics**, market share, and device penetration.
    - Examined **ARPU (Average Revenue Per User)** to project revenue growth.
2. **Subscriber Forecasting**:
    - Based on:
        - Current 3G and LTE subscriber data.
        - Growth margins using the **Base Forecasting Method**.
3. **Device and Infrastructure Surveys**:
    - Assessed LTE-A device availability and capabilities.
    - Surveyed small cells for **indoor and outdoor deployments**.

4. Combined Descriptive and Analytical Approaches

- **Descriptive Methods**:
    - Contextualized the LTE-A technological landscape.
    - Outlined infrastructure requirements and resource challenges.
- **Analytical Methods**:
    - Numerical analysis of statistical data, such as throughput and subscriber growth.
    - Mathematical modeling for capacity and coverage dimensioning.

Conclusion

This methodology enables a holistic assessment of LTE-A deployment in Addis Ababa by combining standards-based compliance, rigorous data analysis, and market insights. The approach ensures that both the technical and economic aspects of LTE-A rollout are comprehensively addressed, providing a robust foundation for the proposed strategies.

Summery:

This thesis employs a multifaceted approach to validate its hypothesis, drawing on a broad range of resources, including standards, academic publications, vendor reports, and related studies. Key data sources include literature on LTE-A, IEEE articles and journals, 3GPP documentation, International Telecommunications Union (ITU) publications, and techno-economic analysis (TEA)-centered dissertations. Additional data was gathered from Ethio Telecom's documentation and project reports, with a focus on analyzing the 2600, 1800, and 800 MHz spectrum bands for performance. These bands were evaluated to develop optimal LTE-A deployment strategies for Addis Ababa, in compliance with the 3GPP Technical Specification 36.101 Release 14 (3GPP TS 36.101 R'14).

The study analyzed the feasibility and throughput of LTE-A following the identification of deployment strategies. Coverage dimensioning was carried out using the COST-231 Hata model and an Excel-based link budget, while subscriber forecasts, cell capacity, and data plans were used to inform capacity dimensioning for various scenarios. Indoor and outdoor small cell requirements were assessed based on existing LTE traffic, standards, product surveys, demographic data, and projected subscriber growth. The ITU-T forecasting method was employed to determine the spectrum requirements.

Market analysis encompassed identifying target subscribers, market share, device penetration, and average revenue per user (ARPU). Subscriber forecasts for Addis Ababa were based on existing 3G and LTE subscriber numbers, incorporating growth margins and the Base forecasting method to evaluate LTE-A's market potential. This analysis also included assessments of LTE-A device availability, capabilities, and surveys of small cells for both indoor and outdoor deployment.

The methodologies varied depending on the task, combining descriptive and analytical techniques with statistical and mathematical models. Statistical data was analyzed numerically, while descriptive methods were employed to outline and contextualize the system's technological landscape. These combined approaches enabled a thorough assessment of the infrastructure and resource requirements for LTE-A deployment.

Data collection

For this thesis, a formal data collection permission letter was issued to Ethio Telecom through Addis University. A detailed survey was conducted to gather information on key elements such as spectrum bands, carrier aggregation configurations, radio frequencies, cell structures, channel configurations, modulation techniques, MIMO types, Coordinated Multi-Point (CoMP) configurations, channel bandwidth, data bandwidth, data rates, throughput, and infrastructure. The survey revealed that Ethio Telecom utilizes four radio frequency bands:

- **2600 MHz** (Band 7)
- **800 MHz** (Band 20)
- **1800 MHz** (Band 3)
- **2100 MHz** (Band 1).

Each eNodeB site comprises three cells: one operating on the 1800 MHz band with 100% coverage, another on the 2600 MHz band with 46% coverage, and a third using either the 2100 MHz or 800 MHz band, covering approximately 29%. The 800 MHz band is predominantly used in environments requiring short-range coverage, such as indoor areas, garages, rooftops, buildings, and densely populated locations, as it offers more focused coverage compared to the 1800 MHz and 2600 MHz bands.

Carrier aggregation (CA) is implemented using up to two component carriers (20+20 MHz) or three component carriers (10+20+20 MHz), resulting in a total channel bandwidth of 50 MHz aggregated across the three cells or sectors in an eNodeB. Carrier aggregation is limited to the

same eNodeB and its associated spot cells, which restricts LTE-A in Ethio Telecom from fully utilizing CoMP configurations for CA in macro cells at the edge users.
Ethio Telecom employs various MIMO configurations, allowing customers to benefit from enhanced data throughput enabled by carrier aggregation, MIMO, adaptive modulation schemes, and efficient radio frequency scheduling. However, in the case of 5G New Radio (NR), carrier aggregation is configured across different frequency bands of macro and hotspot eNodeBs, leveraging CoMP and heterogeneous networks (HetNets) infrastructure for improved performance.

Summery:

In this thesis an official data collection permission letter is written to ethio telecom from Addis University and detail data collection survey is performed from ethio telecom for collecting; spectrum band, carrier aggregation, radio frequency, cell structure, channel configurations, modulation types, MIMO types, CoMP configurations, Channel bandwidth, data bandwidth, data rate, throughput, infrastructures, … According to survey assessment, ethio telecom uses four radio frequencies bands: *2600MHZ in band 7, 800MHZ in band 20, 1800MHZ in band 3 and 2100MHZ in band 1*. A site (eNodeB) has three cells (1800MHZ with 100% coverage, 2600MHZ with 46% coverage and either 2100MHZ or 800MHZ with about 29% coverage). RF 800MHZ is mostly used for eNodBs for indoor, garage, rood, buildings and dense areas with small range coverage comparatively with 1800&2600 MHZ RFs. And also there are up to 2CC (20+20 MHZ) or 3CC (10+20+20 MHZ) carrier aggregations.
And carrier aggregation of three bands having a total of 50MHZ channel bandwidth from the three cells or sectors in eNodeB. The carrier aggregation is only possible from the same eNodeB and from the different spot cells. Hence LTE-A in ethio telecom is not effectively applied for coordinated multi point EURAN CA configurations from the same macro cells at the edge users. It has also different types of MIMO configurations. So ethio telecom customers can enjoy with high bandwidth data throughput from the carrier aggregation, MIMO, adaptive modulations and radio frequency scheduling. But 5G NR radio carrier aggregations configurations are deployed from different bands of macro or hot spot eNodeBs using CoMP and HetNets infrastructures.

Data processing and analysis

The analytical approach is used to define and evaluate the input and output variables within the system. This involves the application of analytical techniques and mathematical modeling to analyze assessments and computational algorithms. A combination of analytical, empirical, and descriptive methods, along with mathematical models, is employed to optimize resource utilization. The synthesis method is utilized to compile theorems and derive results and conclusions, while the empirical method is applied to formulate numerical theorems and algorithms for calculations. Additionally, mathematical models are used for arithmetic computations.

This thesis includes an extensive literature review, incorporating various forms of technical analysis to enhance channel bandwidth and throughput. For example, the analysis of LTE Releases 8/9 reveals that a theoretical peak data rate of 300 Mbps for downlink and 75 Mbps for uplink can be achieved. This is accompanied by a specified transmission bandwidth of 20 MHz for both downlink and uplink, and peak spectral efficiencies of 15 bps/Hz for downlink and 3.75 bps/Hz for uplink. These figures are attainable through core and radio technology optimizations within the UMTS 3G network, meeting the requirements of an all-IP network.
For LTE-Advanced Releases 10/11, the analysis indicates that it is theoretically possible to achieve a peak data rate of 1 Gbps for downlink and 500 Mbps for uplink. The corresponding transmission bandwidths are 100 MHz for downlink and 40 MHz for uplink, with peak spectral

efficiencies of 30 bps/Hz and 15 bps/Hz, respectively. These enhancements are achieved by optimizing parameters such as transmission power, transmission frequency (using carrier aggregation spectrums), adaptive modulation schemes, multiplexing techniques, antenna input power and diversity types, RF efficiency improvements, RRM scheduling, and propagation environment adjustments, fulfilling the requirements of an all-IP network.
The data collection and analysis section of this thesis includes detailed discussions, clarifications, mathematical evaluations, and technical documentation from Ethio Telecom, as previously outlined. This section provides comprehensive insights into the technical and operational aspects of LTE and LTE-A deployment.

Optimization

From the literature hypothesis and data collection or analysis from ethio telecom part, it can be justified that the LTE-advanced in ethio telecom is not maximally utilized in the carrier aggregation, CoMP, HetNets, RF scheduling and RRM scheduling even though in the 5G network it is well solved.

1.6 Potential contribution

Contributions and Applications of the Thesis

The outcomes of this thesis serve multiple purposes, including providing a performance project systems plan, optimizing resource utilization, supporting propagation studies for engineering research, compiling technical documentation, and offering references for further studies.
Key benefits include:

- **Enhanced Network Monitoring**: Enabling effective monitoring of cellular networks through LTE/LTE-A tools and systems.
- **Efficient Troubleshooting**: Facilitating the identification and resolution of issues across various cellular technologies and resources.
- **System Upgrades and Activation**: Supporting the activation and upgrading of services and resources to enhance offerings such as high throughput and video surveillance through mobile systems.
- **Support for Professional Needs**: Serving as a resource for discussions, recommendations, reports, and presentations.

Additionally, this thesis contributes to workforce development by providing professionals with:

- Practical skills and knowledge in wireless, cellular/mobile, radio networks, core networks, VAS/IN networks, IP and multimedia networks, and transmission networks.
- Opportunities for work-related improvements and advancements in engineering expertise.

Overall, this work equips stakeholders with tools and insights to maximize the performance and utility of modern cellular systems.

1.7 Scope and limitation

This thesis explores the feasibility of deploying LTE and LTE-A technologies for Ethio Telecom by assessing various dimensions such as service, economic, capacity, coverage, and technical aspects. The study employs methods including evaluation, analysis, and resource optimization to highlight the significance of LTE and LTE-A technologies. It evaluates their impact on service quality, technical performance, and economic feasibility. The research defines relevant deployment scenarios and performs dimensioning for macro cells, small cells, and spectrum, along with data rate analysis. The analysis is based on technical literature and Ethio Telecom data, using a scenario-based planning approach to optimize resource utilization.

Limitations:

- **Small Cell Dimensioning**: The analysis is constrained by insufficient data, such as incomplete data rate information, limited sample areas, and assumptions needed to accurately estimate the number of small cells required.
- **Frequency Spectrum and CoMP Configurations**: Ethio Telecom faces limitations in implementing frequency spectrum carrier aggregation with HetNets and CoMP EURAN configurations. Due to coverage, capacity, and site distribution challenges, CoMP is not utilized within the E-UTRAN infrastructure.
- **Signal Strength for Moving Users**: For users on the move, the likelihood of receiving strong signals from multiple eNodeBs is low, complicating bearer transitions between sites during calls.
- **Carrier Aggregation Constraints**: Carrier aggregation in Ethio Telecom is restricted to 50 MHz channel capacity, falling short of the maximum 100 MHz capacity specified for LTE-A.
- **Licensing and Administrative Challenges**: Implementing LTE-A at its full potential requires additional licenses, advanced administrative configurations, and costly upgrades for maximum resource optimization.

In summary, while the thesis addresses critical aspects of LTE-A deployment, certain limitations in data availability, infrastructure configurations, and administrative processes present challenges that need to be addressed for optimal implementation.

CHAPTER TWO

DETAIL TECHNICAL OPTIMIZATIONS OF LTE AND LTE-ADVANCED NETWORKS

3.1 Technical optimizations of LTE technology

3.1.1 General over view of LTE technology

Wireless or cellular channel briefing and basics

When radio waves are emitted from a transmitting antenna, they traverse the vacuum of space but interact with the environment in ways that alter their propagation. These interactions include **diffraction**, **absorption**, **reflection**, **refraction**, and **scattering**, all of which are influenced by environmental factors like air, terrain, and obstacles such as buildings, bridges, hills, and trees. These physical phenomena shape the unique characteristics of the signal received at the destination.

Two primary models describe these propagation behaviors:

1. **Fading**: Caused by variations in the signal amplitude due to multipath effects.
2. **Additive White Gaussian Noise (AWGN)**: Represents the noise added to the signal during transmission.

Wireless transmission systems face challenges such as **attenuation**, **noise**, **multipath effects**, and **interference**. To meet the increasing demand for diverse, high-quality services, modern transceivers must comply with requirements like **high capacity**, **variable bit rate transmission**, and **efficient bandwidth utilization**. Traditional single-carrier systems struggle in wireless environments due to fading and multipath delay spread, which can cause signal amplitude variations and **intersymbol interference (ISI)**. These issues result in higher error rates and reduced system performance.

A promising solution to these challenges is **multi-carrier modulation**, a physical-layer approach that divides a high-data-rate signal into multiple lower-rate streams, each transmitted using a unique orthogonal frequency. One of the most prominent implementations of multi-carrier modulation is **Orthogonal Frequency-Division Multiplexing (OFDM)**.

Key Characteristics of OFDM:

- **Orthogonality**: Ensures that subcarriers do not interfere with one another, maximizing spectrum efficiency.
- **Efficient Spectrum Usage**: Overlapping narrowband subcarriers transmit simultaneously, dividing the spectrum into multiple orthogonal subchannels, each experiencing near-flat fading.
- **Robustness**: Offers high data rates while mitigating the detrimental effects of fading and multipath interference in radio channels.

Applications of OFDM:

- Widely adopted as the standard for high-data-rate wireless communication systems.
- Extensively used in **European digital audio and video broadcasting**.
- Supported by international standards like **IEEE 802.11a**, **IEEE 802.11g**, and **HIPERLAN2**, enabling IP-based services.
- Increasingly explored for broadband indoor wireless communication.

In summary, OFDM has emerged as the preferred modulation technique for modern wireless communication systems, meeting the demands for high-speed data transmission and efficient bandwidth utilization.

Channel state and service estimation

1. Evolution of Mobile Communication Systems

- **UMTS to LTE**:
  UMTS 3G technologies built on GSM's success, offering significant advantages. However, increasing demands for higher data rates and improved spectral efficiency necessitated innovations like LTE.
- **LTE Evolved Packet System (EPS)**:
  - Fully **IP-based**, supporting both data and real-time services.
  - Assigns IP addresses dynamically for communication sessions.
  - Incorporates **higher-order modulation (64-QAM)** and **OFDMA** for efficient downlink transmission, with bandwidths from **1.4 MHz to 20 MHz**.
  - Supports **spatial multiplexing (up to 4x4 MIMO)** in the downlink, achieving theoretical peak rates of **300 Mbps (DL)** and **75 Mbps (UL)**.

2. Role of Channel Estimation

- **Challenges in Wireless Channels**:
  - **Multipath propagation** causes rapid changes in signal phase and amplitude, degrading system performance.
  - Effective communication requires precise estimation of channel variations to mitigate these effects.
- **Importance of Channel State Information (CSI)**:
  CSI helps to characterize wireless channel properties, accounting for effects like **fading** and **scattering**, and ensuring reliable data transmission.
  - **Instantaneous CSI**: Provides real-time channel conditions for adaptive transmission.
  - **Statistical CSI**: Offers a generalized view, including fading patterns and spatial correlations.

3. Channel Estimation Techniques

Channel estimation methods are categorized as follows:

1. **Blind Techniques**:
   - Estimate channel parameters without explicit reference signals, relying on inherent signal properties.
   - Pros: Requires no extra bandwidth.
   - Cons: Computationally intensive and less reliable in noisy environments.
2. **Semi-Blind Techniques**:
   - Combine reference signals with blind estimation methods.
   - Strike a balance between complexity and performance.
3. **Pilot-Aided Techniques** (used in LTE):
   - Utilize **cell-specific reference signals (pilot symbols)** embedded in subframes.
   - Pilot symbols provide discrete channel estimates in the time and frequency domains, enabling interpolation for robust performance across subframes.

4. Key LTE Features for Channel Estimation

- **Pilot Symbols**:
  - Allow precise channel estimation at known reference points.
  - Embedded in LTE subframes with predefined structures for both time and frequency.

- **Interpolation**:
    - Extends channel estimates to other subframes, maintaining system reliability.

5. Implications for System Performance

- Accurate channel estimation enables:
    - **Efficient utilization of bandwidth and power** through adaptive techniques.
    - **Improved throughput** by minimizing errors caused by multipath fading.
    - **Consistent QoS**, ensuring robust performance under varying conditions.

By leveraging pilot-aided techniques and CSI analysis, LTE achieves high data rates and spectral efficiency, setting the foundation for advanced wireless networks like LTE-Advanced and 5G.

3.1.1.1 Fading

What is Fading?

Fading occurs in wireless communication when a signal transmitted from a source reaches the receiver via multiple paths. Each of these paths may differ in length, causing the signal components to arrive at different times and with varying amplitudes.

- **Constructive vs. Destructive Interference**:
    - Signal components can combine **constructively**, enhancing the signal, or **destructively**, weakening it, based on their relative **phase alignment**.
    - These interactions result in a **composite signal** that often differs significantly from the original transmitted signal.
- **Impact on Signal Quality**:
    - The process of multiple signal paths and their varying interactions leads to **signal degradation**, termed as **fading**.
    - Fading reduces the signal's strength and clarity, severely affecting wireless system performance.

Visualizing Fading

1. **Spectrum Analyzer Amplitude Profiles**:
    - Comparing the amplitude profiles of faded and non-faded signals reveals distinct irregularities caused by fading.
    - While absolute amplitude values may not be directly comparable, the **overall patterns** highlight how fading disrupts the signal across the channel bandwidth.
2. **Constellation Diagrams**:
    - These diagrams represent the received signal quality:
        - **Non-faded signals**: Exhibit well-defined, closely clustered points.
        - **Faded signals**: Display scattered and distorted points, reflecting higher error rates and reduced clarity.

Effects of Fading on System Performance

- **Physical (PHY) Layer**:
    - Fading decreases the PHY layer's transmission rate due to signal degradation and increased error rates.
- **Higher Protocol Layers**:

  - The decline in PHY performance propagates to layers like the **Packet Data Convergence Protocol (PDCP)**, reducing overall data delivery efficiency.
- **Data Rates**:
  - In faded environments, data rates drop across layers, leading to poorer end-user experience.

Analyzing and Mitigating Fading

Tools and metrics used to study fading include:

1. **Spectrum Profiles**: Highlight amplitude variations and irregularities caused by fading.
2. **Constellation Diagrams**: Show error patterns and signal distortions due to fading.
3. **Data Rate Graphs**: Track performance impacts at different protocol layers.

Mitigation efforts focus on improving **signal reliability** and **system performance**, leveraging techniques like:

- **Diversity Schemes**: Spatial, frequency, and time diversity reduce the impact of fading.
- **Equalization**: Corrects distortions in the received signal.
- **Adaptive Modulation and Coding (AMC)**: Dynamically adjusts transmission parameters to match channel conditions.

By understanding and addressing fading, wireless communication systems can ensure more robust and reliable performance, enhancing data delivery and user experience.

3.1.2 Detail of LTE technological descriptions

LTE basic terminologies

LTE primarily operates as a data-centric technology, but it also supports voice services through two main approaches:

1. **CS Fallback**: When a call is made or received, the User Equipment (UE) transitions from the LTE network to UMTS or GSM circuit-switched (CS) network components. Alternatively, a dual-connection system enables the UE to maintain simultaneous connections with LTE and UMTS/GSM networks for handling voice calls. The voice codec remains consistent across GSM and UMTS, with calls routed through the CS components of these networks.
2. **VoLTE (Voice over LTE)**: While not explicitly mentioned here, VoLTE is another method that leverages LTE's IP-based architecture to provide voice services.

Key LTE Features and Terminology:

1. **Resource Element (RE)**:
   - The smallest unit of transmission resources in LTE.
   - Each RE corresponds to one OFDMA symbol on a 15 kHz subcarrier transmitted in 0.5 milliseconds.
2. **Subcarrier Spacing**:
   - The frequency interval between adjacent subcarriers, fixed at 15 kHz in LTE.
   - Instead of frequency guard bands, a guard interval called the cyclic prefix mitigates inter-symbol interference.
3. **Cyclic Prefix**:
   - A series of samples replicated from the end of a symbol and added to its beginning.
   - Ensures subcarrier orthogonality and prevents inter-symbol interference in OFDM systems.
4. **Time Slot**:
   - LTE frames are divided into ten 1-millisecond slots, each containing two 0.5-

millisecond sub-slots.
    - Each sub-slot carries seven OFDM symbols per subcarrier.

5. **Resource Block (RB)**:
    - A unit of time-frequency resource in LTE, spanning 12 subcarriers over 0.5 milliseconds.
    - For example, with a 20 MHz bandwidth, after allocating 10% of the bandwidth for guard bands, the effective bandwidth is 18 MHz.
        - **Subcarriers**: 18 MHz/15 kHz=1200 subcarriers.
        - **Resource Blocks**: 18 MHz/(15 kHz×12 subcarriers)=100 RBs.

Planning and Optimization for LTE Networks:

This terminology and resource structure play a critical role in LTE network dimensioning, which involves planning coverage and assessing traffic demand within specific areas. For effective radio access network (RAN) design:

- Area coverage and capacity requirements are prioritized.
- RF planning considers factors like bandwidth, resource allocation, and network expansion potential.

Such systematic planning ensures efficient use of resources, scalability, and the ability to meet future traffic demands.

dimensioning.

3.1.2.1 Network or system architectures and functions

LTE Duplexing and Bandwidth

LTE supports two types of duplexing methods for bidirectional communication:

1. **Frequency Division Duplex (FDD)**:
    - Uplink and downlink operate on separate frequency bands.
    - This separation allows symmetrical throughput, meaning the data rates for both uplink and downlink can be equivalent.
2. **Time Division Duplex (TDD)**:
    - A single frequency band is shared for both uplink and downlink by time-slicing.
    - The overall throughput is divided between the two directions, depending on the time allocation for each.

LTE offers scalable bandwidth options of **1.4, 3, 5, 10, 15, and 20 MHz**, a significant improvement over earlier mobile technologies with fixed bandwidths, such as GSM (200 kHz), CDMA (1.25 MHz), and UMTS (5 MHz). LTE reserves 10% of its total bandwidth for guard bands, leaving the remainder for active transmission. For example:

- In a **10 MHz carrier**, 1 MHz is used for guard bands, leaving 9 MHz for active bandwidth.
- A **20 MHz LTE channel** contains 1,200 subcarriers (calculated as 20 MHz/15 kHz.

Each subcarrier operates at a frequency of **15 kHz** and receives varying power levels, contributing to the flexibility and efficiency of LTE's spectrum usage.

SFN and Subframe Synchronization

Effective LTE communication relies on precise synchronization between the transmitter and receiver. LTE employs a dual-arm clock system, akin to a wristwatch, to maintain this synchronization:

1. **System Frame Number (SFN)**:
    - The "10-millisecond arm" of the LTE clock.
    - Its range spans from 0 to 1023, representing a cycle of 10 seconds.
2. **Subframe Number**:
    - The "1-millisecond arm" of the LTE clock.

  - It cycles from 0 to 9 within each SFN, dividing each 10-millisecond period into 10 subframes.

Before communication begins, the User Equipment (UE) aligns its clock with the network's clock through a process called **cell search and time synchronization**. This ensures both the SFN and subframe numbers match between the UE and the base station. During this process:

- The UE receives the SFN number from the **Master Information Block (MIB)**, which contains key timing information.
- Synchronization ensures the UE and base station operate in a coordinated mode, enabling efficient data exchange.

This dual-clock system ensures LTE's precise timing, which is critical for resource allocation, scheduling, and maintaining orthogonality in OFDM-based transmissions.

Modulation and coding rate: As **Modulation and Coding Rate in LTE**

Modulation Types:

In **LTE Release 8**, the supported modulation schemes are:

- **Downlink**: QPSK, 16QAM, and 64QAM.
- **Uplink**: QPSK and 16QAM.

Each modulation type determines the number of bits carried per symbol:

- **QPSK**: 2 bits per symbol.
- **16QAM**: 4 bits per symbol.
- **64QAM**: 6 bits per symbol.

Coding Rate:

The coding rate reflects the efficiency of a modulation scheme by specifying the proportion of information bits to the total transmitted bits. For example:

- A coding rate of **0.5** for 64QAM means that half of the transmitted bits are actual information bits (3 bits), while the other half (3 bits) is redundancy for error correction.

LTE dynamically adjusts the modulation scheme and coding rate based on channel conditions to optimize the balance between throughput and reliability.

Modulation Coding Scheme (MCS):

The combination of modulation type and coding rate forms the **Modulation Coding Scheme (MCS)**. Each MCS corresponds to a specific **Transport Block Size (TBS)** index, which maps:

- The size of the transport block (TB).
- The number of Physical Resource Blocks (PRBs) required.

Transport Block Size (TBS) and Throughput Calculation:

The TBS table includes control overhead and helps determine the number of data bits transmitted within a subframe (Transmit Time Interval, TTI).

- For example, with **100 PRBs** and an **MCS index of 28**, the TBS is **75376 bits**.
- In a **4x4 MIMO** configuration, the throughput is calculated as: Throughput=TBS×MIMO layers=75376×4=301.5 Mbps.

This flexibility enables LTE to dynamically allocate bandwidth and maintain high data rates across varying network conditions.

Note: The specific details of MCS-to-TBS mapping can be found in the MCS table in the **Appendix**.

Network architecture over view

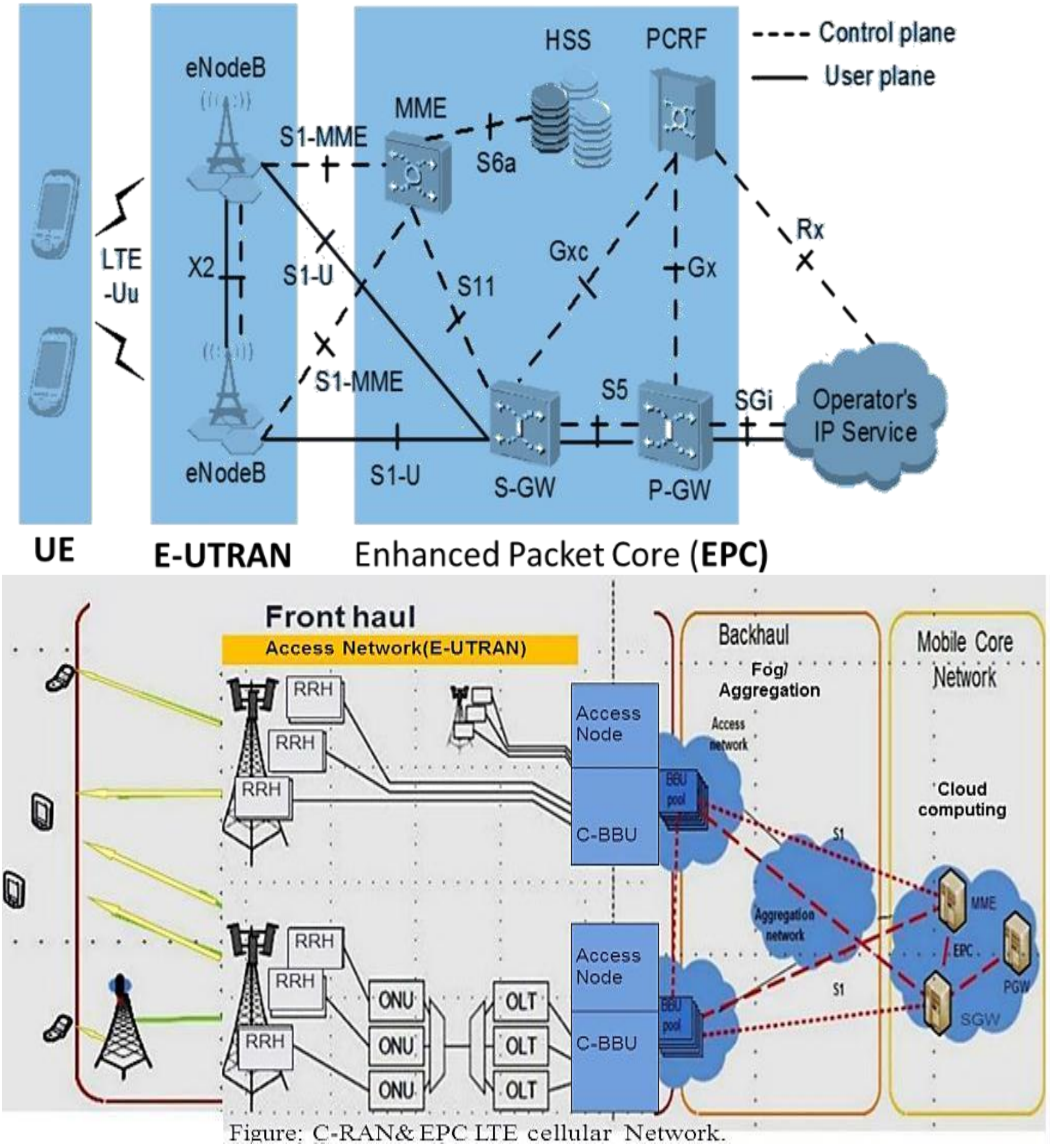


Figure: C-RAN& EPC LTE cellular Network.

Figure 3. 2: LTE networks architecture (EPC and EUTRAN), mobile core network cloud

Computing and Mobile Backhaul Fog/Access Aggregations

Modern telecommunication networks rely on a **hierarchical and integrated architecture** for data transmission and access aggregation. Key components and technologies involved in mobile backhaul and front haul access networks include optical, microwave, and fiber-based solutions. Here’s a breakdown:

1. Backhaul Technologies

Optical Transport Networks (OTN):

- **DWDN (Dense Wavelength Division Multiplexing):**

  - **Purpose**: Increases fiber capacity by transmitting multiple wavelengths (channels) over a single fiber.
  - Used for **OTN backbone fiber connections** to aggregate and transport data between core and edge networks.
  - **Advantages**: High bandwidth, scalability, and long-distance transmission.
- **IP Multimedia over CWDN/DWDN:**
  - Provides support for **IP multimedia traffic**, including voice, video, and data over CWDN (Coarse Wavelength Division Multiplexing) or DWDN.
  - Technologies like **GM8 transmissions** optimize multimedia delivery with high spectral efficiency.

ATN, CSG, ASG Nodes:

- **ATN (Aggregation Transport Nodes):**
  - Collect and forward traffic from multiple sources to higher-level network elements.
- **CSG (Cell Site Gateways) & ASG (Aggregation Site Gateways):**
  - Interface between mobile access points (e.g., base stations) and core/backhaul networks.

Microwave Line-of-Sight (LOS) Connections:

- **NEC PASOLINK NEO:**
  - Provides microwave-based LOS backhaul solutions where fiber is unavailable.
  - Used in both urban and rural deployments for quick and flexible connectivity.
  - **Key Features**:
    - High capacity.
    - Resilient under challenging terrains.
    - Cost-effective for medium-distance links.

2. Mobile Front Haul Access Networks

Direct Connections:

- Fiber-based **direct connections** link radio units (e.g., RRUs) to baseband units (BBUs), enabling low-latency communication.

FLNGN Fiber Connections:

- **FLNGN (Fixed Line Next Generation Networks)**:
  - High-capacity fiber connections that support mobile front haul.
  - Ensure ultra-low latency and high throughput for dense urban areas.

Multimedia Fiber Connections:

- **OLT (Optical Line Terminals):**
  - End-point hardware for passive optical networks, connecting fiber to customer premises.
  - Supports high-speed internet, VoIP, and video services.
- **MSAN (Multi-Service Access Nodes) and MSAG (Multi-Service Access Gateways):**
  - Integrate voice, data, and multimedia traffic into a unified access platform.
  - Facilitate efficient aggregation of **mobile front haul** and **fiber-to-the-premises (FTTP)** connections.

Application of Backhaul and Front Haul in Mobile Networks

- **Fog Computing Integration:**
  - Backhaul and front haul networks are increasingly leveraging **fog computing** to process and aggregate data closer to end users, reducing latency and offloading core network traffic.
- **Benefits:**
  - Scalable and efficient **data aggregation**.
  - Improved user experiences with high-speed multimedia and internet services.

  - Support for advanced mobile technologies such as **5G** and **IoT** through high-capacity backhaul.

By combining **OTN fiber backbones**, **microwave LOS**, and advanced **fiber multimedia solutions**, operators can achieve robust, scalable, and efficient networks suitable for modern high-demand mobile environments.

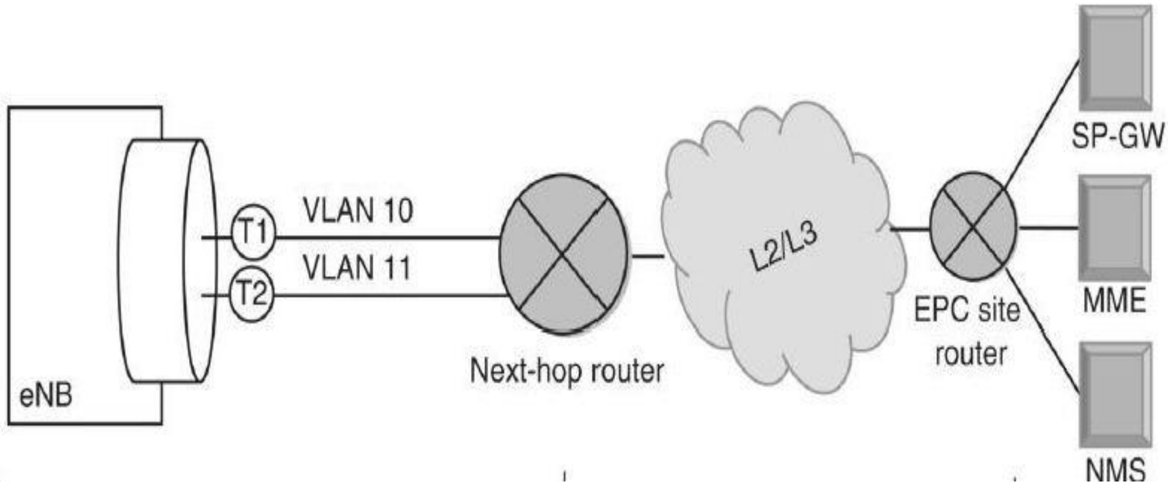


Figure 3.3: IP multimedia transmission tunneling and VLAN labeling

The 3G systems developed by 3GPP have evolved into the **Evolved Packet System (EPS)**, with the **Evolved Packet Core (EPC)**—also known as **System Architecture Evolution (SAE)**—serving as its IP-based core. The EPC ensures **Quality of Service (QoS)**, security, and revenue generation, forming a crucial backbone of LTE networks. Key components of the EPC include:

- **Mobility Management Entity (MME)**: Handles mobility anchoring, Non-Access Stratum (NAS) security, idle mode UE mobility management, and IP address assignment.
- **Serving Gateway (S-GW)**: Facilitates mobility management and packet routing.
- **Packet Data Network Gateway (P-GW)**: Manages packet filtering and IP address allocation.
- **Home Subscriber Server (HSS)**: A combination of the Home Location Register (HLR) and Authentication Center (AUC), providing user profile data, authentication, encryption, integrity protection, and user identification.
- **Policy and Charging Rule Function (PCRF)**: Detects service data flows, enforces policies, and manages charging based on data usage.

In the **radio access network (RAN)**, LTE introduces **enhanced NodeBs (eNodeBs)**, which replace the traditional Base Station Controller (BSC) and Radio Network Controller (RNC). This simplification supports high data rates, up to **100 Mbps for high-speed mobility** and **1 Gbps for stationary users**.

Interfaces and RAN Functions

- The **S1 interface** connects eNodeBs to core network entities, while the **X2 interface** facilitates interconnection between eNodeBs.
- eNodeBs perform critical tasks, such as:
  - Radio access control.
  - Scheduling and radio interface measurements.
  - Admission and mobility control.
  - Inter-cell resource management.

LTE Radio Access Enhancements

LTE upgraded UMTS's radio access network into the **Evolved Universal Terrestrial Radio Access Network (E-UTRAN)**. Components include:

- **Evolved User Equipment (eUE)**.
- **eNodeBs (eNB)**, which integrate functions of NodeB and the RNC.

When equipped with **Voice over LTE (VoLTE)**, the LTE network may also incorporate **IMS (IP Multimedia Subsystem)** to handle voice and multimedia services.

Duplexing and Access Methods

In the LTE downlink, **Orthogonal Frequency Division Multiple Access (OFDMA)** is used, while the uplink employs **Single Carrier Frequency Division Multiple Access (SC-FDMA)**—also referred to as **Discrete Fourier Transform (DFT)**—with a **Cyclic Prefix (CP)** to mitigate inter-symbol interference. These technologies:

- Provide orthogonality among users to reduce interference.
- Enhance overall network capacity and efficiency.

This streamlined architecture and advanced technologies make LTE a powerful and efficient mobile communication system, capable of supporting high-speed data and multimedia applications in modern networks.

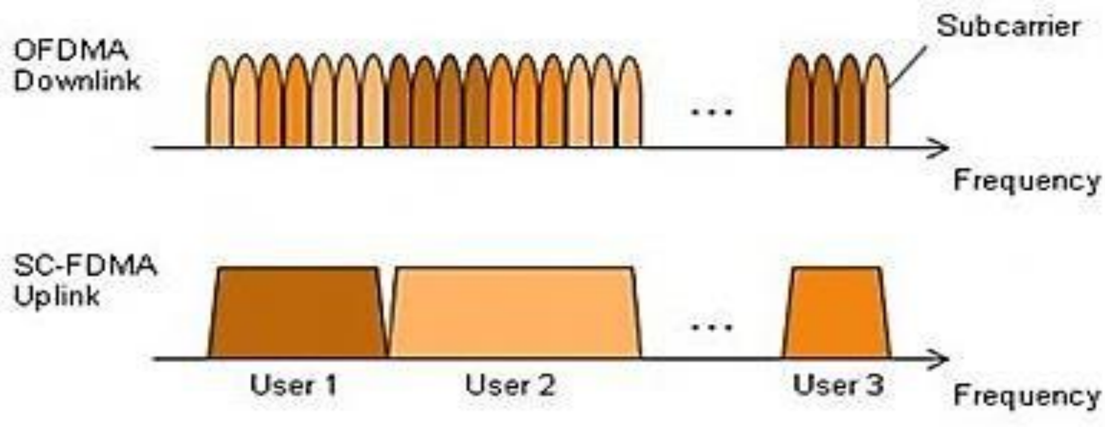


Figure 3.4: LTE multiple access schemes

Resource Blocks and Frequency Allocation in LTE

In LTE, **Resource Blocks (RBs)** are allocated in both the uplink (UL) and downlink (DL) across the frequency dimension, each RB spanning **180 kHz**. The allocation and usage of RBs vary based on the uplink and downlink requirements:

1. **Uplink (UL)**:
    - RBs are allocated **continuously** within the spectrum to enable **single-carrier transmission**.
    - This continuous allocation minimizes spectral fragmentation and supports the efficient operation of the terminal's power amplifier, which is crucial for extending the battery life of user equipment (UE).
2. **Downlink (DL)**:
    - RBs can be distributed from **any part of the spectrum**, offering more flexibility in resource allocation.
    - This flexibility allows the system to adapt dynamically to varying traffic conditions and optimize spectrum utilization.

Spectrum Flexibility in LTE

LTE is designed to be highly flexible in its spectrum usage, capable of operating across bandwidths ranging from **1.4 MHz to 20 MHz**, depending on the available spectrum. This adaptability enables LTE to:

- Operate efficiently in diverse deployment scenarios, from narrow-band environments to wide-band operations.
- Maximize spectral efficiency regardless of the bandwidth provided by regulatory or deployment constraints.

The combination of flexible RB allocation, efficient uplink transmission, and adaptable bandwidth usage ensures that LTE can cater to a wide range of use cases while maintaining high performance and user experience.

System architecture nodes and functions

LTE E-UTRAN: LTE E-UTRAN (Evolved Universal Terrestrial Radio Access Network) is a radio access network designed to replace UMTS, HSDPA, and HSUPA. Unlike HSPA, LTE's E-UTRA introduces an entirely new air interface system, optimized for lower latency and enhanced data rates, particularly for packet data. E-UTRAN comprises the eNB (base station), which manages all radio aspects of LTE. The eNB allocates uplink and downlink resources, oversees radio bearers, and controls admission during UE (User Equipment) power-up. It also compresses IP headers, encrypts data streams, and forwards payloads to the SGW with a GTP-U header. Additionally, it selects an MME, ensures QoS, manages broadcast and paging messages, and applies bearer-level rate controls.

LTE Evolved Packet Core (EPC): The EPC includes MME (Mobility Management Entity), SGW (Serving Gateway), PGW (Packet Gateway), HSS (Home Subscriber Server), and PCRF (Policy and Charging Rules Function).

SAE (Service Architecture Evolved): SAE refers to the LTE network framework. It encompasses the LTE architecture and its integration with other networks like UMTS and GSM. Diagrams range from simple representations of LTE components to more detailed combinations with other systems. Understanding how LTE architecture diagram blocks correspond to RRC/NAS message information elements is essential.

MME (Mobility Management Entity): The MME is the central signaling hub in SAE, performing the following key tasks:

- Tracks UE in idle mode.
- Manages paging and bearer activation/deactivation.
- Selects the UE's SGW during initial attachment.
- Facilitates intra-LTE core network handovers.
- Authenticates users via HSS communication.
- Terminates NAS messages and assigns temporary IDs to UEs.
- Grants PLMN access and enforces roaming restrictions.
- Serves as the ciphering and integrity termination point for NAS signaling.
- Manages security keys and supports lawful interception.
- Provides mobility control across LTE and legacy 2G/3G networks, similar to SGSN.

SGW (Serving Gateway): The SGW is the central node for user or packet data, performing the following:

- Routes and forwards user data packets.
- Acts as the mobility anchor for user data during inter-eNodeB handovers.
- Connects LTE with other 3GPP technologies.
- Suspends downlink data flow and initiates paging when the UE is idle.
- Maintains UE context, including routing and IP bearer service settings.
- Duplicates user traffic for lawful interception when required.

PGW (PDN gateway): The **User Equipment (UE) and PDN Gateway (PGW):**
The UE connects to external packet data networks through the PDN Gateway (PGW). The PGW is responsible for tasks such as:

- Authorized interception.
- Charging support.
- Packet screening and filtering.
- Policy enforcement for specific users.

The PGW also functions as a mobility anchor, supporting both 3GPP and non-3GPP technologies, including WiMAX and 3GPP2 (CDMA 1X and EvDO).

Home Subscriber Server (HSS):
The HSS is a centralized database for user and subscription data, integrating functions of HLR (Home Location Register), AuC (Authentication Center), and additional LTE-specific features. Key functions include:

- **Mobility management**: Tracks user movement across the network.
- **Call and session initiation**: Supports establishing and maintaining connections.
- **Access authorization and authentication**: Verifies users and grants access.

The HSS maintains real-time information about users, such as their associated MME, and provides data about accessible packet data networks (PDNs). It may also integrate an AuC to generate security keys and authentication vectors.

Policy Control and Charging Rules Function (PCRF):
The PCRF is integrated into the PGW and governs flow-based charging through the Policy Control Enforcement Function (PCEF). It performs the following:

- Grants **Quality of Service (QoS)** permissions, including QoS Class Identifier (QCI) and bit rate allocation.
- Ensures alignment with the user's subscription profile.
- Oversees how the PCEF manages individual data flows in accordance with policy rules.

Carrier aggregations device implementations: User equipment category capability classes and supported features
New UE Categories and Communication Enhancements in LTE

Introduction of New Categories in 3GPP Release 12:
To improve maximum communication speeds, Release 12 introduced new categories for downlink (DL) and uplink (UL). Key features include:

- **Carrier Aggregation (CA)**: Enhanced bandwidth utilization.
- **Higher-order MIMO**: Improved spectral efficiency.
- **Device segmentation**: Tailored for varying performance needs.
- **Enhanced propagation speeds**: Reducing fragmentation while increasing speed.
- **UE DL Category 12**: Achieves a downlink speed of **600 Mbps**.
- **UE UL Category 13**: Provides an uplink speed of **150 Mbps**.

These categories are specified in **MD8430A** and leverage a bandwidth of **20 MHz** under specific frequency bands. Devices operating below **1 GHz** typically use narrower bandwidths, while those above **1 GHz** rarely utilize frequencies below **5 MHz**.

Device Capability Classes and Data Rates:

- LTE devices are classified into **five capability classes**, with uplink speeds ranging from **5 to 75 Mbps** and downlink speeds from **10 to 300 Mbps**.
- **Category 5** devices uniquely support **64QAM** for uplink, offering higher modulation efficiency.
- All device categories, except **Category 1**, support MIMO and receiver diversity.

Evolution of UE Categories:

1. **Release 8**:

    - Introduced five UE categories (Categories 1–5).
    - Devices achieved up to **300 Mbps DL** and **75 Mbps UL**.
2. **Release 10 (LTE-Advanced)**:
    - Added Categories 6, 7, and 8.
    - Enhanced CA and supported up to **8x8 DL MIMO** and **4x4 UL MIMO**.
3. **Release 11**:
    - Added Categories 9 and 10.
4. **Release 12**:
    - Focused on further extending CA and MIMO capabilities.

Backward Compatibility and Current Trends:

- A **Rel-10** UE must specify a **Release 8** category for backward compatibility.
- Similarly, a **Rel-11** UE must indicate both a **Release 10** and a **Release 8** category.

Commercial UEs:

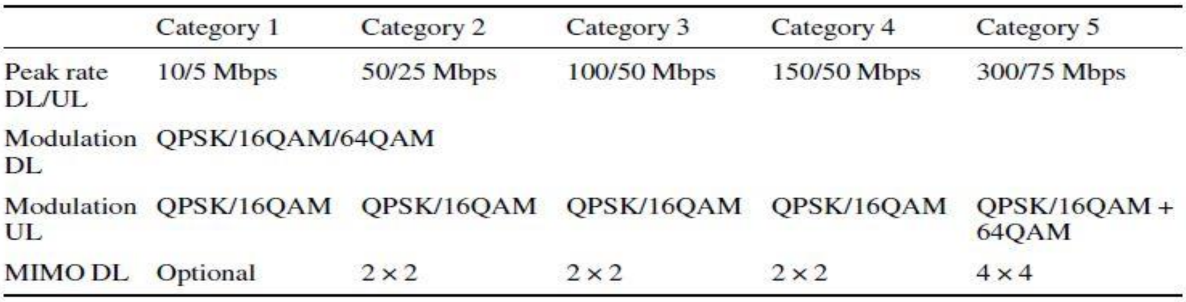
- Most devices are **Category 3**, featuring:
    - **One transmitter chain** and **two receiver chains**.
    - No support for **64QAM** in uplink.

Category 5 devices are the only ones supporting **64QAM uplink** in Releases 8 and 9. The current highest data rate achievable remains with **UE-5** devices.

UE categories for CA

✓ 3GPP specifies UE categories for placing devices into specific segments according to combined DL and UL capabilities(MIMO, modulation level, CA etc.)

UE Category	Carrier Aggregation	MIMO	DL Peak Rate	Commercial Availability
Category 4	10 + 10 MHz DL 10 MHz UL	2 x 2	150 Mbps	2013
Category 6	20 + 20 MHz DL 20 MHz UL	2 x 2	300 Mbps	2014
Category 9	20 + 20 +20 MHz DL 20 MHz UL	2 x 2	250 Mbps	2015
Category 11/12	4 × 20 MHz DL 20 + 20 MHz UL	2 x 2	600 Mbps	2016
...	5 × 20 MHz DL	4 x 4	1+ Gbps	??



	Category 1	Category 2	Category 3	Category 4	Category 5
Peak rate DL/UL	10/5 Mbps	50/25 Mbps	100/50 Mbps	150/50 Mbps	300/75 Mbps
Modulation DL	QPSK/16QAM/64QAM				
Modulation UL	QPSK/16QAM	QPSK/16QAM	QPSK/16QAM	QPSK/16QAM	QPSK/16QAM + 64QAM
MIMO DL	Optional	2 × 2	2 × 2	2 × 2	4 × 4

Table 3.2 LTE device categories

3.1.2.2 Maximum throughput calculation with maximum band width

MT Scheduling Algorithm in LTE

The **Maximum Throughput (MT)** scheduling algorithm focuses on optimizing total throughput by allocating radio resources to users with the capability to transmit data during the current

Transmission Time Interval (TTI). The algorithm prioritizes users with higher **Channel Quality Indicator (CQI)** values, enhancing overall cell throughput.
However, this method can be inequitable for users with lower CQI values, such as those at the cell edge, as they may receive fewer resources.

Throughput Calculation

- **Symbols per Second**: Throughput in LTE is measured in symbols per second and can be converted to bits per second based on the modulation scheme.
    - In a **20 MHz** channel, there are **100 resource blocks (RBs)**.
    - Each RB contains **168 symbols/ms** (calculated as 12×7×2 in normal CP), resulting in:
        - 16800 symbols/ms
        - 16800000 symbols/second (16.8 Msps).
- **Modulation Example**: Using **64QAM**, which encodes **6 bits per symbol**, the throughput is:
    - 16.8 Msps×6=100.8 Mbps (single chain)

MIMO Configurations and Throughput

LTE supports **MIMO** configurations of **2x2, 2x4, 4x2, and 4x4**, which significantly increase throughput:

- With **4x4 MIMO**, the throughput is multiplied by 4, giving:
    - 100.8 Mbps×4=403.2 Mbps
- Accounting for a **25% overhead** due to control and signaling, the effective downlink throughput is approximately **300 Mbps**.

Example Using MCS/TBS Table

- For **100 RBs** and an **MCS index of 28**, the **Transport Block Size (TBS)** is **75376 bits/ms**.
- Using **4x4 MIMO**, the peak data rate is:
    - 75376 bits/ms×4=301.5 Mbps

Note: The **300 Mbps** effective throughput applies only to the **downlink**.

Uplink Throughput

- The UE supports only **one transmit chain** in uplink.
- For a **20 MHz** channel:
    - Maximum uplink throughput is **100.8 Mbps**.
    - After accounting for **25% overhead**, the effective uplink throughput is reduced to **75 Mbps**.

This breakdown explains the throughput calculations for both downlink and uplink in a single LTE cell while accounting for MIMO configurations and protocol overheads.

3.1.3 General optimization design for OFDMA, OFDM, and SC-FDMA modulations, multiplexing, and approaches in LTE technology

3.1.3.1 Introduction to multi-carrier modulation and transmission

Multi-Carrier Transmission in Modern Wireless Systems

Modern wireless mobile systems leverage **multi-carrier modulation (MCM)** to deliver high bit rates with minimal errors. MCM operates by dividing the outgoing data stream into multiple symbol streams that modulate several sub-carriers at much lower symbol rates. This approach offers several key advantages over single-carrier systems:

- Greater resistance to **impulsive noise interference**.
- Improved resilience to **multipath fading**.
- Enhanced resistance to **interference**.

These attributes make MCM integral to various protocols, including **Digital Video Broadcast-Terrestrial (DVB-T)**, **IEEE 802.11x**, and **IEEE 802.16x**.

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is the most prevalent form of MCM. It uses orthogonal sub-carriers and digital modulation to transmit data across multiple concurrent streams. When data streams are allocated to different terminals or users, this technique is referred to as **Orthogonal Frequency Division Multiple Access (OFDMA)**. In OFDMA:

- Data signals are transmitted over a shared physical medium divided into **frequency resource units**.
- It supports simultaneous transmission to multiple users, enhancing spectrum efficiency.

Challenges in Uplink Transmission:

- Power distortion poses a significant challenge for uplink OFDM/OFDMA transmissions, especially given the complexity constraints of user terminals.
- To mitigate this, **Single-Carrier Frequency Division Multiple Access (SC-FDMA)** is used in uplink transmissions. SC-FDMA employs **Single Carrier Frequency Domain Equalization (SC-FDE)**, which, while derived from OFDM, utilizes only a single carrier.

OFDMA in LTE Systems

In LTE, **OFDMA** is employed in the **downlink** to achieve:

- Higher data rates.
- Improved signal quality using advanced techniques such as:
    - **MIMO antennas**.
    - **Higher-order modulation**.
    - **Wide bandwidths**.
    - **Spatial multiplexing**.
    - **Transmit diversity**.

Multi-antenna strategies distribute modulated data signals across distinct antenna ports. Each antenna generates **OFDM symbols**, which are mapped to the **resource grid**. In a **MIMO–OFDM** configuration, OFDM modulation and resource-grid mapping are replicated across multiple antennas to optimize data transmission.

Fundamentals of Multi-Carrier Transmission

The core idea of OFDM lies in **multi-carrier transmission**, which expands transmission bandwidth and reduces signal degradation caused by frequency selectivity in the radio channel. Key points include:

- Instead of transmitting a single wideband signal, multiple **narrowband subcarriers** are transmitted in parallel.
- These subcarriers are frequency-multiplexed and sent together over a shared radio link.

Benefits of Subcarriers:

- Transmitting NN subcarriers in parallel increases the total data rate by a factor of NN.
- The impact of frequency selectivity in the radio channel is minimized because each subcarrier operates within a smaller bandwidth.

Bandwidth Efficiency:

- Multi-carrier transmission enables the extension of overall bandwidth while ensuring that signal degradation due to channel frequency selectivity is minimized, equivalent to a system with a bandwidth equal to that of each subcarrier.

This design is illustrated in **Figure 3.5**, where the transition from a single wideband signal to multiple narrowband subcarriers is depicted, showcasing the advantages of multi-carrier systems in expanding data capacity and improving robustness.

Challenges in the Evolution of Multi-Carrier Systems

As multi-carrier systems evolve, **spectrum packing** becomes increasingly difficult when narrowband radio access technology is scaled to support wider transmissions through the parallel transmission of NN additional narrowband carriers. This scaling introduces two significant issues:

1. **Bandwidth Efficiency Reduction**:
    - The parallel arrangement of multiple carriers can create gaps or dips in the overall transmission spectrum.
    - These gaps lead to a decrease in overall bandwidth efficiency, undermining the advantages of broad-spectrum usage.
2. **Fluctuations in Transmit Power**:
    - Multi-carrier systems experience greater variations in **instantaneous transmit power**, which adversely affects:
        - The efficiency of the **transmitter power amplifier**.
        - Overall **power consumption**, leading to increased operational costs for power amplification.

Implications for Transmission Power

- Multi-carrier transmission results in higher **power amplifier demands** and greater energy use.
- To address this, reducing the **average transmission power** can mitigate the associated power efficiency challenges, though this may come at the expense of overall performance.

Downlink vs. Uplink Suitability

Due to the above issues, **downlink transmissions** are better suited for multi-carrier systems than uplink transmissions. The inherent limitations of uplink—such as terminal complexity and power constraints—make single-carrier approaches like **SC-FDMA** preferable for uplink use.

OFDM for Multi-Carrier Modulation

Orthogonal Frequency Division Multiplexing (OFDM) serves as an effective method for implementing multi-carrier modulation, balancing the trade-offs between bandwidth efficiency, power demands, and system complexity. Further exploration of this approach is presented in the next section.

3.1.3.2 Design of a system model for single carrier frequency division multiple access (SC-FDMA)

SC-FDMA and OFDMA: Enhancements to SC-FDE for Multiple Access

Both **SC-FDMA (Single Carrier Frequency Division Multiple Access)** and **OFDMA (Orthogonal Frequency Division Multiple Access)** build upon **SC-FDE (Single Carrier Frequency Domain Equalization)**, providing multiple access capabilities with a complexity comparable to OFDMA. These methods share commonalities in their use of frequency-domain channel estimation and equalization, yet they differ in signal processing steps and suitability for specific applications.

Transition from SC-FDE to SC-FDMA

SC-FDMA facilitates multiple access by partitioning the available frequency spectrum among users. The process involves:

1. **N-point FFT**:
    - Applied to the output of the symbol mapper.
    - Generates frequency-domain components that represent the user's data.
2. **Subcarrier Assignment**:
    - N of M subcarriers are allocated, where M=Q×N.
    - Q: Bandwidth expansion factor, representing the number of simultaneous users.
3. **M-point IFFT**:
    - Converts the signal back to the time domain for transmission.
4. **Receiver Operations**:
    - Extracts NN relevant frequencies from the received signal.

  - Applies equalization and reconstructs the original signal using an NN-point IFFT.

Key Difference: DFT Pre-Coding
The primary distinction between SC-FDMA and OFDMA is the inclusion of a **Discrete Fourier Transform (DFT)** pre-coding stage (and its inverse at the receiver) in SC-FDMA. This process:

- Spreads the energy of a single subcarrier across all assigned subcarriers, mitigating spectral nulls through energy averaging.
- Reduces the **Peak-to-Average Power Ratio (PAPR)** by up to **2 dB**, enhancing power efficiency—especially beneficial for user equipment.

Advantages of SC-FDMA

1. **Lower PAPR**:
   - Results in more efficient power consumption, a critical requirement for user terminals.
2. **Uplink Suitability**:
   - Optimized for uplink transmission in LTE due to its focus on lower complexity at the transmitter (user equipment), shifting processing to the receiver (base station).

SC-FDMA Subcarrier Allocation Methods
SC-FDMA employs two main subcarrier allocation techniques:

1. **Localized FDMA (LFDMA)**:
   - Allocates NN adjacent subcarriers to a user.
   - Minimizes frequency offset sensitivity and interference, as at most two users are adjacent.
2. **Interleaved FDMA (IFDMA)**:
   - Distributes NN subcarriers evenly across the available bandwidth (every QQ-th subcarrier).
   - Exhibits higher frequency offset sensitivity similar to OFDMA but benefits from spectral averaging.

Unused subcarriers in both methods are set to zero, and a **cyclic prefix (CP)** is inserted to mitigate inter-block interference (IBI) from multipath propagation.

Comparison with OFDMA

- **SC-FDMA**: Each data symbol modulates the entire wideband carrier, resulting in single-carrier-like behavior.
- **OFDMA**: Each data symbol modulates an individual subcarrier, emphasizing multi-carrier characteristics.

In SC-FDMA, the multiplexing of multiple users using LFDMA (as illustrated in **Figure 3.6**) ensures efficient bandwidth utilization while keeping inter-user interference low. Each user can leverage the entire bandwidth in a time-multiplexed manner.

Conclusion
SC-FDMA's design effectively combines the advantages of SC-FDE with the multiple-access flexibility of OFDMA while addressing power efficiency challenges. These attributes make it a natural choice for uplink transmissions in **3GPP LTE**, contrasting with OFDMA’s suitability for downlink, where terminal complexity is less of a concern.

In **SC-FDMA**, the modulated symbols are transmitted **sequentially** through a single carrier. This contrasts with **OFDMA**, where the transmitted signal is a combination of multiple designated subcarriers. Despite these differences, both methods achieve the following:

- Transmit the **same number of data symbols** within the same time duration.

- Utilize the **same bandwidth** for transmission.

Transmission Methodology

- **SC-FDMA**:
  - Symbols are sent sequentially over a **single carrier**, giving it a single-carrier behavior.
  - This results in a lower **Peak-to-Average Power Ratio (PAPR)**, making it more power-efficient, particularly beneficial for uplink transmissions.
- **OFDMA**:
  - Symbols are transmitted in **parallel** over multiple subcarriers.
  - This provides high spectral efficiency and flexibility in downlink transmissions.

FDMA Characteristics in SC-FDMA

SC-FDMA achieves **frequency-domain multiplexing** of users, a feature shared with traditional **FDMA**:

- **Orthogonal multiplexing/demultiplexing** in the frequency domain ensures that users occupy distinct subcarrier groups.
- This orthogonality eliminates inter-user interference, a hallmark of FDMA-like behavior, but with better spectral efficiency.

In summary, **SC-FDMA combines the benefits of single-carrier transmission and frequency-domain access**. It achieves power efficiency, retains spectral efficiency, and effectively supports multiple users in uplink transmission, making it distinct from OFDMA's parallel multi-carrier approach.

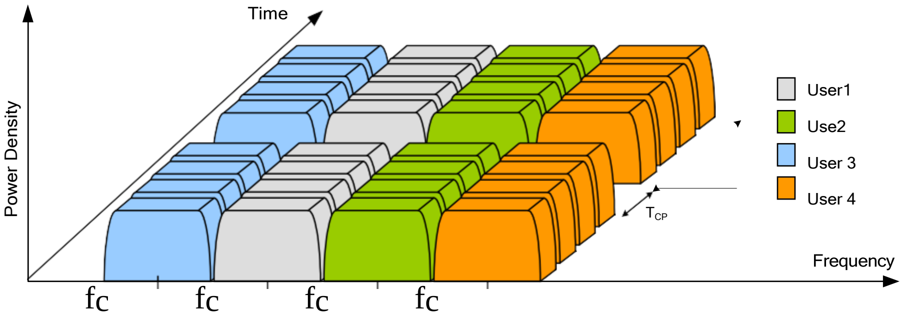


Figure 3.7: User allocation example in SC-FDMA (LFDMA)

Comparison between the localized and interleaved frequency diversity schemes

SC-FDMA in LTE Uplink Transmission

SC-FDMA is the preferred technique for LTE uplink transmissions, offering several advantages, particularly in challenging conditions such as **deep fading**. Key benefits include:

- **Adaptive Bandwidth Allocation**: Dynamically adjusts to channel conditions.
- **Low Peak-to-Average Power Ratio (PAPR)**: Enhances power efficiency.
- **Frequency-Domain Equalization**: Ensures high-quality signal recovery.
- **Frequency Diversity**: Distributes information from a single symbol across multiple sub-carriers, reducing the risk of total data loss.

Mapping Modes in SC-FDMA

The **mapping mode** significantly affects system performance. Two primary modes are employed:

1. **Localized Mapping**:
    - **Characteristics**:
        - Each user utilizes a **cluster of adjacent sub-carriers**.
        - Data is transmitted over a limited portion of the available bandwidth.
    - **Advantages**:
        - Simple equalization and channel estimation.
        - Effective in frequency-selective channels, provided users' sub-carriers have high channel gain.
    - **Limitations**:
        - Poor frequency diversity.
        - Requires **Channel State Information (CSI)** to optimize data placement.
2. **Distributed Mapping**:
    - **Characteristics**:
        - Sub-carriers are distributed across the entire bandwidth.
    - **Advantages**:
        - Strong frequency diversity, improving **Symbol Error Rate (SER)** performance.
    - **Limitations**:
        - Increased complexity in equalization and channel estimation.
    - **Variant**: **Interleaved SC-FDMA (IFDMA)** disperses sub-carriers evenly but limits user variety due to spaced allocation.

Hybrid Mapping: Block-Wise Consecutive Frequency Mapping

A compromise between localized and distributed mapping, this method organizes users into **blocks of consecutive sub-carriers** spaced uniformly across the bandwidth:

- Combines frequency diversity and user diversity.
- Simplifies channel estimation compared to fully distributed mapping.

Proposed Enhancements to SC-FDMA

- **Circularly Shifted Sub-Carriers**:
    - This new approach introduces **cyclic shifts** to sub-carriers, improving spatial multiplexing and enabling **Cyclic Delay Diversity (CDD)**.
    - These shifts provide additional frequency diversity while maintaining a balance between complexity and performance.
- **Spatial Multiplexing with SC-FDMA**:
    - Explored in **Figure 3.9**, it integrates spatial diversity methods like CDD into the SC-FDMA framework, enhancing robustness and throughput.

Summary

SC-FDMA's versatility and efficiency make it integral to LTE uplink communications. By leveraging various mapping techniques—**localized**, **distributed**, or **block-wise consecutive mapping**—the system effectively balances **performance**, **complexity**, and **efficiency**. Proposed innovations, including **circularly shifted sub-carriers** and **spatial multiplexing**, further improve SC-FDMA's suitability for modern wireless networks, ensuring robust and efficient data transmission.

SC-FDMA adaptive modulation schemes

Adaptive Modulation (AM) is a widely utilized communication method, extensively analyzed in works such as [Goldsmith 05], which provides a comprehensive framework for AM systems. This section focuses on explaining the adaptive modulation strategy used to evaluate spectral efficiency. In this approach, the **instantaneous Signal-to-Noise Ratio (SNR)** at the detector's input (γ\gamma) is fully determined by the channel model and transmission method, assuming a constant transmit power. The modulation scheme applies L Mi bits per symbol for a given γ\gamma value. The switching thresholds ({γi}i=0,1,…,N−1) are optimized to maximize spectral efficiency while ensuring that the instantaneous Bit Error Rate (BER) stays below a predefined target (BERTBER_T).

Key Concepts:

- **Switching Thresholds (γi\gamma_i)**: These determine the SNR boundaries for switching between modulation schemes.
- **Spectral Efficiency**: The number of bits per symbol is adjusted dynamically to maximize efficiency without exceeding BERTBER_T.
- **Outage State**: In poor channel conditions, where SNR falls below a critical threshold, no data transmission occurs to maintain quality.

Figure 3.10 Explanation:

The graph qualitatively demonstrates the adaptive modulation process:

- **BER Curves**: Represent the BER performance of various modulation schemes (MiM_i) under an Additive White Gaussian Noise (AWGN) channel.
- **Intersection Points**: The thresholds (γi\gamma_i) are determined where the BER curve for a modulation scheme meets the target BER (BERTBER_T).
- **Fading Regions (Ri)**: The transmitter adapts to current channel conditions, identified by γ\gamma, and adjusts the modulation scheme accordingly.

Adaptive modulation thus enables a system to dynamically adjust to changing channel conditions, balancing **spectral efficiency** and **transmission reliability**.

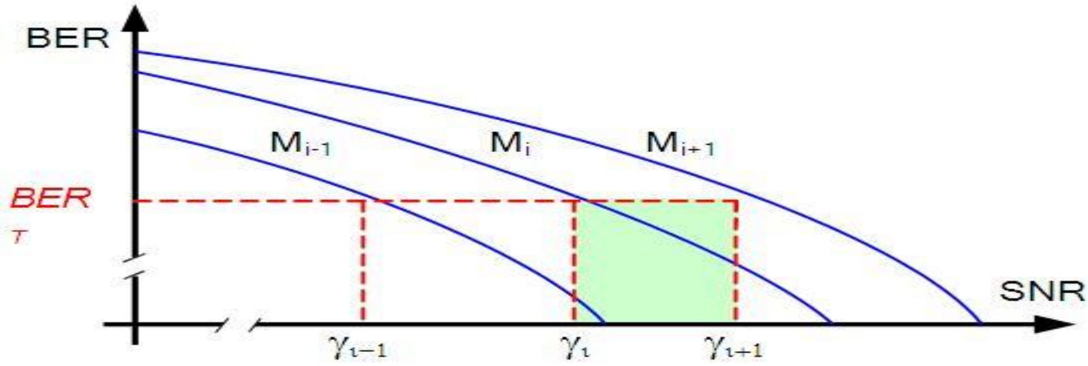


Figure 3.10: Example of adaptive modulation regions

3.1.3.3 OFDMA stands for orthogonal frequency division multiple access

The **OFDMA multiple access method**, originally proposed for the return channel of **Community Antenna Television (CATV)**, divides the available sub-carriers into multiple sub-channels, each allocated to a different user. By leveraging the orthogonality of sub-carriers, OFDMA enhances resource allocation efficiency and reduces interference among users.

Sub-Channel Allocation in OFDMA:

1. **Localized FDMA (LFDMA)**: Sub-channels are composed of closely grouped sub-carriers.
2. **Distributed FDMA (DFDMA)**: Sub-channels consist of sub-carriers spread across the entire bandwidth.

  - A variant of DFDMA, known as **Interleaved FDMA (IFDMA)**, evenly distributes sub-carriers throughout the bandwidth.

Localized FDMA, as depicted in **Figure 3.11**, segments the system bandwidth into distinct sub-bands, enabling the multiplexing of multiple users (e.g., four users in the illustration).

Advantages of OFDMA:

- **Scalability**: Supports dynamic resource allocation for diverse user needs.
- **Resilience to Multipath Effects**: Performs well in environments with significant signal reflection and interference.
- **MIMO Compatibility**: Integrates seamlessly with **Multiple-Input Multiple-Output (MIMO)** technologies to enhance throughput and reliability.

Applications:

These features have made OFDMA a key technology in the **802.16 (WiMAX) standards** and **Long Term Evolution (LTE)**, part of the Universal Mobile Telecommunications System (UMTS) specifications.

Challenges with OFDMA:

Despite its advantages, the OFDMA waveform suffers from **high Peak-to-Average Power Ratio (PAPR)**, causing:

- The need for costly linear power amplifiers to handle signal fluctuations.
- Increased energy consumption, leading to shorter battery life for user terminals.

Thus, while OFDMA offers superior flexibility and performance, its high PAPR remains a notable limitation, especially for mobile devices.

3.1.3.4 Design of a system model for orthogonal frequency division multiplexing (OFDM)

3.1.3.4.1 Detail descriptions and differences between OFDMA and SC-FDMA

How FDM and OFDM differ from one another

Key Characteristics of the LTE Physical Layer

1. ***Channel Configurations***:
    - ***FFT Sizes***: *Options include 128, 256, 512, 1024, 1536, and 2048.*
    - ***Bandwidths***: *Supported channel bandwidths are 1.4, 3, 5, 10, 15, and 20 MHz.*
    - ***Cyclic Prefix***: *Both* ***Extended*** *and* ***Normal Cyclic Prefix*** *are available.*
2. ***Multiple Access Schemes***:
    - ***Downlink***: *Utilizes* ***Orthogonal Frequency Division Multiple Access (OFDMA)***.
    - ***Uplink***: *Employs* ***Single-Carrier Frequency Division Multiple Access (SC-FDMA)***.
3. ***Duplexing Methods***:
    - *Supports* ***Frequency Division Duplexing (FDD)*** *and* ***Time Division Duplexing (TDD)***.
4. ***Subcarrier Features***:
    - ***Localized Subcarrier Mapping***.
    - ***Subcarrier Hopping***.
5. ***Data Modulation***:
    - *Supports* ***QPSK***, ***16QAM***, *and* ***64QAM*** *modulation schemes.*
6. ***Subcarrier Spacing***:
    - *Fixed at* ***15 kHz***.
7. ***MIMO Configurations***:
    - *Supports* ***2x2*** *and* ***4x4*** *configurations for both transmit and receive antennas.*
8. ***Channel Coding***:

   - *Implements **Convolutional Coding** and **Turbo Coding** techniques.*
9. ***HARQ (Hybrid Automatic Repeat Request)**:*
   - *Utilizes **incremental redundancy** to improve error correction and retransmission efficiency.*

These features collectively enable LTE's high spectral efficiency, robustness, and adaptability to diverse communication scenarios.

LTE EARFCN **Summary of LTE EARFCN and FDM vs. OFDM**

LTE EARFCN (E-UTRA Absolute Radio Frequency Channel Number):

- **Definition**: LTE EARFCN identifies specific uplink (N_UL) and downlink (N_DL) channels in the LTE system.
- **Frequency Calculation**: Based on the LTE EARFCN formula, it translates EARFCN values into carrier frequencies in MHz.
- **Range**: The EARFCN spans from **0 to 65535**.
- **Utility**: A **calculator** is available to convert between EARFCN and frequency, simplifying channel and frequency management.

Key Differences Between FDM and OFDM:

1. **Carrier Arrangement**:
   - **FDM**: Carriers are spaced apart with **guard bands** to prevent overlap.
   - **OFDM**: Carriers are closely packed and orthogonal, meaning the peak of one carrier aligns with the nulls of others, eliminating interference.
2. **Bandwidth Efficiency**:
   - **OFDM**: More efficient than FDM due to orthogonality.
   - **FDM**: Requires additional bandwidth for guard bands.
3. **Data Rate**:
   - **OFDM**: Delivers higher data rates within the same bandwidth, making it suitable for broadband applications like LTE, WLAN (802.11g/11n), and WiMAX (802.16d/16e).
   - **FDM**: Commonly used in satellite and traditional radio communications.
4. **PAPR (Peak-to-Average Power Ratio)**:
   - **OFDM**: Higher PAPR, which can increase power amplifier costs and complexity. PAPR reduction techniques, like scramblers, are often employed.
   - **FDM**: Lower PAPR by design.
5. **Multipath Interference**:
   - **OFDM**: More prone to multipath interference, mitigated using methods like cyclic prefix insertion.
   - **FDM**: Less affected by multipath interference.
6. **User Accommodation**:
   - **OFDM**: Divides bandwidth into numerous narrowband channels, supporting more users and channels.
   - **FDM**: Uses the entire bandwidth for transmission, accommodating fewer users.

Applications:

- **OFDM**: Adopted in LTE, WLAN, and WiMAX technologies for broadband internet services requiring high data rates.

- **FDM**: Predominantly used in satellite communication and traditional radio services.

Understanding these differences is crucial for optimizing the efficient use of frequency resources and tailoring systems to specific communication needs.

Information about SC-FDMA and OFDMA

OFDMA **Summary of OFDMA and SC-FDMA in LTE**

Downlink: OFDMA

- **Bandwidth and Sub-carriers**:
  - The entire LTE bandwidth is divided into numerous sub-carriers.
  - Subcarrier spacing is defined as Δf = 1/Tsymb, based on symbol duration.
- **Reuse Factor**:
  - LTE operates with a reuse factor of 1, meaning all cells can use the entire bandwidth.
- **Interference Mitigation**:
  - Inter-Cell Interference Coordination (ICIC) is employed to manage resource allocation among neighboring cells, reducing interference.
- **Modulation Techniques**:
  - Narrowband modulation methods (QPSK, 16-QAM, 64-QAM) are applied, with selection based on Channel State Information (CSI).
- **Key Features**:
  - OFDM employs fixed subcarrier allocation for users, which may cause performance issues in the presence of interference or narrowband fading.
  - OFDMA enhances flexibility by integrating **TDMA** elements, enabling dynamic subcarrier allocation among users.
- **Robustness and Capacity**:
  - OFDMA improves system robustness by scheduling users across frequencies to counteract multipath fading and narrowband interference.
  - Transport efficiency supports multiplexing low-rate users and dynamically redistributing capacity as needed.

Uplink: SC-FDMA

- **Choice of SC-FDMA**:
  - SC-FDMA is preferred in uplink transmission to minimize **power consumption**, particularly critical for user equipment.
  - It features a **lower Peak-to-Average Power Ratio (PAPR)** compared to OFDMA, enabling more efficient power usage.
- **Signal Structure**:
  - Resource Blocks (RB) serve as the basic allocation unit for SC-FDMA, each comprising 12 continuous subcarriers (or 4 in examples).
  - SC-FDMA transmits data symbols **sequentially**, with each symbol occupying a wider bandwidth (e.g., 12 × 15 kHz) compared to OFDMA, which sends data symbols in **parallel** over individual subcarriers.
- **Symbol Duration**:
  - Both OFDMA and SC-FDMA have a symbol duration of 66.7 µs, but

SC-FDMA symbols consist of multiple "sub-symbols" that carry the modulating data sequentially.

- **Key Distinction**:
    - OFDMA transmits symbols in parallel across subcarriers.
    - SC-FDMA transmits symbols in series, making it more suitable for power-constrained devices.

Resource Block Allocation:

- In both downlink (OFDMA) and uplink (SC-FDMA), LTE allocates resources using **Resource Blocks (RBs)** or integer multiples of RBs. This strategy ensures efficient bandwidth usage and supports flexible resource management.

This combination of OFDMA for the downlink and SC-FDMA for the uplink allows LTE to balance flexibility, robustness, and efficiency while addressing power consumption challenges for user devices.

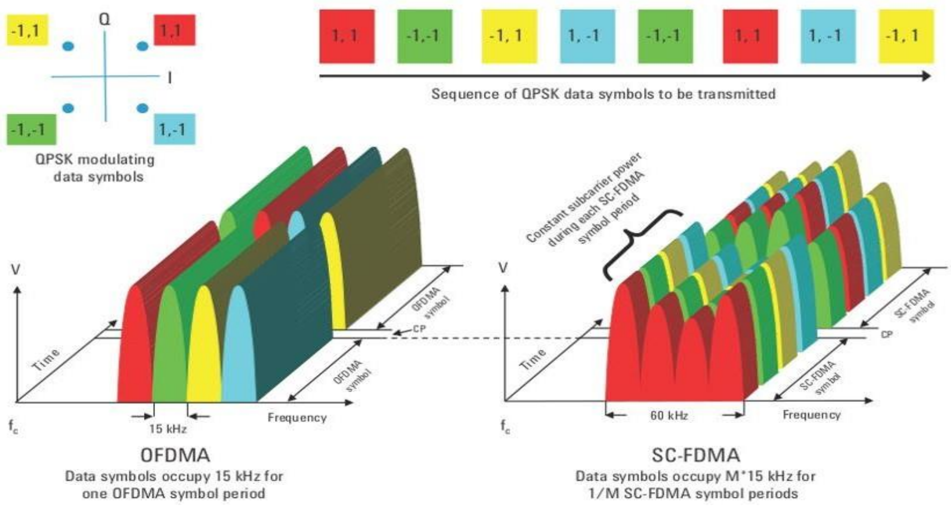


Figure 3.13: OFDMA vs. SC-FDMA. Comparison of OFDMA and SC-FDMA transmitting a series of QPSK symbols (example uses only four sub-carriers for SC-FDMA instead of 12).

In LTE, **Orthogonal Frequency Division Multiple Access (OFDMA)** and **Single Carrier Frequency Division Multiple Access (SC-FDMA)** utilize sub-carriers differently to achieve efficient signal transmission. The distinction between the two schemes can be illustrated by examining the way sub-carriers are modulated and how symbols are transmitted.

Sub-Carrier Usage in OFDMA and SC-FDMA

1. **OFDMA (Left Side of the Figure):**
    - Each **sub-carrier** is individually modulated with a distinct **QPSK symbol**.
    - The sub-carriers are represented with different colors to indicate the unique modulation on each.
    - Symbols on each sub-carrier last for a relatively long period of time, referred to as one **FDMA symbol period**.
2. **SC-FDMA (Right Side of the Figure):**
    - All sub-carriers are combined into a single carrier.
    - Unlike OFDMA, all sub-carriers are modulated with the **same QPSK symbol**, which is represented by a uniform color.
    - This ensures a lower **Peak-to-Average Power Ratio (PAPR)**, making SC-FDMA more energy-efficient for uplink transmission in LTE.

Practical Example in LTE Signals

- In real LTE systems, **12 sub-carriers** are typically grouped into a **Resource Block (RB)**, which serves as the smallest unit of frequency-time resource allocation.

- In OFDMA, each sub-carrier within the RB can carry a unique modulated symbol, allowing flexibility in data allocation.
- In SC-FDMA, all sub-carriers within the RB share the same modulated symbol, maintaining a single-carrier structure while utilizing the frequency domain for transmission.

Key Differences and Advantages

- **OFDMA:**
    - Used in LTE **downlink** due to its high spectral efficiency and ability to handle interference.
    - Allows each sub-carrier to operate independently, facilitating robust and flexible transmission.
- **SC-FDMA:**
    - Employed in LTE **uplink** to reduce PAPR and improve power efficiency, which is critical for user equipment (UE).
    - Combines sub-carriers to mimic a single-carrier structure, optimizing energy consumption.

These differences highlight the tailored approaches of OFDMA and SC-FDMA in LTE to meet the distinct requirements of uplink and downlink communication.

3.1.3.4.2 System model for orthogonal frequency division multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is a multichannel transmission technology designed to improve **bandwidth efficiency** by using multiple orthogonal subcarriers for data transmission. It serves as the foundation for LTE systems and provides robust performance in multipath environments.

Key Features of OFDM:

1. **Spectrum Efficiency Through Orthogonality:**
    - OFDM divides the available spectrum into **N orthogonal narrowband subchannels**.
    - These subcarriers overlap in frequency without causing interference, maximizing spectral efficiency.
2. **Use of Discrete Fourier Transform (DFT) and Inverse DFT (IDFT):**
    - Orthogonal subcarriers are generated using **DFT** for modulation and **IDFT** for demodulation.
    - These operations are computationally efficient due to the use of **Fast Fourier Transform (FFT)** and **Inverse FFT (IFFT)**.

OFDM Process in LTE Downlink:

1. **Input Data Modulation:**
    - The input data stream is modulated using **QPSK**, **16-QAM**, or **64-QAM**, generating a stream of complex symbols.
2. **Serial-to-Parallel Conversion:**
    - The modulated data stream is converted into **N parallel streams**, each corresponding to a subcarrier.
3. **Frequency Domain Representation:**
    - These parallel symbols represent discrete frequency components produced by the OFDM modulator, corresponding to the subcarriers.
4. **IFFT Operation:**
    - The IFFT transforms the frequency-domain symbols into a composite time-domain signal that includes all subcarriers.
5. **Cyclic Prefix (CP):**
    - A **cyclic prefix** is added to the time-domain signal as a **guard interval**.
    - The CP ensures that the transmitted signal appears periodic, mitigating the

effects of **multipath propagation** by converting the time-dispersive channel into a **cyclic convolution**.

Cyclic Prefix and Multipath Handling:

- **Purpose of the CP:**
  - The CP acts as a buffer to eliminate **Inter-Symbol Interference (ISI)** caused by delayed multipath signals.
  - Its duration must exceed the **maximum excess delay** of the channel.
- **At the Receiver:**
  - The receiver removes the CP and applies an **FFT** to recover the frequency-domain symbols.
  - The periodic nature of the transmitted signal ensures that the channel's effects can be accurately modeled as a cyclic convolution, simplifying equalization.

Summary of OFDM System Model:

- **Input Modulation**: QPSK, 16-QAM, or 64-QAM.
- **Orthogonal Subcarriers**: Generated using FFT/IFFT.
- **Cyclic Prefix**: Mitigates multipath effects and ISI.
- **Advantages**:
  - High spectral efficiency.
  - Resilience to multipath fading.
  - Simplified channel equalization through cyclic convolution.

By leveraging these features, OFDM ensures reliable and efficient data transmission in LTE downlink, making it a cornerstone technology for modern wireless communication systems.

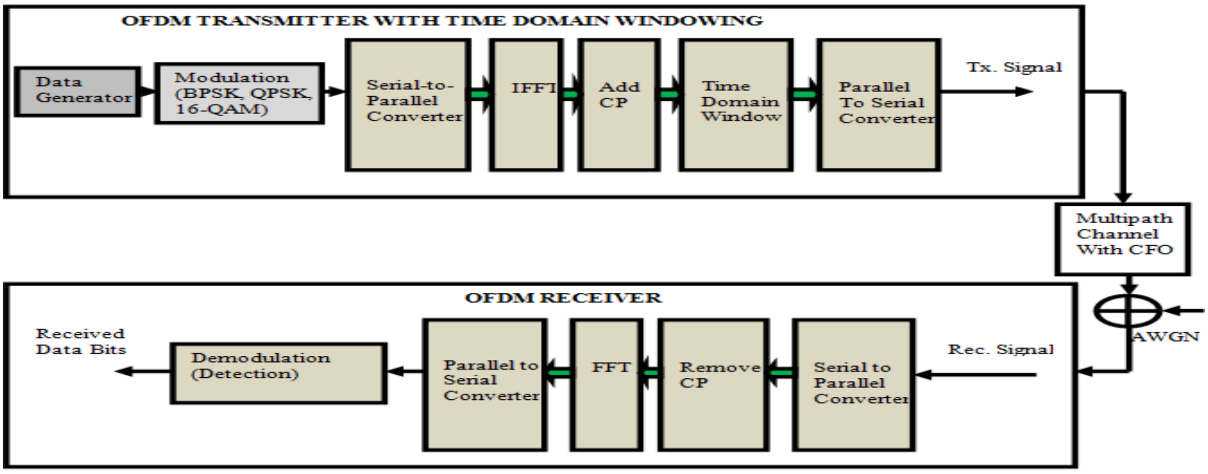


Figure 3.14: Time domain equalization with windowing OFDM system model

Conversion from serial to parallel: In **Conversion from Serial to Parallel in OFDM Systems**

Orthogonal Frequency Division Multiplexing (OFDM) divides a wideband channel into multiple narrowband sub-carriers, enabling efficient spectrum utilization and resilience against multipath fading. To achieve this, specific operations are performed at both the transmitter and receiver:

Transmitter Operations:

1. **Serial-to-Parallel Conversion**:
    - The incoming **serial bit stream** is divided into multiple **parallel streams**, each corresponding to a distinct sub-carrier.
    - This division allows data to be transmitted over multiple frequency bands simultaneously.
2. **Modulation on Sub-Carriers**:
    - Each parallel stream is modulated onto its respective sub-carrier, which acts as an independent channel.
    - Modulation techniques such as **QPSK**, **16-QAM**, or **64-QAM** are applied based on channel conditions.
3. **Combining Sub-Carriers via IFFT**:
    - The modulated sub-carrier signals are combined into a single **composite signal** using the **Inverse Fast Fourier Transform (IFFT)**.
    - The IFFT transforms the frequency-domain data (sub-carriers) into a **time-domain waveform**, enabling efficient transmission.
    - The number of sub-carriers is equal to the number of points in the IFFT operation.
4. **Cyclic Prefix Addition**:
    - A **cyclic prefix (CP)** is added to the time-domain signal to act as a guard interval, mitigating the effects of multipath fading and **Inter-Symbol Interference (ISI)**.

Receiver Operations:

1. **Composite Signal Reception**:
    - The receiver captures the transmitted composite signal, which contains the data from all sub-carriers combined.
2. **Cyclic Prefix Removal**:
    - The CP is stripped off, leaving the original time-domain signal for further processing.
3. **FFT Transformation**:
    - The time-domain signal is converted back into the **frequency domain** using the **Fast Fourier Transform (FFT)**.
    - The FFT separates the composite signal into individual sub-carriers for independent demodulation.
4. **Parallel-to-Serial Conversion**:
    - The independently demodulated data streams are recombined into a single **serial bit stream**, reconstructing the original transmitted data.

Key Features of OFDM Processing:

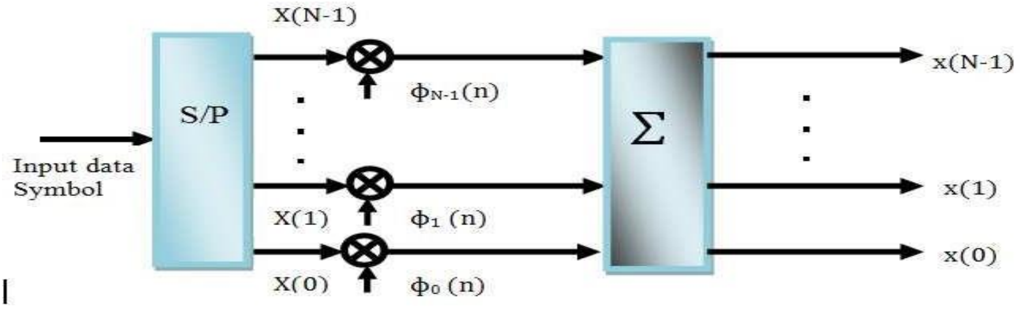
1. **Efficient Sub-Carrier Modulation**:
    - The IFFT block at the transmitter replaces traditional sub-carrier modulation hardware, simplifying system design.
    - Similarly, the FFT block at the receiver eliminates the need for multiple demodulators.
2. **Adaptation to Channel Conditions**:
    - Sub-carriers can use different modulation techniques based on **channel quality (e.g., SNR)**, allowing dynamic adjustment for optimal performance.
3. **Linear Transformations for Fading Channels**:

  - High-data-rate streams are transformed into **N lower-rate streams**, each undergoing **flat fading**, which simplifies equalization.

Advantages of Serial-to-Parallel Conversion in OFDM:

- **Spectral Efficiency**:
  Closely spaced sub-carriers overlap in frequency without interference due to orthogonality.
- **Resilience to Fading**:
  Dividing the data stream reduces the impact of multipath fading, as each sub-carrier experiences flat fading.
- **Simplified System Design**:
  The use of IFFT and FFT eliminates the need for multiple modulators, demodulators, and filters.

By leveraging FFT/IFFT and digital signal processing, OFDM achieves efficient, high-speed, and reliable data transmission, forming the backbone of modern wireless communication systems like LTE.



Where, $\phi_k(n) = \frac{1}{\sqrt{N}} e^{\frac{j2\pi kn}{N}}, n = 0,1,\dots,N$

Figure 3.15: Discrete time OFDM system with N-subcarriers

Note:

- ➢ IFFT receives inputs in the form of parallel frequency domain data streams, each of which controls a single frequency.
- ➢ Results The outputs of IFFT are discrete time samples of multiplexed and modulated signals.

Assume that the data set to be transmitted is X (0), X (1),..., X(N-1), where N is the total number of sub-carriers.

3.1.3.4.3 OFDM subcarrier orthogonality and spectral analysis optimizations

The sub-channel carriers' orthogonality:

1. Subcarrier Orthogonality in OFDM Systems

Definition and Mechanism:

- Subcarrier **orthogonality** in OFDM ensures that overlapping subcarriers do not interfere with each other, even when spaced closely in the frequency domain.
- Orthogonality is achieved by setting the subcarrier spacing (Δf\Delta fΔf) to the reciprocal of the useful symbol period (TTT): Δf=1/T
- **Orthogonality Criterion**:

Two signals f(t)f(t)f(t) are orthogonal if their dot product integrated over a symbol period equals zero: ∫fi(t)·fj(t) dt=0 for i≠j

Mathematical Representation:

For NNN subcarriers, the orthogonal signals are expressed as:

f(t)=ej2πnΔft, n=0,1,2,…,N−1

- This ensures that the spectrum of each subcarrier exhibits a **null** at the center frequencies of all other subcarriers, avoiding **inter-carrier interference (ICI)**.

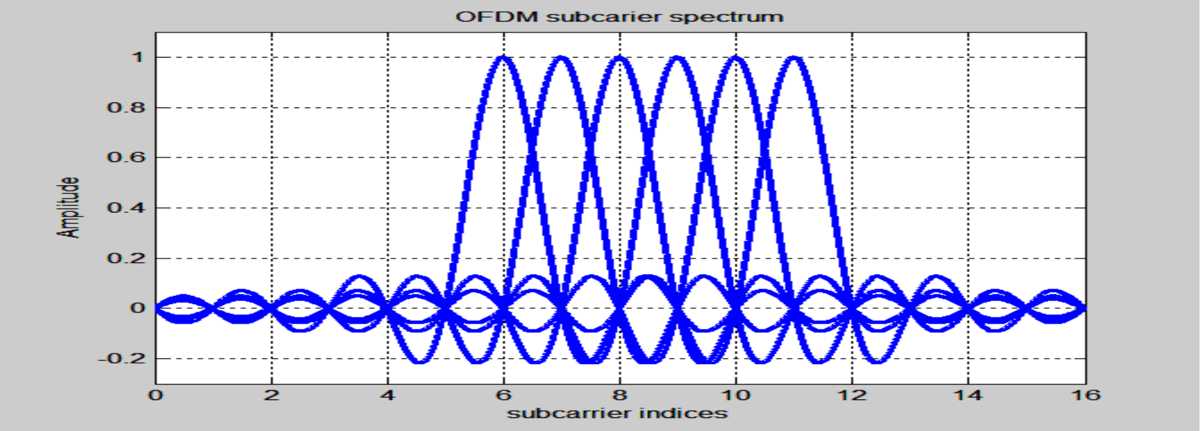


Figure 3.16: frequency domain representation of an OFDM system

2. Subcarrier Spectrum and Inter-Carrier Interference (ICI)

- **Subcarrier Spectrum Shape**:
  - Each subcarrier in OFDM has a **sinc(x)** spectral profile.
  - The main lobe represents the signal power, while side lobes decay slowly.
- **ICI Causes**:
  - **Frequency offsets** (e.g., due to Doppler shifts or oscillator errors) cause phase misalignments and spectral shifts, introducing interference.
- **ICI-Free Condition**:
  - Without frequency offsets, subcarriers remain orthogonal, retaining their sinc(x) profiles without interference.
  - Figure 3.16 demonstrates the **frequency domain representation** of overlapping subcarriers, showing how their orthogonality eliminates interference even in a densely packed spectrum.

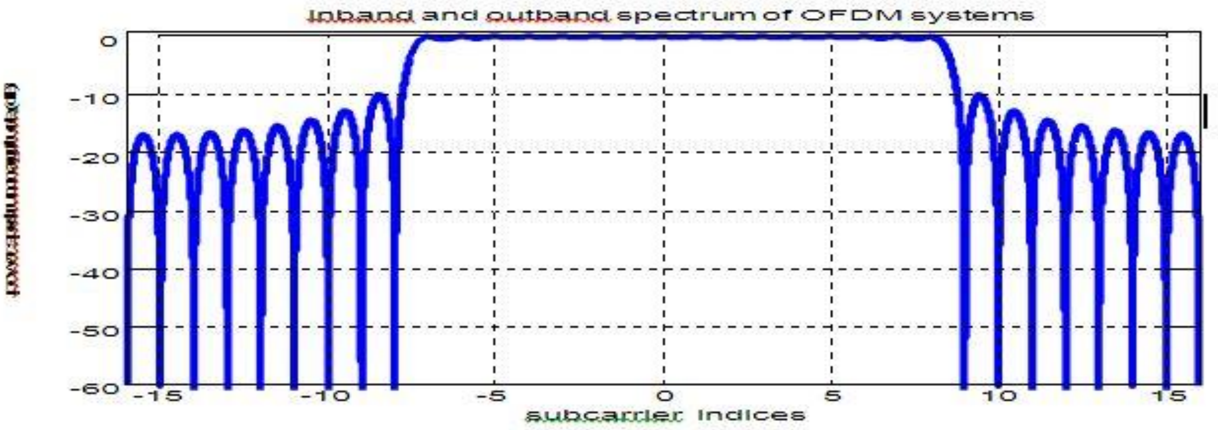


Figure 3.17: Power spectrum of the transmitted OFDM signal

3. Power Spectrum and Spectral Efficiency

- **OFDM Power Spectrum**:
    - The power spectrum of an OFDM signal is the sum of the spectra of all subcarriers across a symbol period.
    - Each subcarrier's spectrum is derived from a **Fourier transform** of its time-domain signal, as shown in Figure 3.17.
- **Spectral Efficiency**:
    - OFDM improves efficiency by overlapping subcarriers within a single channel, boosting throughput without increasing bandwidth.
    - This is achieved by exploiting orthogonality, ensuring interference-free operation despite the overlap.

4. Out-of-Band Power and Spectral Roll-Off

- **Side Lobe Impact**:
    - The **sinc(x)** profile of each subcarrier includes slowly decaying side lobes, resulting in significant **out-of-band power**.
    - This can interfere with adjacent channels, especially in scenarios with high subcarrier counts or wide bandwidths.
- **Mitigation Techniques**:
    - **Time-Domain Equalization with Windowing**:
        - Applies smoothing to transitions at symbol boundaries, reducing abrupt signal changes.
        - Results in:
            - **Reduced out-of-band power.**
            - **Faster spectral roll-off.**
            - **Improved Bit Error Rate (BER) performance.**
    - Figure 2.6 illustrates how windowing improves spectral behavior by minimizing interference with adjacent broadcasts.

Summary of Optimization Techniques for OFDM

1. **Ensure Subcarrier Orthogonality**:
    - Maintain proper spacing ($\Delta f = 1/T$) to prevent inter-carrier interference.
2. **Minimize Frequency Offsets**:
    - Employ advanced synchronization techniques to avoid phase shifts and maintain orthogonality.
3. **Reduce Out-of-Band Power**:
    - Use time-domain windowing to suppress side lobes, accelerate spectral roll-off, and improve spectral efficiency.

By addressing these aspects, OFDM systems can maximize spectral efficiency, minimize interference, and enhance overall system performance.

Strengths and Weaknesses of OFDM

OFDM is a widely adopted technology in modern wireless communication systems and is a promising alternative to CDMA for future networks. Its strengths make it highly suitable for handling challenges in wireless channels, while its weaknesses require careful mitigation strategies.

Strengths of OFDM

1. **Resilience to Frequency-Selective Fading**:
    - OFDM divides a frequency-selective fading channel into multiple **narrowband flat-fading subchannels**.
    - This approach significantly improves performance in wireless environments prone to multipath fading.
    - As shown in **Figure 3.18**, OFDM ensures only a small portion of data is affected during fading, and the lost data is often recoverable.
2. **High Spectral Efficiency**:
    - By overlapping subcarriers in the frequency domain without causing interference (due to orthogonality), OFDM achieves **high spectral efficiency**.
3. **Mitigation of Inter-Symbol Interference (ISI)**:
    - OFDM mitigates ISI by converting a high-data-rate signal into multiple **lower-rate signals**.
    - This increases symbol duration, reducing the effect of **delay spread** caused by multipath propagation.
4. **Robustness in Multipath Environments**:
    - Techniques like **guard intervals** and **cyclic prefix (CP)** further reduce ISI and ensure reliable transmission in multipath scenarios.
5. **Data Distribution Across Subcarriers**:
    - Unlike single-carrier systems, where signal loss during a fading interval can affect the entire transmission, OFDM spreads data across subcarriers.
    - This ensures that only a small fraction of data is impacted, enhancing reliability and robustness.

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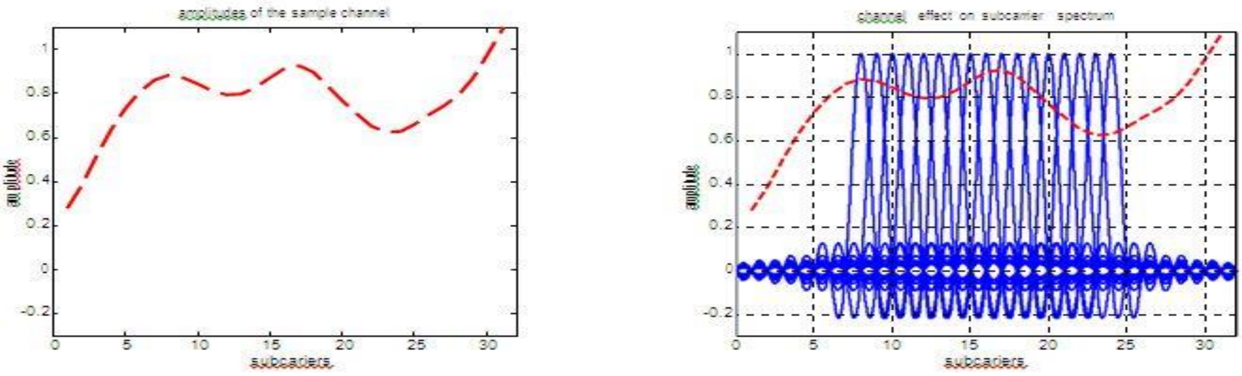


Figure 3.18: Robustness of OFDM to Frequency Selective fading channel

(a) Channel frequency response (b) Signal frequency spectrum

Weaknesses of OFDM

1. **Vulnerability to Inter-Carrier Interference (ICI)**:
    - OFDM systems are prone to **ICI**, caused by frequency offsets (e.g., Doppler shifts or oscillator mismatches).
    - Frequency offsets result in subcarrier misalignment, leading to **rotation and attenuation** of subcarriers, which degrades performance.
2. **Sensitivity to Carrier Frequency Offset (CFO)**:
    - CFO causes a loss of orthogonality between subcarriers, increasing ICI and reducing signal quality.
3. **High Peak-to-Average Power Ratio (PAPR)**:
    - The combination of multiple subcarriers results in a signal with large amplitude variations, requiring linear and power-efficient amplifiers, which can be expensive and inefficient.
4. **Out-of-Band Emissions**:
    - The **sinc(x)** spectrum of subcarriers produces side lobes, leading to significant **out-of-band power**.
    - This can cause interference with adjacent channels unless mitigated using techniques like **windowing** or advanced filtering.

Conclusion

Why OFDM is Favored:

- **Strengths** like resilience to fading, high spectral efficiency, and ISI mitigation make OFDM highly suitable for modern wireless systems, including LTE and 5G.

Addressing Weaknesses:

- Robust techniques are needed to mitigate weaknesses:
    - **Frequency synchronization** to reduce ICI.
    - **PAPR reduction techniques** (e.g., clipping, coding, or precoding) to handle power efficiency.
    - **Windowing** to minimize out-of-band emissions.

Despite its drawbacks, OFDM's advantages far outweigh its limitations, making it a cornerstone technology for reliable and efficient wireless communication systems.

The distinction between OFDM and SC-FDMA

Differences Between SC-FDMA and OFDM Modulation Schemes

SC-FDMA (Single Carrier Frequency Division Multiple Access) and **OFDM** (Orthogonal Frequency Division Multiplexing) differ in key structural and performance aspects:

1. **Structure**:
    - In SC-FDMA, an **IDFT** module is added to the receiver chain, and a **DFT** module is inserted in the transmitter chain before the IFFT module. This modification converts the OFDM chain into an SC-FDMA chain. Without these modules, the chain functions as a standard OFDM transmit and receive system.
2. **Performance**:

   - SC-FDMA generally outperforms OFDM in terms of **Peak-to-Average Power Ratio (PAPR)**, making it more power-efficient.
   - SC-FDMA is also less susceptible to frequency offset compared to OFDM.
3. **Applications**:
   - **OFDM** is widely used in broadband technologies such as **WLAN-11a**, **WLAN-11n**, and **WLAN-11ac**, and in the downlink (eNodeB transmit path) of LTE systems.
   - **SC-FDMA** is typically used in the transmit path of LTE subscriber terminals due to its lower PAPR and better power efficiency.
4. **Data Transmission**:
   - OFDM uses multiple RF carriers at different frequencies to transmit bits over several closely spaced orthogonal subchannels, resembling Frequency Division Multiplexing (FDM).
   - SC-FDMA transmits data over a single carrier, making it inherently different from OFDM.

Advantages of OFDM

- **High Spectral Efficiency**: Closely spaced orthogonal subchannels overlap in frequency.
- **Resilience to ISI**: Effective against inter-symbol interference caused by multipath delay spread.
- **Robustness**: Performs well in channels with frequency-selective fading.
- **Efficient Implementation**: Utilizes IFFT/FFT for easy and efficient signal processing.
- **Low Time Synchronization Errors**: Minimal susceptibility to timing faults.
- **Simplified Equalization**: Eliminates the need for complex adaptive channel equalization.

Disadvantages of OFDM

- **Sensitivity to Frequency Offset**: Doppler shifts and synchronization errors lead to inter-carrier interference (ICI).
- **High Peak-to-Average Power Ratio (PAPR)**: Requires linearization in high-power amplifiers and a wide dynamic range in low-noise amplifiers.
- **Guard Interval Losses**: Guard intervals, while mitigating ISI, result in bandwidth and power loss, which can be significant in some scenarios.

3.1.3.4.4 Optimization effects on OFDM prefix, carrier frequency offset, BER and SNR

Proposed window function and system model

Optimization techniques like time-domain windowing and correlative coding can significantly enhance the performance of OFDM systems. These methods mitigate key challenges such as inter-carrier interference (ICI), improve the bit error rate (BER), and maximize the signal-to-noise ratio (SNR).

Proposed Window Function and System Model

The proposed **time-domain windowing function** is:

$w(n)=(1-\alpha\cdot ej2\pi n/N)L, n=0,1,\ldots,N-1$

- **Parameters**:
   - NNN: FFT size or the number of subcarriers.
   - α\alphaα: Coefficient of the window function, influencing system complexity and demodulation.
   - LLL: Correlation order.
- **Purpose**:

  - This window function integrates with **correlative coding** to suppress ICI by aligning with OFDM's block-wise modulation structure.
  - It creates **self-canceling ICI terms** between adjacent subcarriers within an OFDM block.
- **Implementation**:
  - The window function is applied at the **transmitter** after the IFFT block (Figure 3.19).
  - This reduces system complexity and ensures compatibility with OFDM's modulation structure.

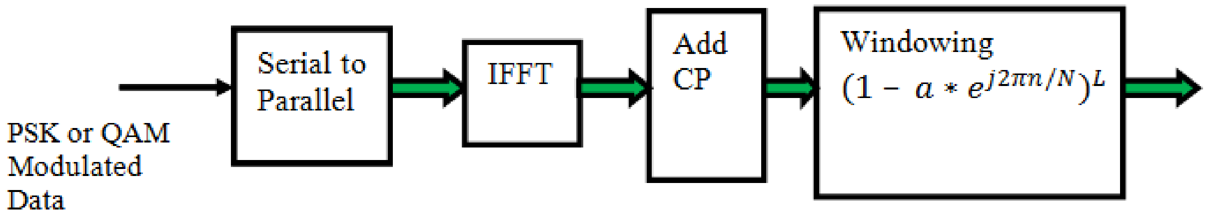


Figure 3.19: General form of window function in an OFDM transmitter

Mathematical Analysis of Optimization

1. **Windowing Effect on Time-Domain Signals**:
   The time-domain OFDM signal x(n) is multiplied by the window function w(n):

$x'(n)=x(n)\cdot(1-\alpha\cdot ej2\pi n/N)L$

2. **Frequency-Domain Representation**:
   At the receiver, the received signal for a subcarrier k, denoted as R(k), is computed using the DFT of the windowed time-domain signal:

$R(k)=\mathrm{DFT}\{x'(n)\}$

   - **Result**: The window function introduces correlation in the frequency domain, minimizing interference between adjacent subcarriers and the target subcarrier.
3. **Optimization of α**:
   - The coefficient α affects the **Carrier-to-Interference Ratio (CIR)** and demodulation complexity.
   - Optimal value: α=1, which balances performance and complexity.

Impact on OFDM Performance

1. **Inter-Carrier Interference (ICI) Suppression**:
   - The self-canceling ICI terms reduce interference from adjacent subcarriers.
   - Figure 3.20 illustrates how frequency-domain correlation minimizes ICI, enhancing symbol detection accuracy.
2. **Bit Error Rate (BER) Improvements**:
   - By reducing ICI, the system achieves lower BER, especially in high-noise environments.
   - Enhanced SNR leads to better decoding performance at the receiver.
3. **Signal-to-Noise Ratio (SNR)**:
   - The interplay between time-domain windowing and frequency-domain correlation increases the effective SNR for the target subcarrier.
4. **Carrier Frequency Offset (CFO) Mitigation**:
   - Time-domain windowing reduces the effects of CFO by maintaining

orthogonality between subcarriers, preventing phase misalignment.

5. **Spectral Efficiency**:
    - The optimized windowing function retains the overlap of subcarriers while minimizing out-of-band emissions.
    - Improved CIR ensures efficient utilization of the spectrum.

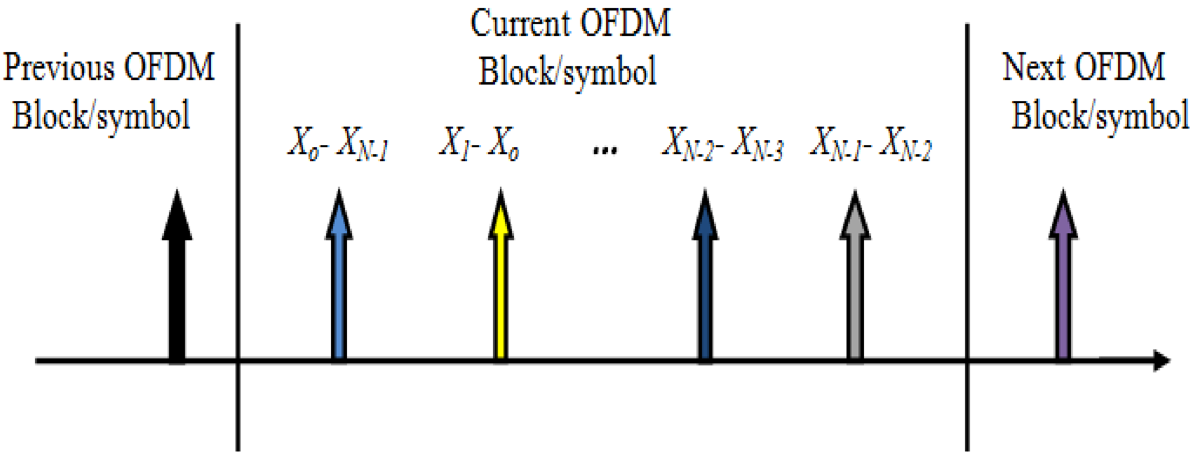


Figure 3.20: Frequency domain realization of windowing on OFDM receiver symbols

Challenges and Trade-Offs

- **Demodulation Complexity**:
    - Non-integral values of α introduce fractional energy levels in receiver symbols, complicating decision-making in modulation schemes like BPSK.
    - Optimal selection of $\alpha=1$ minimizes this complexity.
- **Symbol Correlation**:
    - The correlation introduced by windowing requires additional consideration in receiver algorithms, increasing computational requirements.

Conclusion

The proposed windowing function and system model optimize OFDM performance by effectively addressing ICI, BER, SNR, and CFO challenges. Key outcomes include:

- Enhanced **ICI suppression** through self-canceling terms.
- Lower **BER** and higher **SNR**, improving overall system reliability.
- Reduced **CFO sensitivity**, ensuring robust performance in dynamic environments.

These optimizations make OFDM more efficient for modern wireless systems, including LTE and 5G, while maintaining manageable complexity at both the transmitter and receiver.

Cyclic Prefix Ratio and Number of Subcarriers

Figure 5.1 illustrates the importance of appropriately selecting both the cyclic prefix ratio and the number of subcarriers in OFDM systems. As the number of subcarriers increases, the frequency gap between adjacent carriers narrows, exacerbating the effects of **carrier frequency offset** (CFO) and increasing **inter-carrier interference (ICI)**. While the cyclic prefix reduces inter-symbol interference (ISI), the ICI becomes more pronounced as the number of subcarriers grows. Simulations using 128 subcarriers in a specific OFDM channel were conducted to demonstrate the effects of frequency offset and explore potential mitigation techniques.

The **length of the cyclic prefix** is determined by the channel's delay spread. For the specified maximum delay spread of 10 µs, **Figure 5.2** shows the optimal cyclic prefix ratio for achieving the best BER performance. The results indicate that BER does not improve for cyclic prefix ratios smaller than **1/8**, even at high SNR levels. When the delay spread exceeds the effective guard period, BER increases sharply. The optimal cyclic prefix ratio for this scenario is concluded to be **1/4**, which effectively accounts for different channel conditions without significantly impacting transmission rate. While ratios larger than **1/4** can further reduce ISI, they do so at the expense of a lower transmission rate, offering diminishing returns.

Carrier Frequency Offset and BER Performance

To assess the impact of carrier frequency offset on BER, **Figure 5.3** compares the BER performance for different modulation schemes under CFO conditions. It specifically examines the effects for normalized frequency offset (c=0.14c = 0.14) in **AWGN** and **multipath fading channels** using **BPSK**, **QPSK**, and **16-QAM** modulation.

1. **Vulnerability by Modulation Scheme**:
    - **16-QAM** is the most vulnerable to carrier frequency offset due to its densely packed constellation points, which makes it more sensitive to phase and amplitude distortions caused by CFO.
    - **QPSK** is moderately affected, while **BPSK** is the least impacted because its constellation has widely spaced symbols, offering better tolerance to distortions.
2. **BER and SNR Requirements**:
    - For a BER of 10−3 or 10^{-3}, the required SNR varies by modulation scheme:
        - **BPSK**: SNR of ~8 dB.
        - **QPSK**: SNR of ~14 dB.
        - **16-QAM**: SNR of >30 dB.
    - **Figure 5.3 (a)** highlights these SNR requirements under AWGN conditions, while **Figure 5.3 (b)** extends the analysis to multipath fading environments, showing similar trends.

Impact of Time-Domain Windowing

Time-domain windowing is an effective method for reducing the effects of inter-carrier interference (ICI) and enhancing bit error rate (BER) performance in OFDM systems affected by carrier frequency offset (CFO). By smoothing signal transitions and minimizing spectral leakage, this technique reduces interference and strengthens overall system robustness. Additional studies highlight its efficiency under diverse channel conditions and modulation formats.

3.1.3.4.5 LTE radio diversity (receive, transmit, spatial, delay, multiplexing, beam) diversity optimizations

Multiple Input Multiple Output (MIMO) in Wireless Communications

Overview of MIMO

MIMO technology enhances data rates, capacity, and system performance in wireless communications by utilizing multiple antennas at both the transmitter and receiver. This approach increases the total received signal power without requiring additional transmit power.

- **Key Benefits**:
    - **Higher Data Rates**: Achieved by transmitting independent data streams simultaneously.
    - **Improved Coverage**: Increased signal robustness, especially in multipath environments.
    - **Enhanced Capacity**: Supports multiple users with better quality of service.

MIMO System Configuration

- **System Representation**:

  - A MIMO system uses M transmit antennas and N receive antennas, represented by the transmission matrix H, which has dimensions N×M.
  - The received signal vector y, transmit signal vector x, and noise vector n are related as: y=Hx+n
  - The elements hij in H denote the channel coefficients between the i-th receive and j-th transmit antennas.
- **MIMO Matrix Example**:

$$H=\begin{bmatrix} h_{11} & h_{21} & \cdots & h_{n1} \\ h_{12} & h_{22} & \cdots & h_{n2} \\ h_{1m} & h_{2m}\dots\dots & & h_{nm} \end{bmatrix} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; (2.1)$$

The following transmission formula is created from receive antenna vector y, transmit antenna vector x, taking noise n into account.

$$y = Hx + n \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; (2.2)$$

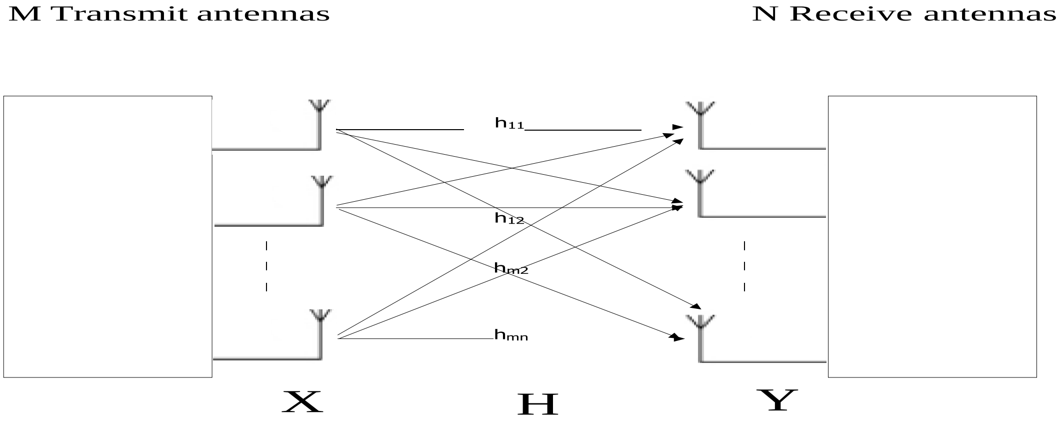


Figure 3.23: MIMO systems.

MIMO Techniques in LTE

LTE incorporates MIMO through three main strategies, each tailored to specific use cases and channel conditions:

1. Spatial Diversity:
    - Transmits duplicate data streams across multiple antennas to improve signal reliability.
    - Mitigates the effects of fading by ensuring that the signal is likely to reach the receiver through at least one path.
2. Spatial Multiplexing:
    - Sends independent data streams from different antennas to increase data rates.
    - Requires high Signal-to-Noise Ratio (SNR) and sufficient channel separability (measured by matrix H's rank).
3. Beamforming:
    - Uses channel state information (CSI) to direct signal energy toward the target receiver, increasing signal strength and reducing interference.
    - Appears to the receiver as a single "virtual antenna" (e.g., antenna port 5 in LTE).

Channel Model Parameters for MIMO Performance Evaluation

1. Doppler Frequency (Impact of Mobility):
    - Reflects the relative velocity of the User Equipment (UE) and affects signal stability due to frequency shifts.
    - Typical Doppler frequencies include:
        - 5 Hz: Pedestrian speeds (~2.7 km/h).
        - 70 Hz: Vehicle speeds (~37.8 km/h).
        - 300 Hz: High-speed scenarios (~162 km/h).
2. Delay Profiles (Multipath Propagation):
    - Represents the time dispersion caused by multipath channels.
    - Profiles used include:
        - Pedestrian: For low-speed scenarios.
        - Vehicular: For medium speeds (~70 Hz).
        - Typical Urban: For high-speed and dense urban environments.
        - High-Speed Train: Custom profile for rapid mobility.

Beamforming in LTE MIMO Systems

1. Mechanism:
    - Beamforming exploits the relative phases of downlink channels for all transmitting antennas to focus the signal energy at the receiver.

  - This requires UE-specific reference signals to ensure consistent weighting across data and reference signals.

2. Key Features:
   - Signal transmission appears to originate from a single "virtual" antenna (e.g., antenna port 5) to the UE.
   - Enhances signal strength and quality at the receiver.
   - Reduces interference, improving system performance in dense networks.
3. Applications:
   - Ideal for scenarios requiring targeted signal delivery, such as in high-density urban areas or cell-edge coverage improvement.

Conclusion

MIMO technology has transformed wireless communication systems by increasing data rates, improving coverage, and enhancing capacity. Its integration into LTE, through spatial diversity, spatial multiplexing, and beamforming, ensures robust performance across a range of mobility and multipath conditions. Beamforming, in particular, demonstrates how advanced signal processing techniques can optimize network efficiency and quality of service for users.

3.1.3.4.6 Channel estimation

Channel estimation is critical for mitigating the effects of the transmission medium on wireless signals, ensuring accurate reconstruction of transmitted data at the receiver. This section focuses on **pilot-based channel estimation**, the preferred method due to its simplicity and effectiveness. It also briefly outlines other techniques like blind and semi-blind estimation.

The Role of Channel Estimation

- **Channel Characteristics**:
  Wireless communication channels are subject to **frequency selectivity** and **time variability**, influenced by factors like **fading**, **scattering**, and **attenuation**.
- **Objective**:
  Channel estimation provides **Channel State Information (CSI)**, allowing the receiver to account for and mitigate these effects, enabling more reliable communication.
- **Importance of Accurate CSI**:
  - Ensures improved signal decoding.
  - Reduces errors caused by channel distortions.
  - Enhances system performance, especially in broadband wireless systems.

Methods of Channel Estimation

1. **Pilot-Based Estimation**:
   - **Description**:
     Pilot symbols or preambles, known to both transmitter and receiver, are embedded in the transmitted signal. The receiver uses these symbols to estimate the channel's response.
   - **Process**:
     1. **Pilot Transmission**: Transmit predefined pilot symbols.

        2. **Channel Response Estimation**: Evaluate the channel's effect on these pilots.
        3. **Interpolation**: Apply algorithms (e.g., linear, spline, or polynomial interpolation) to estimate the channel response for subcarriers between pilot tones.
    - **Advantages**:
        - Simple and effective.
        - Provides reliable channel estimates under varying conditions.
    - **Challenges**:
        - Overhead from pilot symbols reduces spectral efficiency.
        - Accuracy depends on the interpolation method and pilot placement.

2. **Blind Estimation**:
    - **Description**:
      Relies on **statistical properties** of the channel and transmitted signal characteristics to infer channel parameters without explicit pilot symbols.
    - **Advantages**:
        - No pilot overhead.
        - Higher spectral efficiency.
    - **Challenges**:
        - Computationally intensive.
        - Requires large amounts of data for accurate estimation.
        - Less reliable in dynamic or noisy environments.
3. **Semi-Blind Estimation**:
    - **Description**:
      Combines pilot-based and blind techniques to balance simplicity, accuracy, and spectral efficiency.
    - **Advantages**:
        - Reduces pilot overhead.
        - Offers improved accuracy compared to pure blind methods.
    - **Challenges**:
        - Increased complexity compared to purely pilot-based methods.

Why Pilot-Based Estimation is Preferred

- **Simplicity**:
  Straightforward implementation with predefined symbols.
- **Robustness**:
  Effective in a wide range of channel conditions, including high mobility and fading scenarios.
- **Interpolation Options**:
  Flexibility to use different algorithms (e.g., linear, cubic spline) for varying levels of complexity and accuracy.

Conclusion

Pilot-based channel estimation is a cornerstone of modern wireless communication systems, providing a reliable method to derive accurate CSI. Its effectiveness and ease of implementation make it the preferred choice, particularly in systems like LTE, where maintaining consistent performance across diverse environments is crucial. Although blind and semi-blind methods offer potential efficiency gains, their complexity and limitations often render them less practical for real-world deployment.

3.1.3.5 LTE resource grid, frame structure, resource allocation types, RRM scheduling, transmission systems, channel systems, protocol stack, radio resource management (RRM) and bandwidth usage

3.1.3.5.1 Actual transmission system briefing

Tutorial: Fundamentals of Voice over LTE and Its Variants

Voice over LTE (VoLTE) enables high-quality voice communication over LTE's all-IP network. While LTE is optimized for data and internet services, VoLTE integrates voice services into this architecture through two main approaches:

1. IMS-Based VoLTE (Voice over IP - VOIP)

- Mechanism:
  - Utilizes the IP Multimedia Subsystem (IMS), a standardized framework for delivering multimedia and voice over IP (VoIP) services.
  - Voice calls are treated as data packets and transmitted using LTE's IP-based infrastructure.
- Features:
  - High Definition (HD) Voice: Improved clarity and call quality.
  - Seamless Integration: Direct IP-based voice services without requiring fallback to legacy networks.

. CSFB with SRVCC (Circuit Switched Fall Back with Single Radio Voice Call Continuity)

- Mechanism:
  - When initiating a voice call, the user equipment (UE) falls back to 2G/3G circuit-switched networks, which handle the call.
  - SRVCC ensures that ongoing calls are handed over seamlessly between LTE and legacy networks without dropping.
- Use Case:
  - Preferred when IMS is not fully implemented or supported.
  - Suitable for networks in transition from circuit-switched to fully IP-based systems.

Specifications for LTE Downlink

The LTE downlink is structured into a resource grid, representing how resources are allocated for communication.

1. Resource Grid Structure:
    - Two dimensions:
        - Subcarriers (NDLRBN): Frequency domain.
        - OFDM Symbols (NDLSymbN): Time domain, within each slot.
2. Bandwidth and Subcarriers:
    - The transmission bandwidth determines the number of subcarriers (NDLRBN), which ranges between 6 and 100 values.
    - The specific values are defined in LTE standards (e.g., Table 3.5).

Antenna Port Configurations for Multi-Antenna Transmissions

Each antenna port in an LTE system has its own resource grid, characterized by its reference signal.

1. Antenna Port Numbers (pp):
    - p=0,{0,1},{0,1,2,3}:
        - For non-MBSFN transmissions with one, two, or four antenna ports.
    - p=4:
        - For MBSFN (Multicast Broadcast Single Frequency Network) reference signals.
    - p=5 :
        - For UE-specific reference signals, used in beamforming and other UE-directed transmissions.

Comparison of VoLTE Approaches

Feature	IMS-Based VoLTE (VOIP)	CSFB with SRVCC
Network Dependency	Fully IP-based (LTE only).	Falls back to 2G/3G.
Call Quality	HD Voice.	Standard 2G/3G quality.
Handover Support	Within LTE.	SRVCC for inter-network.
Implementation Complexity	Higher due to IMS setup.	Simpler; relies on legacy systems.
Preferred Use Case	Modern, fully IP-based networks.	Transitional deployments.

Conclusion

VoLTE is a key technology for integrating voice into LTE networks, offering high-quality voice services and a seamless user experience. While IMS-based VoIP is the long-term solution, CSFB with SRVCC remains essential for networks in transition. Understanding these approaches and LTE's resource allocation structures ensures efficient deployment and operation of voice services in LTE environments.

3.1.3.5.2 LTE physical layer over view

The LTE physical layer is designed to enhance the radio interface between base stations and user equipment (UE), offering significant improvements over earlier cellular technologies. It supports peak data rates of over 100 Mb/s on the downlink and 50 Mb/s on the uplink, as specified in the 3GPP Release 8 (3GPP 25.913). Key features include:

- **Flexible Bandwidths:** Ranging from 1.25 MHz to 20 MHz to accommodate various user capabilities.
- **Advanced Techniques:** Utilization of Orthogonal Frequency Division Multiplexing (OFDM) and multi-antenna technologies to boost spectral efficiency (3GPP 36.201).
- **Duplex Modes:** Supports both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) modes for paired and unpaired frequency bands.

The physical layer facilitates frequency-domain scheduling and link adaptation to optimize performance in the time and frequency domains.

LTE Interfaces and Functions

- **S1 Interface:**
  - **S1-U:** Transfers user data using GTP over UDP.
  - **S1-C:** Manages signaling between eNodeB and the MME via SCTP for reliability.
  - Functions include bearer management, mobility support, paging, and load balancing across MMEs.
- **X2 Interface:**
  - Handles control and user planes. The user plane uses GTP/UDP, while the control plane employs SCTP.
  - Functions include error handling, eNodeB load management, and intra-LTE mobility support.

LTE Frame Structure and Resource Grid

LTE employs two frame structures based on duplexing technology:

1. **Type-1 (FDD):** Used for paired frequency bands.

2. **Type-2 (TDD):** Designed for unpaired bands.

Each frame lasts 10 ms and consists of 10 subframes, with each subframe containing two time slots.

The **resource grid** organizes data in frequency and time. Key components include:

- **Resource Element (RE):** Represents one OFDM symbol in a subcarrier. It can transmit 2–6 bits depending on the modulation scheme (QPSK, 16-QAM, or 64-QAM).
- **Resource Block (RB):** Composed of 84 REs (12 subcarriers × 7 OFDM symbols) covering a bandwidth of 180 kHz and one time slot.

The base station assigns RBs for frequency-dependent scheduling, optimizing data transmission across subframes.

Physical Resource Structure of LTE

As per the 3GPP TR 36.211 V8.7.0 specification [11], the LTE time domain signal duration is defined by:

- **Time unit (Ts):** Ts=1/(115000×2048) seconds.
- **Radio frame duration (Tf):** Tf=307200×Ts=10 ms

LTE supports two frame types:

- **Type-1:** For FDD systems.
- **Type-2:** For TDD systems.

These frame structures organize uplink and downlink transmissions efficiently, enabling high data rates and robust communication.

The LTE frame

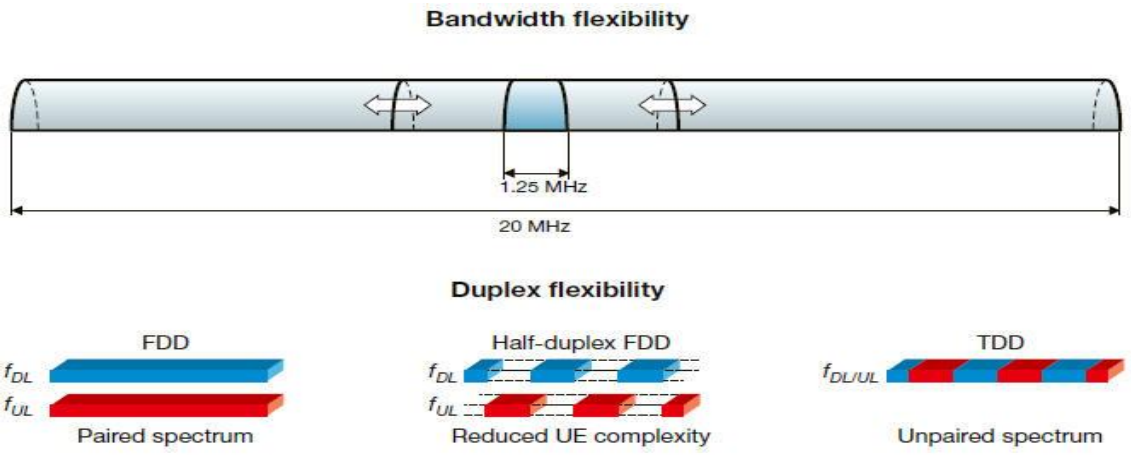


Figure 3.33: LTE frame

i. ***Type-1 (FDD) frame structure:***

This frame structure, endorsed by 3GPP and highlighted in Ericsson's insights, forms a cornerstone of the LTE (Long-Term Evolution) radio interface. LTE delivers remarkable improvements in latency, spectral efficiency, and peak data rates. Key elements discussed include spectrum flexibility, power optimization, retransmission mechanisms, scheduling, link adaptation, and multi-antenna systems.

Both **full-duplex** and **half-duplex** Frequency Division Duplex (FDD) modes use the Type-1 frame structure.

Key Characteristics of Type-1 FDD Frame Structure:

- **Frame Duration:** Each radio frame spans 10 ms, divided into 20 slots (0.5 ms each), numbered from 0 to 19.
- **Subframes:** Each subframe consists of two consecutive slots, with subframe **i** containing slots 2i2i and 2i+12i+1. The total subframe duration is 1 ms.
- **Transmission Allocation:** In FDD mode:
    - Ten subframes are allocated for **uplink (UL)** transmissions.
    - Ten subframes are reserved for **downlink (DL)** transmissions, occurring at intervals of 10 ms.
- **Frequency Domain Separation:** UL and DL transmissions are conducted on separate frequency bands, preventing overlap.
- **Duplex Modes:**
    - **Full-Duplex FDD:** Allows simultaneous UL and DL transmissions, enhancing performance.
    - **Half-Duplex FDD:** Restricts the UE from transmitting and receiving simultaneously.

Frame Composition:

- Each radio frame is composed of 307,200×Ts , where: Ts=1/(115000×2048) seconds.
- A subframe lasts 1 ms, and a slot spans 0.5 ms.

By organizing UL and DL transmissions over distinct frequency bands, Type-1 FDD frames achieve efficient, high-capacity LTE communication while maintaining flexibility to adapt to varying duplexing requirements.

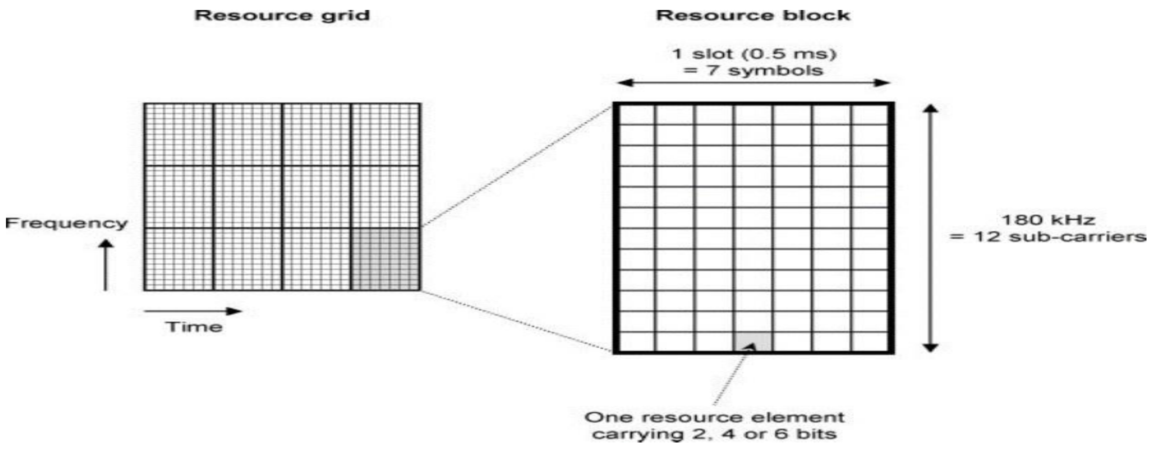


Figure 3.35: C.1. The time and frequency domain structure of the LTE resource grid with a conventional CP (the extended CP has a similar grid, but it uses six symbols per slot instead of seven).

LTE Frame Structures and Resource Components

Type-1 Frame Structure (FDD)

A single LTE frame consists of **10 subframes**, each lasting Tssubframe=1 ms, leading to a total frame duration of Tframe=10 ms. Each frame is divided into **20 time slots** of Tslot=0.5 ms, with each subframe containing two slots.

Key characteristics include:

- **OFDM Symbols:** Each time slot has **7 OFDM symbols**, including a cyclic prefix (CP).
    - Without CP: OFDM symbol duration Tsymb=66.7μs.
    - CP duration: 4.7μs4.7 \mu \text{s}4.7μs (typically) or 5.2μs for the first OFDM symbol in a slot.
- **Downlink and Uplink Transmissions:** In FDD, downlink (DL) and uplink (UL) transmissions occur on different frequency bands.
    - Full-Duplex: Simultaneous UL and DL.
    - Half-Duplex: UL and DL occur alternately.
- **Synchronization:** DL radio frames are sent to the UE before corresponding UL frames are received.

ii. Type 2 (TDD) frame structure

In Type-2 frames, subframes are designated for downlink (D), uplink (U), or special subframes (S). The special subframe SSS comprises:

1. **Downlink Pilot Time Slot (DwPTS):** Used for DL transmissions.
2. **Guard Period (GP):** Facilitates the transition from DL to UL.
3. **Uplink Pilot Time Slot (UpPTS):** Allocated for UL signaling.

Frame Details:

- **Structure:** Each 10 ms frame includes two half-frames of 5 ms each, with subframes identified as 0 to 9.
- **Slot Duration:** Each subframe consists of two slots, each lasting Tslot=0.5 msT_{slot} = 0.5 \text{ ms}Tslot=0.5 ms.
- **Switch-Point Periodicity:**
    - **5 ms:** Special subframes are present in both half-frames.
    - **10 ms:** Special subframes appear only in the first half-frame.
- **Assignments:** Subframes #0 and #5 always serve DL. UpPTS and subsequent

subframes are reserved for UL.

Resource Grid and PRBs in LTE

- **Subcarriers and Resource Elements (REs):**
    - LTE uses scalable bandwidths (1.4 MHz to 20 MHz), divided into **12 subcarriers per Resource Block (RB)**.
    - Each RB spans 180 kHz and contains 12 subcarriers for **1 time slot (0.5 ms)**.
    - **OFDM Symbol Count:**
        - Normal CP: 7 symbols per slot.
        - Extended CP: 6 symbols per slot.
- **PRBs (Physical Resource Blocks):**
    - **Dimensions:** 12 subcarriers×6 or 7 symbols
    - Example: A 10 MHz bandwidth comprises 50 PRBs (600 subcarriers).

Special Characteristics of TDD

- **DwPTS Distinctions:**
    - Typically lasts **1 ms**, but symbol count varies (3 to 12 OFDM symbols).
    - Contains two control OFDM symbols compared to three in regular DL subframes.
    - The primary synchronization signal (P-SCH) is located at the **third OFDM symbol**, helping UEs identify duplexing mode.
- **Guard Period (GP):** Allocated for DL to UL transitions.
- **Configuration Flexibility:** TDD configurations can adapt to traffic patterns (e.g., Configuration 1 for balanced UL/DL, Configuration 5 for DL-heavy scenarios).

Recommendations for TDD Interference Mitigation

To minimize interference, neighboring cells should frequently adopt identical TDD configurations. Variations in configurations are communicated to UEs through system information and allow network operators to tailor setups to traffic demands and reduce cross-cell interference.

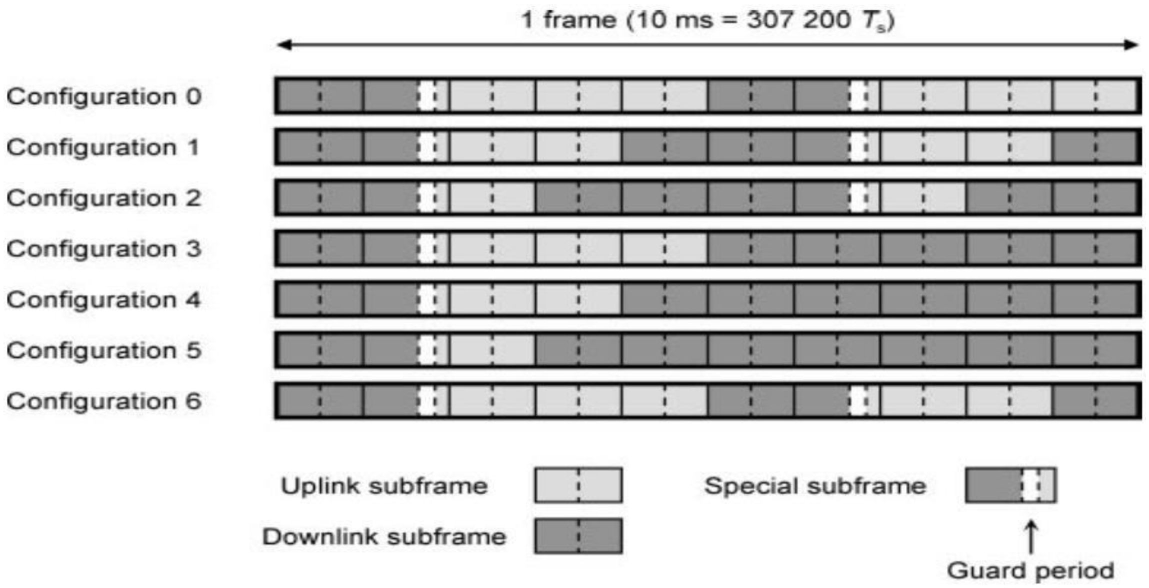


Figure 3.39: C.2. Time synchronization between uplink and downlink frame

3.1.3.5.3 Channel scheduling

Channel scheduling is a critical aspect of **Radio Resource Management (RRM)** in LTE, handled by the **Medium Access Control (MAC)** layer at the eNodeB. Packet schedulers in the MAC layer allocate radio resources to user packets, ensuring efficient distribution based on predefined criteria.

Scheduling Mechanism

1. **Resource Allocation Criteria:**
    - A priority metric determines each user's level of importance for a specific **Resource Block (RB)**.
    - This metric guides the allocation of RBs, which is communicated to users through the **Physical Downlink Control Channel (PDCCH)** during each **Transmission Time Interval (TTI)** (1 ms).
2. **Resource Block Distribution:**
    - **Downlink:** RBs assigned for data transmission via the **Physical Downlink Shared Channel (PDSCH)**.
    - **Uplink:** RBs allocated for data on the **Physical Uplink Shared Channel (PUSCH)**.
    - Allocation details are conveyed via **Downlink Control Information (DCI)** messages through the PDCCH.
3. **Scheduling Process Overview (Five Steps):**
    - **Step 1: CQI Reporting:**
      Each user evaluates the **Channel Quality Indicator (CQI)** after analyzing the reference signal and reports it back to the eNodeB.
    - **Step 2: RB Allocation:**
      The eNodeB uses the CQI feedback to populate an RB allocation mask and make scheduling decisions.
    - **Step 3: AMC Selection:**
      The **Adaptive Modulation and Coding (AMC)** module selects the optimal **Modulation and Coding Scheme (MCS)** for the data transmission.
    - **Step 4: PDCCH Transmission:**
      Scheduling information (e.g., allocated RBs and MCS) is sent to users via the PDCCH.
    - **Step 5: Data Reception:**
      Upon decoding the PDCCH, users connect to the **PDSCH** to receive their scheduled data.

Key Features of LTE Packet Scheduling:

- **Dynamic Allocation:** Repeated every TTI, ensuring users with the highest metrics share RBs efficiently.
- **Real-Time Adaptation:** Scheduling adapts to changing channel conditions using CQI feedback.
- **Bidirectional Scheduling:** Handles both uplink and downlink transmissions simultaneously.

This scheduling process is essential for optimizing LTE network performance, enhancing user experience, and maintaining efficient utilization of radio resources.

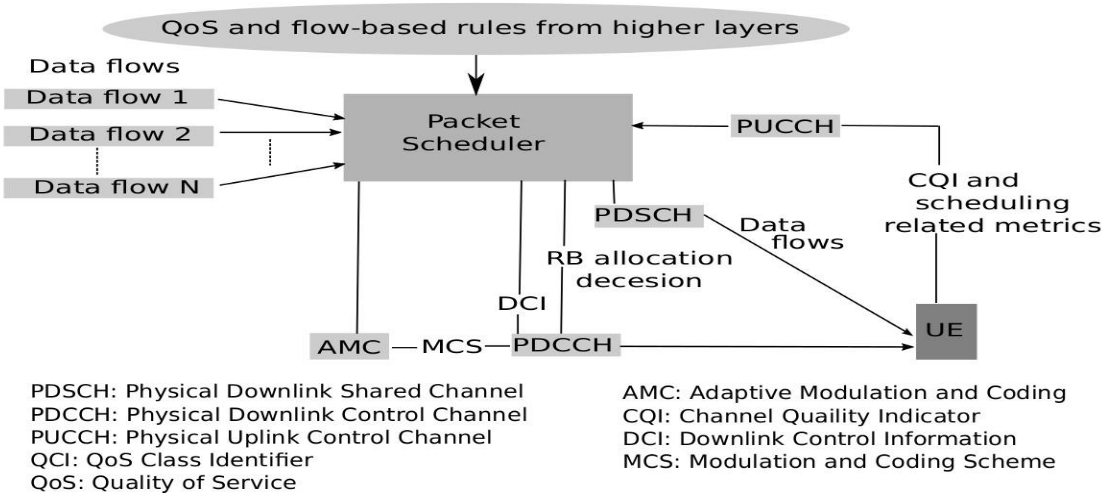


Figure 3.40: A general model of LTE packet scheduler

Interaction Between a User and an Uplink Packet Scheduler
Uplink scheduling is distinct from downlink scheduling as it involves user-initiated data transmissions. The interaction between a user and the uplink packet scheduler can be broken down into **four primary steps**:

1. **Scheduling Request (SR):**
   - The user initiates a Scheduling Request (SR) using **PUCCH format 1** to notify the eNodeB of its intention to upload data.
   - Alongside the SR, the user provides additional **uplink control information (UCI)**, including:
     - **Buffer Status Report (BSR):** Indicates the amount of data waiting in the user's transmission buffer.
     - **Channel Quality Indicator (CQI):** Reports the current uplink channel conditions to the eNodeB.
2. **Resource Evaluation by eNodeB:**
   - The eNodeB evaluates the scheduling request based on:
     - The presence of data in the user's buffer.
     - The channel quality for reliable transmission.
     - The availability of radio resources.
   - If conditions are favorable, the eNodeB decides to allocate resources for the user's uplink transmission.
3. **Scheduling Decision Notification:**
   - The eNodeB communicates its uplink scheduling decision via the **Physical Downlink Control Channel (PDCCH)**.
   - This includes details about the radio resources allocated to the user for data transmission.
4. **Data Transmission:**
   - After interpreting the PDCCH, the user utilizes the allocated resources to upload their data through the **Physical Uplink Shared Channel (PUSCH)**.

This process ensures efficient uplink resource allocation, balancing user data demands with network capacity and channel conditions, while maintaining overall system performance.

Uplink LTE packet scheduling algorithms

Many **Uplink LTE Packet Scheduling Algorithms**
LTE uplink packet scheduling involves assigning radio resources efficiently to multiple User Equipment (UE) devices to optimize performance metrics like throughput, fairness, and latency. Several algorithms are used for this purpose, with most relying on matrix-based resource allocation. The effectiveness of these algorithms is influenced by the construction of the **input matrix**, which can be developed using the **channel-dependent method** or the **proportional fairness approach**.

1. Channel-Dependent Method

This method dynamically allocates resources based on the **channel quality** of each UE for every resource block. It optimizes throughput by prioritizing UEs with better channel conditions.

- **Key Components**:
    1. **Buffer Status Report (BSR)**:
        - The UE provides the **amount of buffered data** and its **priority levels** to the eNodeB.
        - Helps the eNodeB understand data backlog and urgency for each UE.
    2. **Sounding Reference Signal (SRS)**:
        - Transmitted by the UE every millisecond to communicate **channel state information** (CSI) to the eNodeB.
        - Enables the eNodeB to assess the uplink channel quality for each UE on a per-resource-block basis.
- **Process**:
    1. The eNodeB collects **SRS** and **BSR** from UEs.
    2. The **CSI Manager** constructs the **channel condition matrix** using this information.
    3. The scheduler allocates resources to UEs based on their channel quality and buffered data.
- **Advantages**:
    - Maximizes system throughput by prioritizing UEs with good channel conditions.
    - Efficient use of spectral resources.
- **Disadvantages**:
    - UEs in poor channel conditions receive limited resources, potentially causing unfairness in resource allocation.

2. Proportional Fairness Approach

This method balances throughput and fairness by ensuring all UEs receive a share of resources proportional to their channel quality.

- **Mechanism**:
    - UEs with good channel quality are prioritized, but UEs with poor channel quality are still allocated some resources.
    - Fairness adjustments are based on the **current channel conditions** and historical allocations.
- **Process**:

1. The scheduler calculates a **fairness metric** for each UE, combining:
    - Current channel quality (CSI).
    - Historical data rate received by the UE.
2. Resource blocks are allocated to maximize the overall system performance while maintaining fairness.

- **Advantages**:

  - Provides better service to UEs in poor channel conditions compared to purely channel-dependent methods.
  - Ensures equitable resource distribution, enhancing user experience.
- **Disadvantages**:
  - Compromises peak system throughput to maintain fairness.

Comparison of Methods

Aspect	Channel-Dependent Method	Proportional Fairness Approach
Objective	Maximize throughput.	Balance throughput and fairness.
Resource Allocation	Based on channel quality (CSI).	Proportional to channel conditions and fairness metrics.
UE Priority	Favors UEs with good channel quality.	Allocates resources to all UEs proportionally.
Fairness	Low for UEs with poor channel quality.	High fairness for all UEs.
Use Case	High-throughput scenarios.	Scenarios requiring equitable distribution.

Conclusion

Uplink packet scheduling in LTE involves a trade-off between maximizing throughput and ensuring fairness.

- **Channel-dependent methods** excel in throughput but can disadvantage users in poor channel conditions.
- **Proportional fairness approaches** balance fairness and performance, making them suitable for networks with diverse UE conditions.

Choosing the optimal scheduling algorithm depends on network requirements, user profiles, and the desired balance between efficiency and equity.

3.1.3.5.4 Transmission systems (data coding, channel control signal, channel quality, cell selection and power allocation)

Control channel element (CCE) index calculation:

The **Control Channel Element (CCE)** index specifies where control channel data is mapped within an LTE subframe. Since the allocation of control data changes dynamically across subframes, accurately calculating the CCE index is essential for ensuring proper control channel operations.

Key Factors Influencing CCE Index Calculation

1. **Subframe Variability**:
   - The CCE index can change for each subframe due to resource allocation policies and scheduling.
2. **System Bandwidth**:
   - System bandwidth, which determines the number of **Resource Blocks (RBs)**, directly affects the available **Physical Downlink Control Channel (PDCCH)** resources and the CCE index.
3. **Higher Layer Configuration**:
   - The **Master Information Block (MIB)** contains the system bandwidth configuration through an **Information Element (IE)**, set at the **L3 (Layer 3)** level.
   - Modifications to system bandwidth impact the total number of **CCE regions** available.

Steps for Calculating the CCE Index

1. **Determine System Bandwidth**:
    - Obtain the system bandwidth (NRB) from the MIB.
    - NRB represents the total number of resource blocks.
2. **Calculate the Number of CCEs**:
    - The number of available **CCE regions** depends on the system bandwidth and subframe configuration.
    - Each CCE consists of **9 Resource Elements (REs)** in the PDCCH.
    - The number of CCEs in a subframe can be expressed as: NCCE=NREG/9 where NREG is the number of Resource Element Groups in the PDCCH.
3. **CCE Indexing**:
    - Assign an index to each CCE starting from 0 up to NCCE−1.
    - For a specific subframe, control data is mapped to CCE indices based on a predefined scheduling algorithm.
4. **Adjust for Subframe Variability**:
    - Apply the scheduling rules for each subframe to dynamically allocate the control data to appropriate CCE indices.
    - The allocation depends on the **RNTI (Radio Network Temporary Identifier)** and the control channel's aggregation level.

Bandwidth Dependence of CCE Allocation

- Modifying the system bandwidth at the **higher layer (L3)** impacts the total number of resource blocks and subsequently the number of available CCEs.
- Developers or test case implementers must account for these changes to ensure control channel data is properly allocated across subframes.

Example Calculation

1. **System Bandwidth**: Assume NRB=50 (corresponding to a 10 MHz LTE channel).
2. **Resource Element Groups (REGs)**: Calculate NREG for the PDCCH based on the RBs.
3. **CCE Count**: Derive NCCE by dividing NREG by 9.
4. **CCE Indexing**: Map control channel data to available indices based on subframe-specific rules.

Conclusion

The **CCE index** calculation is integral to ensuring dynamic and efficient allocation of control channel data in LTE. By carefully considering factors like system bandwidth, subframe variability, and higher-layer configurations, developers and test case implementers can maintain robust control channel operations across different LTE scenarios.

Parameters in calculating CCE index: *Prepare* ***Parameters and Steps in Calculating the CCE Index***

1. ***Prepare the REG Table***
    - *Create the Resource Element Group (REG) table to define the structure of resource mapping.*
2. ***Choose the System Bandwidth***
    - *Set the system bandwidth BW.*
3. ***Determine the Maximum Number of Resource Blocks***
    - *Calculate the number of Resource Blocks (RBs) based on the bandwidth: NRBN_{RB}.*
4. ***Select the Number of HI Groups***

   - *Define NoHI_Group, the number of HARQ Indicator (HI) groups.*
5. ***Set the REG Utilization Based on the CFI***
   - *Define the number of REGs used for the Control Format Indicator (CFI): REGCFI=4.*
6. ***Determine the CFI***
   - *Specify the CFI value, which can range from 1 to 3, indicating the number of OFDM symbols used for the control region.*
7. ***Retrieve NgNg***
   - *NgNg represents the scaling factor for PHICH (Physical HARQ Indicator Channel) resources and is dependent on system configuration.*
8. ***Construct a CFI vs. Bandwidth\text{CFI vs. Bandwidth} Table***
   - *Build a table CFIBW_Table using NgNg, REGCFI , and NoHI_Group .*
9. ***Create a HI Group vs. Bandwidth\text{HI Group vs. Bandwidth} Table***
   - *Construct HI_GroupBW_Table using NgNg and NRBN_{RB}.*
10. ***Retrieve the HI_Group\text{HI_Group} Value***
    - *Obtain the intersection value from HI_GroupBW_Table where the bandwidth and NgNg match: HI_Group .*
11. ***Retrieve NCCEN_{CCE} from CFIBW_Table***
    - *Fetch the value from CFIBW_Table where the specified CFI\text{CFI} and bandwidth intersect: NCCEN_{CCE}.*
12. ***Select CRNTI and Define Additional Parameters***
    - *Specify the Cell Radio Network Temporary Identifier (CRNTI).*
    - *Define constants and variables AA, DD, Y−1Y-1, and LxLx.*
13. ***Calculate Y0Y_0 to Y9Y_9***
    - *Compute the values of Y0Y_0 to Y9Y_9 using the formula: Yk=(A+D⋅k)mod NCCE,for k=0,1,…,9.Y_k = (A + D)*
14. ***Specify the Aggregation Level***
    - *Set the aggregation level LL, where L∈{1,2,4,8}.*
15. ***Compute the CCE Index***
    - *Calculate the CCE index for each subframe using the formula: CCE Index={Y0,Y1,…,Y9}mod L,with NCCE.*
    - *This systematic approach ensures accurate determination of the CCE index for control channel data assignment across varying subframes and configurations.*

and N_CCE.

3.1.3.5.5 Stack of protocols

The user plane and the control plane are the two protocol planes that LTE maintains a 3GPP separation between (Figure 3.44).

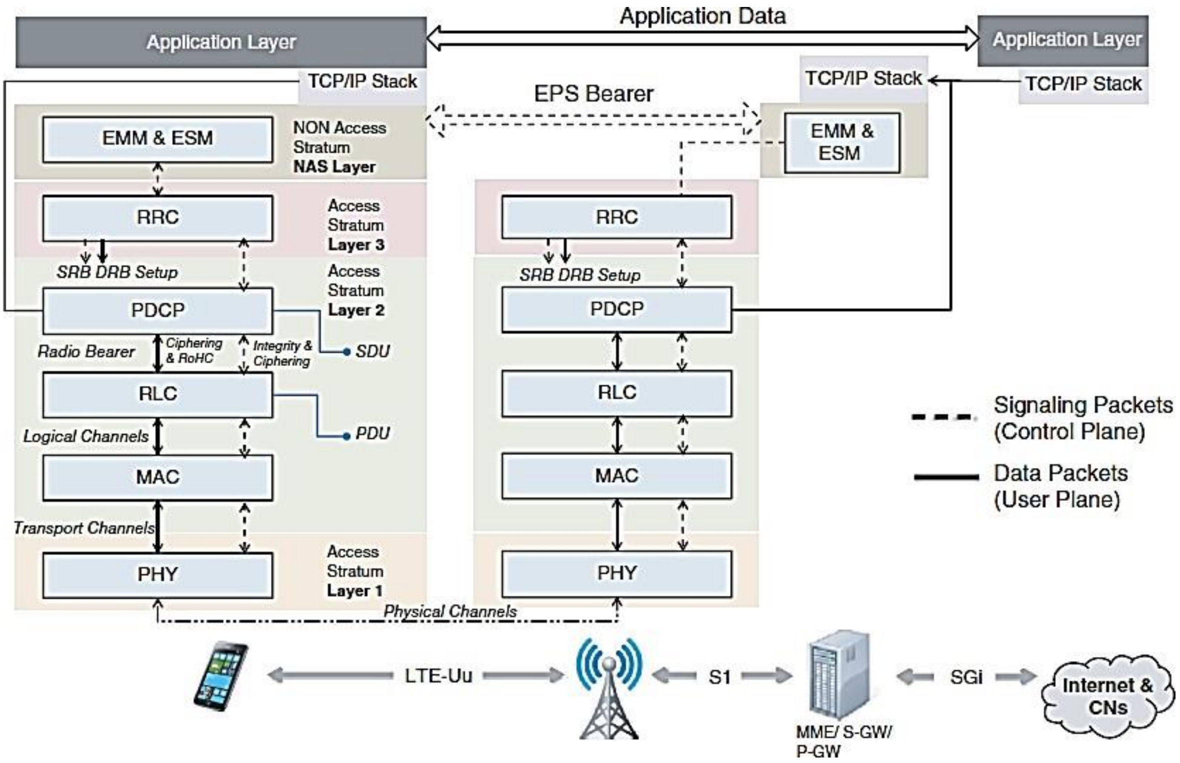


Figure 3.1. Life of an LTE Packet: Downlink

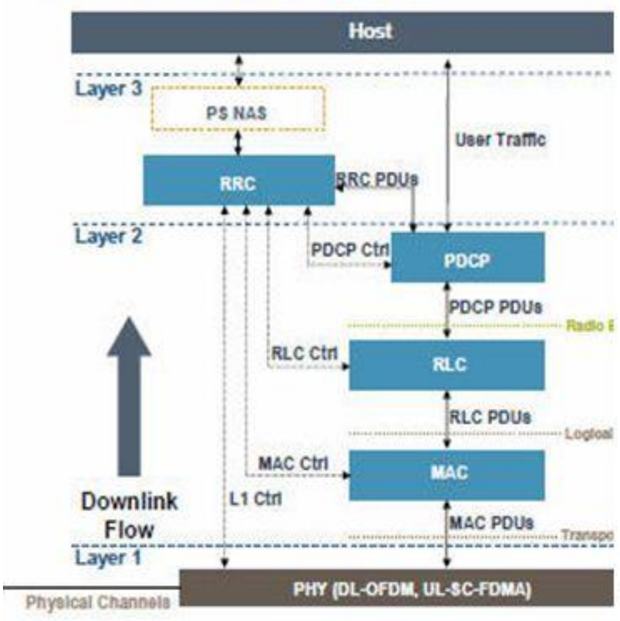
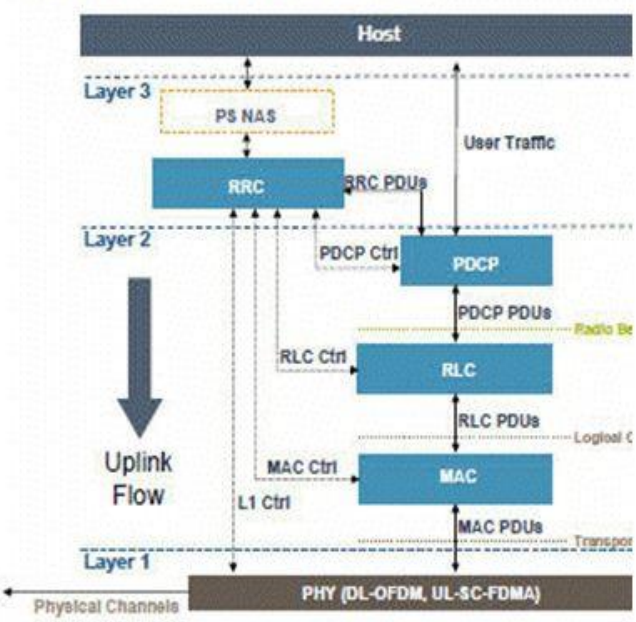


Figure 3.6. Life of an LTE Packet: Uplink



Overview of the LTE Protocol Stack

The LTE protocol stack is a critical component of the LTE system, defining how data is processed, managed, and transmitted across the network. Given the comprehensive nature of the 3GPP standard (spanning tens of thousands of pages), this document focuses on the **core functionalities** and **key aspects** of the protocol stack.

Structure of the LTE Protocol Stack

The LTE protocol stack is organized into **three primary layers**:

1. **Physical Layer (Layer 1)**:
    - **Purpose**: Handles the transmission and reception of raw bits over the air interface.
    - **Functions**:
        - Modulation and coding (OFDM for downlink, SC-FDMA for uplink).
        - Transmission of reference signals for channel estimation.
        - Error detection and correction via HARQ (Hybrid Automatic Repeat Request).
2. **Data Link Layer (Layer 2)**:
    - Divided into three sublayers:

1. **Medium Access Control (MAC)**:
    - Allocates resources for uplink and downlink transmissions.
    - Manages retransmissions (HARQ) and scheduling.
2. **Radio Link Control (RLC)**:
    - Segments and reassembles packets for error correction.
    - Provides reliable or unreliable data delivery depending on the mode (AM, UM, TM).
3. **Packet Data Convergence Protocol (PDCP)**:
    - Compresses headers to optimize bandwidth.
    - Ensures security through encryption and integrity protection.

3. **Network Layer (Layer 3)**:
    - **Radio Resource Control (RRC)**:
        - Manages connections between the UE and eNodeB.
        - Oversees handovers, quality of service (QoS), and power-saving mechanisms.

Key Functional Areas

1. **Time Domain and Information Flow**:
    - Data flows sequentially from higher layers (application/user level) down to the physical layer for transmission.
    - Control signaling (e.g., RRC messages) flows alongside data to maintain system functionality and performance.
2. **Scheduling and QoS**:
    - **Scheduling**: Managed by the MAC layer, scheduling allocates radio resources dynamically based on network conditions and QoS requirements.
    - **QoS**: Ensures that high-priority traffic (e.g., voice or video) receives appropriate bandwidth and latency guarantees.
3. **Management and Control Functions**:
    - Includes mobility management, session management, and security protocols for maintaining connection integrity and performance.
4. **Handovers**:
    - Facilitates seamless transitions between cells or eNodeBs during mobility scenarios, using RRC and signaling protocols.
5. **Power-Saving Operations**:
    - Implements mechanisms like Discontinuous Reception (DRX) to reduce UE power consumption while maintaining connectivity.

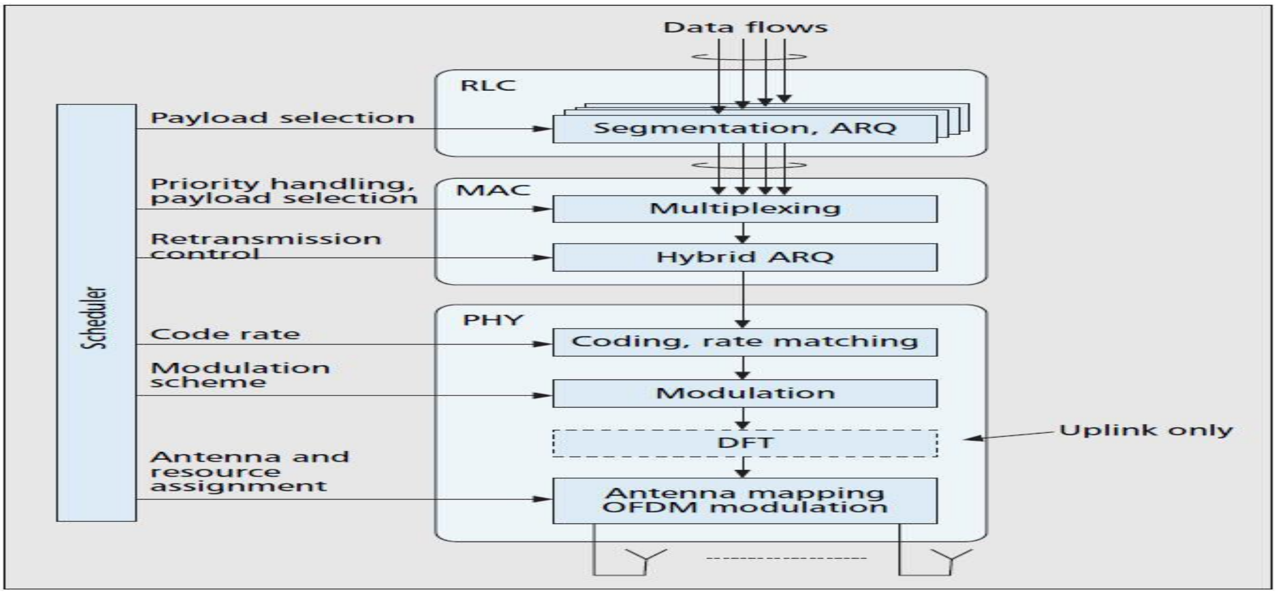
Priorities and Application Needs Driving LTE Design

1. **Increased Data Rates**:
    - LTE is designed to provide **high-speed broadband services** for applications like streaming and online gaming.
2. **Low Latency**:
    - Essential for real-time applications, LTE achieves sub-10ms latencies through efficient scheduling and processing.
3. **Scalability**:
    - Supports various bandwidths (1.4 MHz to 20 MHz) to adapt to different network deployments and application needs.

4. **Mobility Support**:
    - Ensures robust performance even for high-speed users, such as those traveling in vehicles or trains.

Conclusion

The LTE protocol stack is a highly modular system designed to meet the demands of modern wireless networks. While this overview highlights its core components and functionalities, the complete 3GPP standard provides extensive details on implementation specifics, ensuring scalability, flexibility, and high performance in diverse application scenarios. This paper serves as a foundational guide to understanding LTE's operational framework.



Summary of the LTE Radio Interface

This article provides an overview of the LTE radio interface, emphasizing its recently approved **3GPP standards** and delving into key features that define its functionality and performance. The analysis is supported by simulation data to illustrate LTE's capabilities, concluding with predictions for its future evolution.

Key Features of the LTE Radio Interface

1. **Spectrum Flexibility**:
    - **Description**: LTE supports a wide range of spectrum allocations, ranging from **1.4 MHz to 20 MHz**, making it adaptable for diverse deployment scenarios.
    - **Advantage**: Enables efficient utilization of available spectrum resources across different regions and operator needs.
2. **Multi-Antenna Transmission**:
    - **Description**: Incorporates **MIMO (Multiple Input Multiple Output)** techniques for enhanced data rates and reliability.
    - **Types of Multi-Antenna Techniques**:
        - **Spatial Multiplexing**: Increases data rates by transmitting multiple streams.
        - **Beamforming**: Directs signal energy to targeted users for better performance and reduced interference.
    - **Impact**: Boosts capacity, coverage, and throughput in varied environments.
3. **Inter-Cell Interference Reduction**:
    - **Description**: Addresses interference issues in densely deployed networks, particularly at cell edges.
    - **Techniques Used**:
        - **Fractional Frequency Reuse (FFR)**: Divides the spectrum into regions to limit interference.
        - **Coordinated Multi-Point (CoMP)**: Enhances performance by coordinating transmissions across multiple cells.

Performance Illustration Through Simulation Data

- **Simulation Results**:
    - Highlight LTE's capability to deliver **high throughput**, **low latency**, and **efficient spectrum utilization** under various network conditions.

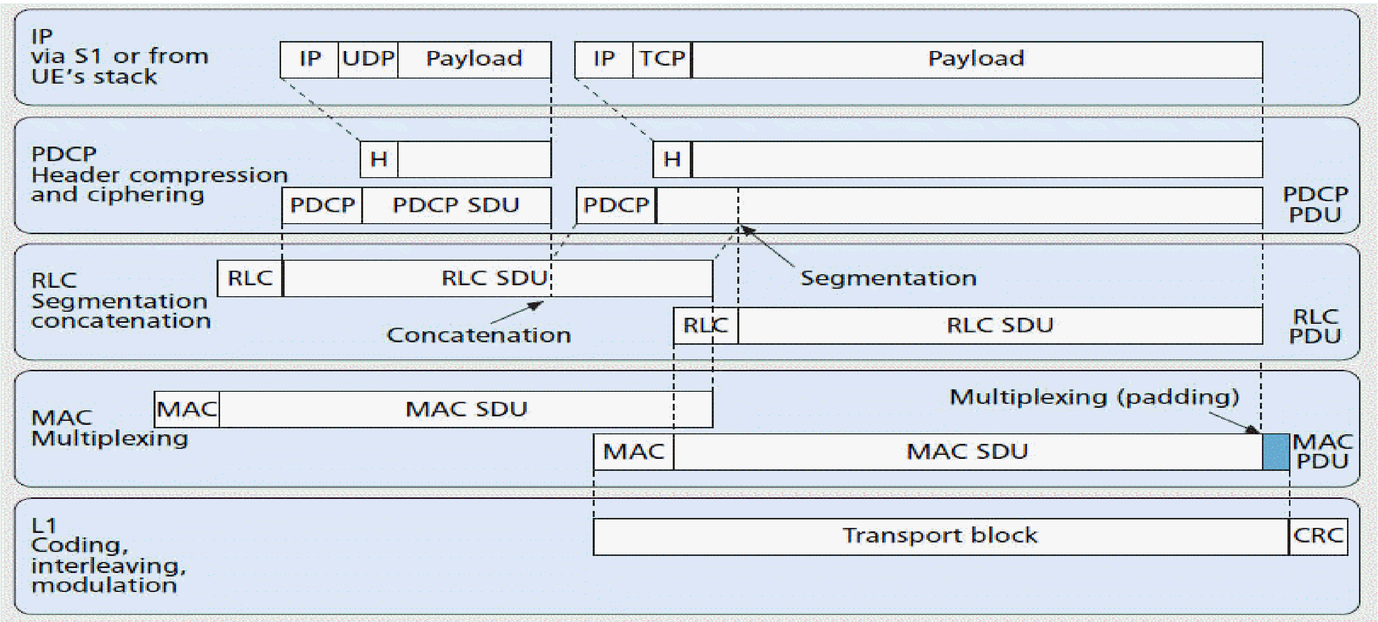
  - Show the benefits of MIMO configurations and interference reduction techniques, particularly in urban and dense deployments.
- **Insights**:
  - LTE performs consistently across different bandwidth allocations.
  - Advanced features like CoMP and beamforming significantly enhance user experiences in challenging scenarios like cell edges.

Future Predictions for LTE Development

1. **Integration with 5G**:
   - LTE will continue to evolve, forming the backbone for early **5G deployments** through technologies like **LTE-Advanced Pro**.
2. **Enhanced Multi-Antenna Capabilities**:
   - Expansion into **Massive MIMO** to support higher capacities.
3. **Increased Spectrum Utilization**:
   - Exploration of unlicensed spectrum and dynamic spectrum sharing for greater flexibility.
4. **Advanced Interference Management**:
   - Adoption of AI-driven coordination for interference reduction in dense networks.

Conclusion

The LTE radio interface is a highly adaptable and efficient technology that has transformed wireless communication. Its features, such as spectrum flexibility, multi-antenna transmission, and interference reduction, make it a robust platform for current and future networks. Simulation data confirms its strong performance, and ongoing advancements will ensure its relevance as part of the 5G ecosystem.



Overview of the LTE Link-Layer Protocols

The LTE radio interface, as specified in **3GPP Release 8**, introduces a set of streamlined **link-layer protocols** designed to abstract the physical layer while meeting the demands of upper-layer protocols. Compared to UTRAN (3G), LTE link-layer protocols are optimized to minimize overhead and latency, ensuring superior performance in modern wireless networks.

Key Characteristics of LTE Link-Layer Protocols

1. **Simplicity and Efficiency**:
   - **Design Philosophy**: Aimed to reduce complexity while maintaining robust functionality.
   - **Result**: Improved latency and reduced protocol overhead compared to legacy systems.
2. **Cross-Layer Optimization**:
   - Developed using a **cross-layer methodology** to ensure seamless interaction between layers.
   - Improves efficiency and performance by enabling protocols to adapt dynamically to varying network conditions.

LTE Protocol Stack Architecture

The LTE link layer is divided into multiple sub-layers, each with specific roles and well-defined interactions:

1. **Physical Layer (PHY)**:

   - Provides the means for transmitting raw bits over the air.
   - Handles key functions such as modulation, coding, and HARQ (Hybrid Automatic Repeat Request).
2. **Medium Access Control (MAC)**:
   - Manages **resource allocation**, **HARQ retransmissions**, and **scheduling requests**.
   - Acts as the intermediary between the physical and higher layers.
3. **Radio Link Control (RLC)**:
   - **Segmentation and Reassembly**: Handles the segmentation of higher-layer packets into manageable sizes for the MAC layer and reassembles received packets.
   - Operates in three modes:
     - **Acknowledged Mode (AM)**: Provides reliable data delivery with retransmissions.
     - **Unacknowledged Mode (UM)**: Focuses on low-latency applications.
     - **Transparent Mode (TM)**: Direct transmission without additional protocol processing.
4. **Packet Data Convergence Protocol (PDCP)**:
   - **Header Compression**: Reduces IP header size for efficient transmission.
   - Ensures **data security** through encryption and integrity protection.
5. **Radio Resource Control (RRC)**:
   - Operates at the control plane, managing UE connection states, handovers, and mobility.
   - Facilitates communication between the core network and the UE.

Key Interactions Between Sub-Layers

- The **cross-layer design** ensures efficient communication between sub-layers:
  1. **MAC and RLC**: The MAC layer allocates resources dynamically based on RLC requirements and network conditions.
  2. **RLC and PDCP**: The RLC layer processes packets from the PDCP layer, ensuring proper delivery even under challenging conditions.
  3. **PHY and MAC**: The PHY layer provides feedback (e.g., CQI, HARQ status) to the MAC layer for adaptive scheduling.

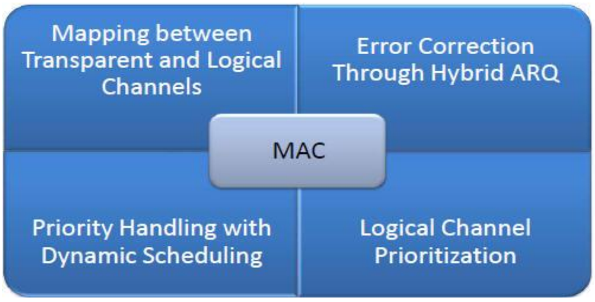
Advantages of the LTE Protocol Architecture

- **Reduced Overhead**: Simplified design minimizes unnecessary signaling and resource usage.
- **Low Latency**: Optimizations in cross-layer interactions and streamlined operations ensure faster data transmission.
- **Scalability**: Supports diverse use cases, from low-latency applications to high-throughput scenarios.
- **Flexibility**: Adaptable to various deployment conditions, such as high mobility or dense urban environments.

Conclusion

The LTE link-layer protocols, as specified in 3GPP Release 8, represent a significant advancement in wireless communication. By abstracting the physical layer and introducing efficient sub-layer interactions, the protocol stack minimizes overhead and latency while enhancing overall system performance. The cross-layer design methodology ensures robust communication, making LTE a highly adaptable and future-ready technology. This explanation simplifies the complexities of the 3GPP specifications, providing a clearer understanding of the LTE protocol stack and its interactions.

3GPP LTE MAC, RLC& PDCP Sub-Layer Presentation



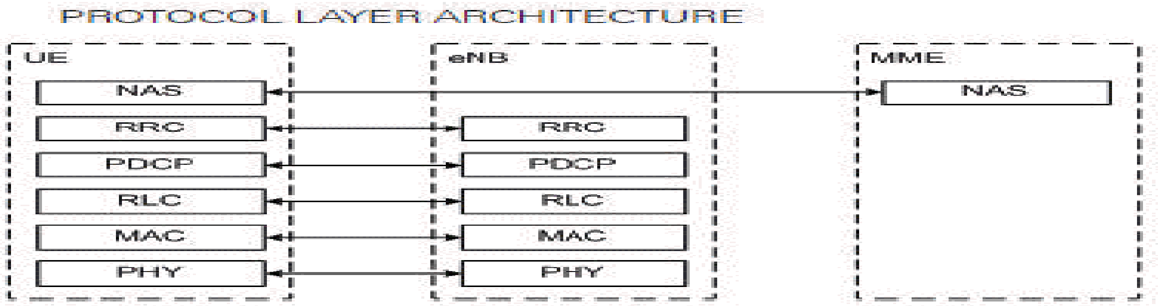


Figure 2: Control plane protocol stack

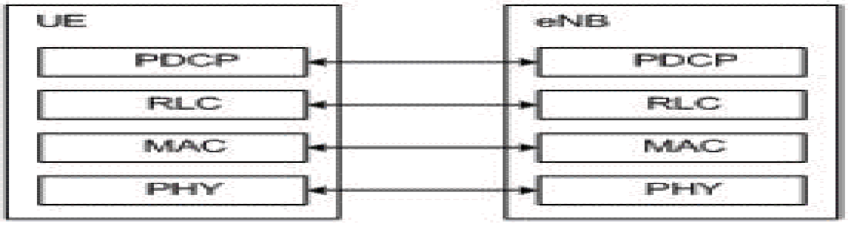


Figure 3.44 LTE protocol stacks(above 6 figures)

This Motorola article provides an outstanding overview of LTE, covering the following key topics:

- **LTE Architecture**
    - Evolution of the Radio Access Network (RAN)
    - Serving Gateway (SGW)
    - Mobility Management Entity (MME)
    - Packet Data Network Gateway (PDN GW)
- **LTE Protocol Stacks**
    - Control Plane Stack
    - User Plane Stack
- **Mobility Management**
- **Evolved Multicast Broadcast Multimedia Services (E-MBMS)**

The Access Stratum (AS) is responsible for user plane signaling, which enables communication between the User Equipment (UE) and the eNodeB. In contrast, the control plane manages Non-AS (NAS) signaling messages exchanged between the UE and the MME, encapsulated within an RRC message. The EPC, Serving Gateway (S-GW), and Packet Data Network Gateway (PDN-GW) operate on the user plane to transmit and receive Internet Protocol (IP) packets.

Key Layer Functions:

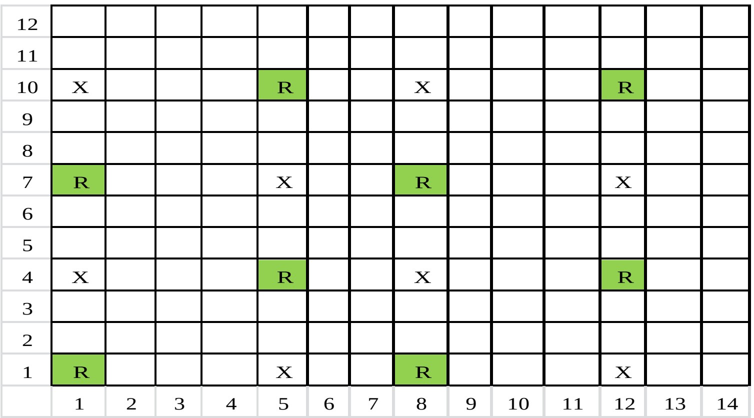
- **Media Access Control (MAC) Layer**:
    - Maps logical channels to transport channels.
    - Multiplexes MAC Service Data Units (SDUs).
    - Provides scheduling information.
    - Handles error correction through HARQ.
    - Manages data priority levels.
- **Radio Link Control (RLC) Layer**:
    - Performs error correction using ARQ.
    - Manages concatenation, segmentation, and reassembly of RLC SDUs.
    - Oversees reordering and duplicate detection.
- **Packet Data Convergence Protocol (PDCP)**:
    - Regulates control plane data flow.
    - Provides ciphering and integrity protection.
- **Radio Resource Control (RRC)**:
    - Handles core control functions within the RAN control plane.
    - Oversees paging and broadcasting system information for both AS and NAS.
    - Manages RRC connectivity between the UE and the EUTRAN.
    - Performs security and mobility management.
    - Manages Quality of Service (QoS) and NAS message transfer.

Downlink Reference Signals:

To enable coherent demodulation at the UE, channel estimation relies on pilot symbols (reference symbols) embedded in the OFDM time-frequency grid.

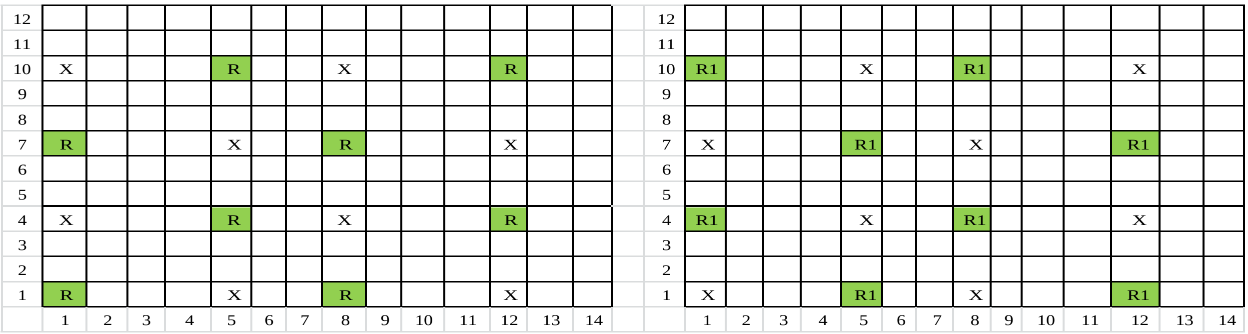
- **Single Antenna Configuration**:
    - Pilot symbols are positioned at the first and third last OFDM symbols within each slot.
    - A three-subcarrier spacing is maintained between the first and second reference symbols in the frequency domain.
    - Each resource block supports four pilot symbols.
- **Two Antenna Configuration**:
    - Pilot symbols for the second antenna are offset by three subcarriers in the frequency domain.
    - Both antennas transmit pilot symbols, with resource elements for one antenna left unused to avoid interference with the other's pilot symbols.

These configurations aim to optimize channel coefficient estimation accuracy. Visual representation of these concepts is provided in Figure 3.45 and accompanying illustrations



12														
11														
10	X				R			X				R		
9														
8														
7	R				X			R				X		
6														
5														
4	X				R			X				R		
3														
2														
1	R				X			R				X		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14

One antenna system pilot symbol arrangements for LTE downlink system .



12														
11														
10	X				R			X				R		
9														
8														
7	R				X			R				X		
6														
5														
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4	R1				X			R1				X		
3														
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1	X				R1			X				R1		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14

Figure 3.45: One port and Two port antenna pilot arrangement for LTE downlink system.

Pilot Symbol Arrangement in Four Antenna Port Configurations

In LTE, the reference signals (RS) serve as **pilot symbols**, enabling the UE to perform channel estimation, synchronization, and cell identification. For configurations involving **four antenna ports**, the arrangement of these pilot symbols differs from those for fewer antenna ports.

Key Aspects of Pilot Symbol Arrangement

1. **Complex Values for Pilot Symbols**:
    - Pilot symbols are **complex values** calculated based on a combination of:
        - **Cell-specific parameters** (e.g., cell identifier).
        - **Signal positioning** within the resource grid.
2. **Cell Identifiers and Reference Signal Sequences**:
    - LTE supports **510 unique cell identities**, each mapped to a specific reference signal sequence.
    - This ensures that each cell has a distinct reference signal pattern, minimizing interference in multi-cell environments.
3. **Four Antenna Port Configuration**:
    - When **four antenna ports** are used, reference signals are distributed across subcarriers and OFDM symbols in a specific pattern to maintain orthogonality and ensure reliable channel estimation.
    - **Antenna Ports**:
        - Ports 0, 1, 2, and 3 are used for transmitting reference signals, with distinct symbol positions for each.

Pilot Symbol Mapping in Four Antenna Ports

- **Resource Grid**:
    - Each antenna port has a unique **resource grid** for its reference signals, ensuring no overlap among ports.
- **Orthogonal Mapping**:
    - Reference signals across the four antenna ports are **orthogonally mapped** to avoid interference.
    - The mapping is influenced by the **cell identifier (ID)** and **positioning rules** defined in the LTE standard.

Purpose of Pilot Symbol Arrangements

1. **Channel Estimation**:
    - The reference signals help the UE estimate the channel conditions for each

antenna port, critical for multi-antenna techniques like MIMO and beamforming.

2. **Cell Identification**:
    - Unique sequences derived from the 510 cell identities enable UEs to distinguish between neighboring cells.
3. **Synchronization and Measurement**:
    - Pilot symbols assist in downlink synchronization and signal quality measurements (e.g., RSRP, RSRQ).

Conclusion

The arrangement of pilot symbols in a four antenna port setup ensures efficient use of the resource grid while maintaining orthogonality and reliability. The integration of **510 unique cell identities** provides a robust framework for multi-cell environments, supporting seamless handovers, interference management, and advanced MIMO capabilities.

3.1.3.5.6 LTE channels, radio resource management (RRM) and bandwidth usage

To facilitate the transfer of various data types over the LTE radio interface, different channels are utilized, ensuring orderly data transmission across the Radio Access Network (RAN). These channels in the LTE protocol hierarchy serve as interfaces to higher protocol layers.

Resource Grid Structure and Resource Block

In LTE, data is organized in a **resource grid**, defined in both frequency and time domains. Key features include:

- **Resource Element (RE):**
    - Smallest unit, representing one symbol and one sub-carrier.
    - Carries 2, 4, or 6 bits of physical channel data, depending on the modulation technique.
- **Resource Block (RB):**
    - Consists of 12 sub-carriers spanning **180 kHz** and lasting **0.5 ms** (one slot).
    - Base stations allocate symbols and sub-carriers in RB units for frequency-dependent scheduling.
- **RB Pair:**
    - Formed by two consecutive RBs that use the same sub-carriers within a given sub-frame.
    - RBs on the downlink resource grid exclude the 0 kHz sub-carrier, instead spanning sub-carrier ranges of **+15 to +180 kHz** and **−15 to −180 kHz**.
    - Avoidance of the 0 kHz sub-carrier is due to high noise and interference levels at that frequency.
- **SC-FDMA Symbol Distribution:**
    - Symbols are dispersed across sub-carriers, reducing susceptibility to interference and minimizing power fluctuations in the SC-FDMA waveform.
    - Despite these challenges, the 0 kHz sub-carrier remains in use for uplink transmissions.

Radio Resource Management (RRM)

RRM ensures efficient use of radio resources while maintaining service quality according to the established **Quality of Service (QoS)** requirements. Various adaptation mechanisms are employed, including:

- **Radio Bearer Control (RBC):** Manages radio bearers for active connections.
- **Radio Admission Control (RAC):** Regulates admission of new users or services

based on resource availability.

- **Connection Mobility Control (CMC):** Oversees mobility between connections.
- **Handover Control (HC):** Manages seamless transitions between cells.
- **Dynamic Resource Allocation (DRA)/Packet Scheduling (PS):** Allocates resources dynamically based on traffic demand.
- **Link Adaptation (LA):** Adjusts modulation and coding schemes to match channel conditions.
- **Power Allocation (PA):** Optimizes power distribution across users and resources.
- **Intercellular Interference Coordination (ICIC):** Reduces interference between neighboring cells.

These techniques work in unison to optimize resource utilization and provide consistent service quality across the network.

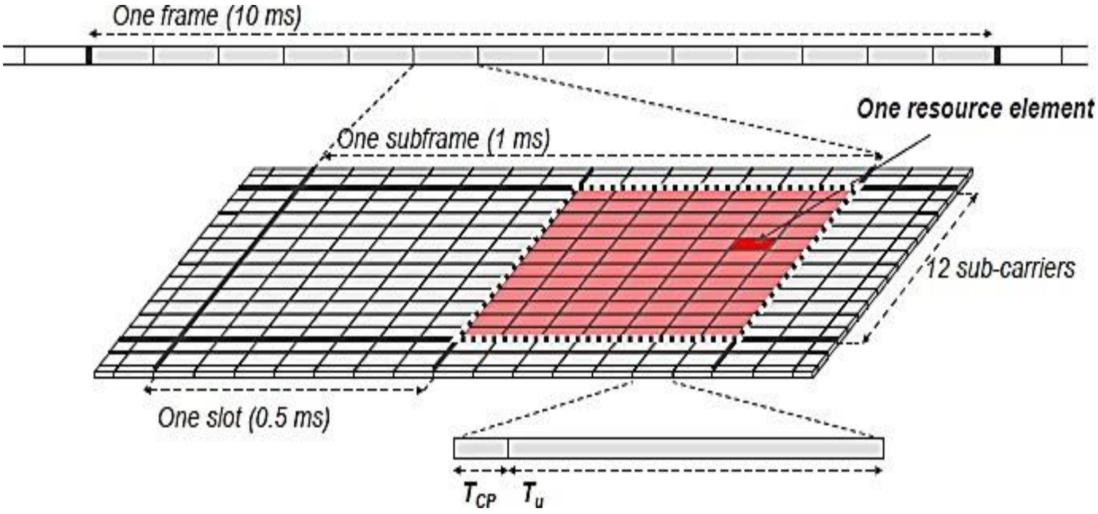


Figure 3:46: Resource grid structure [15]

Bandwidth usage

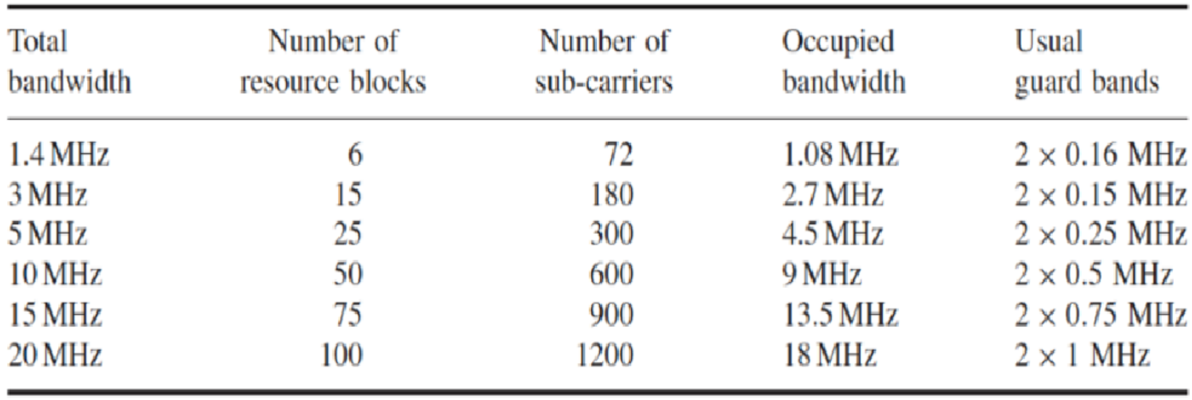
An LTE cell can support multiple bandwidth configurations. In **Orthogonal Frequency Division Multiplexing (OFDM)**, sub-carriers are spaced **15 kHz** apart, meaning the total number of sub-carriers depends on the selected bandwidth. To ensure proper operation and reduce interference, **guard bands** are placed at the edges of the frequency band.

Example of Bandwidth Usage:

- For a **5 MHz** bandwidth configuration:
  - The usable bandwidth is **4.5 MHz** (300 sub-carriers × 15 kHz).
  - The remaining **0.5 MHz** is reserved for two **guard bands** of **0.25 MHz each**, located at the upper and lower frequency edges.

LTE Frequency Division Duplex (FDD):

- LTE FDD typically uses **the same bandwidth for both uplink and downlink** transmissions.
- Common bandwidth options include **1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz**, with **20 MHz** being the most commonly used configuration.



Total bandwidth	Number of resource blocks	Number of sub-carriers	Occupied bandwidth	Usual guard bands
1.4 MHz	6	72	1.08 MHz	2 × 0.16 MHz
3 MHz	15	180	2.7 MHz	2 × 0.15 MHz
5 MHz	25	300	4.5 MHz	2 × 0.25 MHz
10 MHz	50	600	9 MHz	2 × 0.5 MHz
15 MHz	75	900	13.5 MHz	2 × 0.75 MHz
20 MHz	100	1200	18 MHz	2 × 1 MHz

each.

Table 3.7: B.1. Total bandwidth used in LTE

3.2 Technical optimizations of LTE-advanced technology

3.2.1 LTE-advanced system design and optimization techniques for system implementations

LTE-A Enhancements and Performance Criteria

LTE-Advanced (LTE-A) meets the stringent requirements of IMT-Advanced, achieving data rates of **500 Mbps uplink (UL)** and **1 Gbps downlink (DL)** while significantly enhancing spectrum efficiency. The transition from LTE to LTE-A introduces advanced physical-layer technologies and innovative network paradigms, offering improved performance while maintaining compatibility with LTE's channels, RRM, and technical foundations.

RF Specifications and Design Considerations

This section focuses on the RF specifications for an LTE6 User Equipment (UE) transmitter, with particular attention to the I-Q modulator. The I-Q modulator's performance standards are analyzed alongside general characteristics of power amplifiers (PA).

Spectrum Flexibility and Bandwidth

- **LTE Bandwidths:** Supports multiple options, including **1.4, 3, 5, 10, 15, and 20 MHz**.
- **Carrier Aggregation (CA):** Combines bandwidths like **10+20 MHz**, enabling transmission bandwidths up to **40 MHz**—eight times larger than 3G WCDMA's 5 MHz bandwidth.
- **Broadband TX Circuit Design:** The broad spectrum (up to 40 MHz) necessitates innovative broadband techniques.

LTE Frequency Bands

LTE operates within the frequency groups outlined below:

- **Group I:** 699–915 MHz
- **Group II:** 1427.9–2025 MHz
- **Group III:** 2300–2690 MHz
- **Group IV:** 3400–3800 MHz

Handling such a wide range (**0.7–3.8 GHz**) challenges RF design, as the highest frequency exceeds five times the lowest. Adaptive tuning or parallelism in RF circuits is essential for accommodating all uplink frequency bands.

Output Power and Linearity Requirements

- **Transmit Power Levels:**
    - Minimum: **-40 dBm**
    - OFF State: **-50 dBm**
    - Maximum: **23 dBm**
- **Power Amplifier (PA):** With a gain of ~20 dB, the I-Q modulator needs to deliver a peak power of **11–12 dBm**, considering an uplink PAPR of **8.5 dB**.
- **Linearity:** The I-Q modulator must ensure high linearity, minimizing non-linear distortions such as:
    - **Third Harmonic Distortion (HD3)**
    - **Third-Order Intermodulation Product (CIM3)**
      These distortions impact metrics like **Adjacent Channel Leakage Ratio (ACLR)** and **Error Vector Magnitude (EVM)**.

Error Vector Magnitude (EVM)

EVM measures the deviation between the received and ideal constellation points in the modulated signal. Key standards include:

- **BPSK/QPSK:** EVM < **17.5%**
- **16-QAM:** EVM < **12.5%**
  Research suggests that an EVM below **4%** is acceptable when accounting for PA degradation.

The formula for EVM calculation is outlined in the LTE standard, and this study incorporates MATLAB to simulate an LTE/LTE-A environment with an EVM analyzer. Compared to commercial tools like Agilent Signal Studio, this approach provides greater flexibility, such as custom oversampling ratios.

Local Oscillator (LO) Leakage

LO leakage manifests as an unwanted sinusoidal waveform at the carrier frequency (**fc**) in the RF output. Causes include:

- DC offsets in analog baseband circuits.
- LO signal coupling to the TX output.
- I-Q modulator mismatches.

Performance Targets

- LTE standard maximum: **-25 dBc** for high output power.
- Ideal target: **-40 dBc**, accounting for PA imperfections.

Transmitter Design and Analysis

The **MATLAB-based LTE Modulator** simulates QAM generation, signal modulation, and evaluation. Key features include:

- **QAM Constellation:** Generates input symbols for SC-FDMA, supporting formats like **16-QAM**.
- **Flexibility in Testing:** Supports arbitrary oversampling ratios for signal generation and demodulation, surpassing commercial software limitations.
- **EVM and LO Leakage Assessment:** Enables practical evaluation of transmitter non-linearities and modulation quality.

This approach provides insights into optimizing transmitter performance under LTE/LTE-A protocols, ensuring adaptability and compliance with stringent RF requirements.

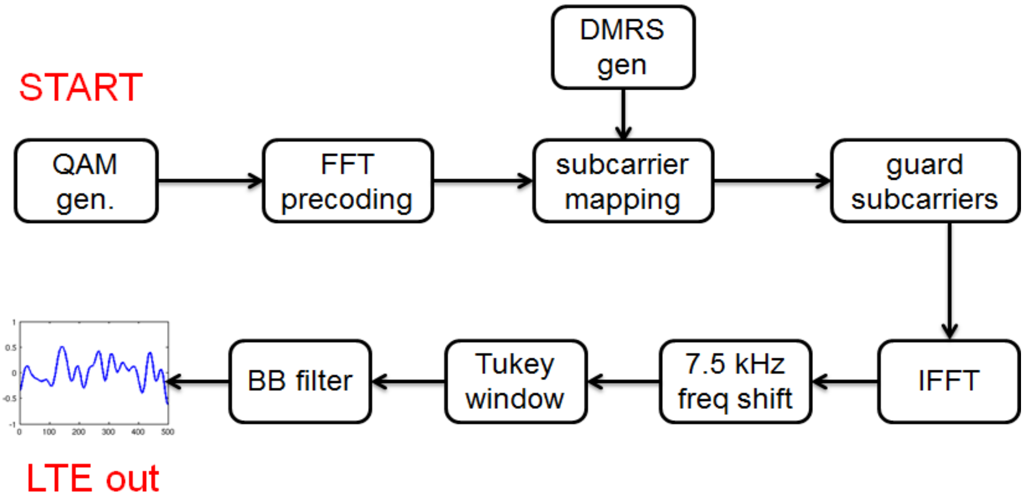


Figure 3.47: Block diagram of the LTE signal generator.

SC-FDMA Signal Processing Steps in LTE Transmitter

1. FFT Transform Pre-Coding

- **Purpose:** Converts groups of input constellation symbols into a frequency-domain representation of the single carrier.
- **Process:** The Fast Fourier Transform (FFT) is applied to the input symbols, enabling efficient single-carrier modulation.

2. DMRS (Demodulation Reference Signal) Generation

- **Purpose:** Produces reference signals for demodulation at the receiver.
- **Method:** DMRS is generated using Zadoff-Chu sequences, as specified in LTE standards. It is sized appropriately for its role in channel estimation and signal alignment.

3. Subcarrier Mapping

- **Process:**
    - **DMRS Assignment:** Allocated to the fourth SC-FDMA symbol in each slot.
    - **Remaining Subcarriers:** The input carrier spectrum occupies the other six symbols per slot.
    - The combined DMRS and input spectrum are mapped to Resource Blocks (RBs), ensuring proper placement in the frequency domain.

4. Guard Subcarrier Insertion

- **Purpose:** Prevents spectral overlap and supports oversampling.
- **Implementation:** Blank Resource Blocks (null subcarriers) are inserted at channel boundaries. The number of guard subcarriers is proportional to the oversampling ratio (OSR).

5. Inverse FFT (IFFT)

- **Purpose:** Converts the frequency-domain signal back into the time domain.
- **Process:** The IFFT is applied to the SC-FDMA symbols, reconstructing the time-domain signal for transmission.

6. Frequency Shift

- **Reason:** A shift of 7.5 kHz (half the subcarrier spacing) is applied to align subcarriers accurately.

- **Implementation:** This adjustment is performed in the time domain.

7. Tukey Windowing

- **Purpose:** Smoothens discontinuities between successive SC-FDMA signals to reduce high-frequency spectral spurs.
- **Effect:**
  - Helps balance Error Vector Magnitude (EVM) and remote noise.
  - Simultaneously generates Cyclic Prefixes (CPs) as part of the windowing process.

8. Baseband FIR Filtering

- **Purpose:** Enhances Adjacent Channel Leakage Ratio (ACLR) and reduces spurious components.
- **Design:**
  - **Filter Type:** FIR equi-ripple design.
  - **Filter Order:** N=70.OSR
  - **Transition Bandwidth:** Center frequency fc=BW/2, width Bc=1.2·BW/20.
- **Effect:** Circular convolution of the time-domain signal with the filter's impulse response ensures spectral cleanliness while preserving circular continuity.

QAM Symbol Organization

- **Input Structure:** Symbols are arranged in an Nsc×6Nslots matrix:
  - Nsc: Number of occupied subcarriers (Nsc=12NRB).
  - Nslots : Number of slots in the LTE frame (typically 20 slots for a full frame).
- **SC-FDMA Symbol Allocation:** Each slot has seven symbols, one reserved for DMRS and six for input carrier data.

Performance Improvements from Filtering

- **ACLR:**
  - Without baseband filtering: ACLR1 = 56 dB (first adjacent channel).
  - With filtering: ACLR1 = 110 dB, providing more headroom for subsequent transmitter stages.
- **Spectrum Comparison:**
  - Self-generated LTE signals (MATLAB) show slightly better high-frequency performance (e.g., reduced spurious power) but may exhibit minor power droop at channel edges compared to commercial tools like Agilent Signal Studio.

Key Metrics

- **EVM Standards:**
  - EVM<17.5% for BPSK/QPSK.
  - EVM<12.5% for 16-QAM.
  - Research indicates EVM<4% is desirable in practical systems.
- **LO Leakage Target:**
  - LTE Standard: LO leakage ≤−25 dBc.
  - I-Q Modulator Ideal: LO leakage≤−40 dBc.

MATLAB Simulation and Implementation

- **Advantages:** Provides flexible signal generation, enabling oversampling ratios beyond commercial tool limitations.
- **Output:** Simulated LTE signals meet 3GPP specifications with improved spurious

performance and ACLR, supporting efficient RF front-end operation.

Optimization Techniques in LTE-Advanced

LTE-Advanced (LTE-A) employs several innovative optimization techniques to meet system requirements, enhance capacity, and improve user experience. Key approaches include **Heterogeneous Networks (HetNets), Coordinated Multi-Point Transmission/Reception (CoMP)**, Carrier Aggregation (CA), and others. Below is a detailed explanation of these methods:

3.2.1.1 Heterogonous networks(HetNets)

HetNets integrate macro cells with smaller cells such as pico-cells, femto-cells, relay stations, and remote radio heads to improve capacity, extend coverage, and enhance network efficiency.

Characteristics and Functionality:

- **Macro Cells**: Provide larger coverage areas (300–2000 m radius) with higher Signal-to-Interference-and-Noise Ratios (SINR).
- **Femto-Cells**: Offer short-range (10–50 m), low-power indoor coverage, with backhaul via DSL or cable modems.
- **Relay Stations (RS)**: Function like femto-cells but use a wireless backhaul.
- **Pico-Cells**: Positioned to handle local traffic loads and complement macro cells.

Key Challenges:

1. **Inter-Cell Interference**: Power disparities between macro and smaller cells cause interference.
2. **Cross-Tier Interference**: Traffic distribution across different cell types can result in unpredictable interference.
3. **Mobility Issues**: High mobility users frequently switching between small cells can disrupt service continuity.

Solutions:

- Enhanced inter-cell interference coordination (eICIC) and further eICIC (FeICIC) reduce interference using techniques like **Almost Blank Subframes (ABS)**.
- Load balancing strategies based on Reference Signal Received Power (RSRP) or Quality (RSRQ).
- Adaptive small cell activation/deactivation based on traffic load.

Features of HetNets:

- **Offloading**: Traffic is shifted from macro cells to small cells by adjusting the RSRP bias of small cells.
- **Mobility Management**: Handovers are optimized with cell-specific parameters and speed-based associations for high mobility UEs.
- **Cost-Effectiveness**: HetNets support high Quality of Experience (QoE) with lower deployment costs compared to traditional macro-only networks.

3.2.1.2 Coordinated Multi Point Transmission/Reception(CoMP)

CoMP enhances throughput and coverage, especially for cell-edge users, by enabling cooperation among multiple base stations (eNodeBs).

Types of CoMP:

1. **Joint Processing (JP)**:
    - Data is transmitted simultaneously to a UE from multiple points.
    - Includes **coherent transmission** (phase-aligned signals) and **non-coherent transmission** (soft combining at the receiver).
2. **Coordinated Scheduling/Beamforming (CS/CB)**:
    - Involves collaboration on scheduling and beamforming decisions to reduce interference.

Deployment Scenarios:

- **Intra-Site CoMP**: Coordination within a single eNodeB site using high-power remote radio heads (RRHs).
- **Inter-Site CoMP**: Coordination across different eNodeB sites, often with low-power RRHs.

Implementation Considerations:

- **Backhaul Requirements**: High-speed backhaul links are essential for real-time coordination between eNodeBs.
- **Channel Information**: Accurate channel state information (CSI) is required for optimal transmit filter design.

Benefits:

- Improves spectral efficiency and reduces inter-cell interference.
- Enhances throughput for cell-edge users.
- Provides better load balancing by utilizing resources across multiple transmission points.

Additional Optimization Techniques:

Carrier Aggregation (CA):

- Combines multiple frequency bands to create a larger effective bandwidth, supporting higher data rates and efficient spectrum usage.

Self-Optimizing Networks (SON):

- Automates network configuration, fault management, and performance optimization.

Advanced MIMO Systems:

- Utilizes multiple antennas for improved spatial diversity and capacity, supporting features like massive MIMO and beamforming.

Key Metrics and Techniques in HetNet and CoMP:

Interference Management:

- HetNet employs eICIC and FeICIC to manage inter-cell and cross-tier interference.
- CoMP uses advanced coordination and joint transmission to minimize interference.

Load Balancing:

- HetNet employs adaptive cell activation and traffic offloading techniques to distribute load efficiently.
- CoMP balances load by allowing simultaneous connections to multiple cells.

Mobility Management:

- HetNet adapts handover parameters based on cell-specific and UE-specific factors.
- CoMP enables smooth transitions for UEs by coordinating decisions across cells.

Quality of Service (QoS):

- HetNet and CoMP improve user experience by ensuring consistent connectivity, even at cell edges.

By integrating these advanced techniques, LTE-Advanced achieves higher capacity, better spectral efficiency, and enhanced user experience, paving the way for future 5G networks.

3.2.1.3 Carrier Aggregation in LTE-Advanced

Carrier Aggregation (CA) is a key feature in LTE-Advanced, enabling the combination of multiple carrier frequencies, or **Component Carriers (CCs)**, to enhance overall bandwidth and increase data rates. This allows **User Equipment (UEs)** to connect to multiple carriers simultaneously, improving efficiency and performance.

Key Features of Carrier Aggregation:

1. **Simultaneous Connection to Multiple Carriers**:
    - UEs can access several CCs concurrently, distributing resources across carriers and facilitating rapid carrier switching without lengthy handovers.
2. **Control Information Allocation**:
    - The **Primary Component Carrier (PCC)** handles control information such as **PDCCH**, **PCFICH**, **PHICH**, and others.
    - Secondary Component Carriers (SCCs) are scheduled using **cross-carrier scheduling**, enabling the PCC to schedule UEs on SCCs.
3. **Bandwidth Flexibility**:
    - Each CC can have a bandwidth of **1.4, 3, 5, 10, 15, or 20 MHz**, and up to five CCs can be aggregated for a maximum bandwidth of **100 MHz**.
4. **Backward Compatibility**:
    - Release 8/9 UEs can access individual CCs provided by the eNodeB, ensuring compatibility with earlier LTE versions.
    - Release 10 UEs can aggregate two or more CCs for both **downlink (DL)** and **uplink (UL)**.

Modes of Operation:

Frequency Division Duplex (FDD):

- The number of **UL CCs** is always equal to or fewer than the number of **DL CCs**.
- Aggregated carriers in DL and UL can vary.

Time Division Duplex (TDD):

- Each CC typically has identical bandwidth and configuration in both DL and UL.

Advantages of Carrier Aggregation:

1. **Increased Bandwidth**:

  - CA allows simultaneous use of multiple frequency bands, effectively boosting the available bandwidth for UEs.

2. **Enhanced Data Rates**:
   - Combining CCs supports higher throughput, meeting the demands of bandwidth-intensive applications.
3. **Resource Optimization**:
   - Cross-carrier scheduling minimizes interference, particularly in Heterogeneous Networks (HetNets), by allocating control and data channels intelligently across layers.
4. **Seamless Operation**:
   - Rapid carrier switching avoids handover delays, ensuring smooth connectivity and efficient network usage.

Applications in Network Design:

Carrier aggregation is crucial for maximizing spectrum utilization, especially in environments where multiple frequency bands are available. It also supports advanced features like **HetNets**, where different CCs can be assigned to macro and small cells to reduce interference and improve load distribution.

By aggregating carriers, LTE-Advanced networks achieve both higher capacity and greater flexibility, paving the way for advanced applications and improved user experiences.

Types of Carrier Aggregation (CA)

Carrier Aggregation (CA) in LTE-Advanced is classified based on how Component Carriers (CCs) are combined, allowing for flexibility and optimized spectrum utilization. The two main types of CA are **Intra-Band** and **Inter-Band** CA.

. Intra-Band Carrier Aggregation

This type aggregates CCs within the same frequency band and is further divided into:

a. Contiguous CA:

- **Description**: Component Carriers are adjacent to each other in the frequency spectrum.
- **Use Case**: Simplest configuration for CA, requiring minimal adjustments in hardware like RF front-end design.
- **Applicability**: Used when a single frequency band can provide sufficient bandwidth (e.g., exceeding 20 MHz).

b. Non-Contiguous CA:

- **Description**: Component Carriers are within the same band but separated by unused frequencies.
- **Use Case**: Employed when contiguous spectrum is unavailable within a band but still provides intra-band aggregation advantages.

2. Inter-Band Carrier Aggregation

- **Description**: Combines CCs from different frequency bands.
- **Use Case**: Ideal for networks with fragmented spectrum allocations across multiple bands.
- **Advantages**:
    - Maximizes spectrum utilization across non-contiguous bands.
    - Improves overall capacity and user data rates.
- **Challenges**: Requires more complex RF hardware, as different bands often have varying propagation characteristics and hardware requirements.

Summary of CA Types:

Type	Configuration	Use Case	Complexity
Intra-Band Contiguous	Adjacent CCs within one band	Simplest and most efficient configuration	Low
Intra-Band Non-Contiguous	Non-adjacent CCs within one band	Useful when contiguous spectrum is unavailable	Moderate
Inter-Band	CCs from different bands	Optimal for fragmented spectrum allocations	High

These CA configurations, as depicted in **Figure 3.54**, enable LTE-Advanced networks to achieve bandwidths greater than 20 MHz, fulfilling diverse deployment needs and supporting higher data rates.

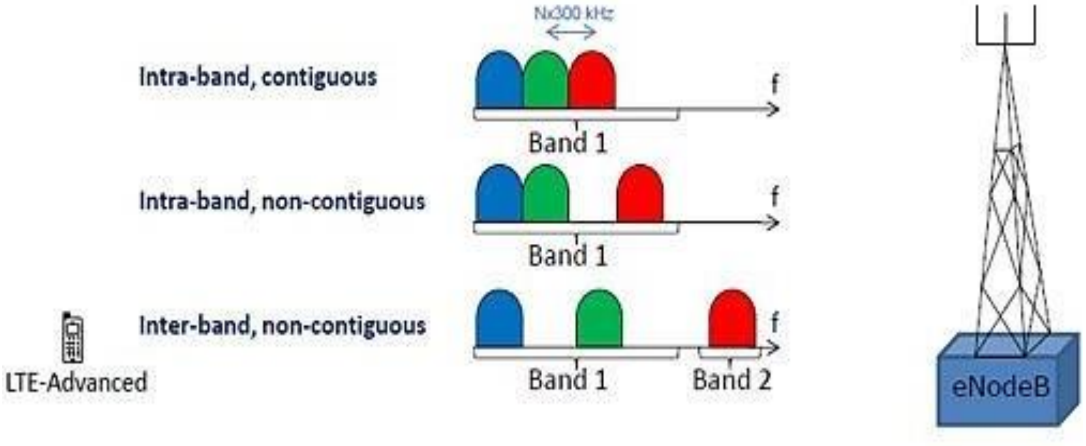


Figure 3.54: CA types [30, 3GPP]

Carrier Aggregation (CA) Configuration in LTE-Advanced

Carrier Aggregation (CA) configurations define the structure, spacing, and capabilities for combining multiple Component Carriers (CCs). These configurations ensure efficient spectrum utilization and compatibility with existing LTE standards.

Frequency Spacing Rules and Alignment:

1. **Contiguous CA**:
   - **Spacing**: Successive CCs must maintain a frequency spacing of **N × 300 kHz**, where NN is an integer.
   - **Reason**: This spacing ensures alignment with the **15 kHz subcarrier grid** and the **100 kHz frequency-numbering system**, allowing a single **Fast Fourier Transform (FFT)** to process multiple CCs.
   - **Advantage**: Simplifies receiver design by avoiding the need for separate FFTs for each CC.
2. **Non-Contiguous CA**:
   - **Spacing**: Requires at least one frequency gap between CCs.
   - **Flexibility**: Facilitates aggregation of fragmented spectrum across intra-band or inter-band configurations.

Restrictions and Capabilities:

1. **Intra-Band Carrier Aggregation**:
   - **Limitations**: Restricted to **two CCs** within the same band (e.g., Band 1).
   - **Alignment**: CCs must align on the same **15 kHz subcarrier grid** for efficient FFT processing.
2. **Inter-Band Carrier Aggregation**:
   - **Release 10**: Initially limited to bands **1 and 5**.
   - **Subsequent Releases**: Expanded support for additional bands to accommodate diverse spectrum scenarios.

CA Bandwidth Class and Terminology:

The **CA bandwidth class** categorizes UEs based on their ability to aggregate a specific number of CCs and total bandwidth. This classification supports precise configuration and communication about a UE's capabilities.

1. **Key Terms**:
    - **Aggregated Physical Resource Blocks (PRB)**: Total PRBs allocated across aggregated CCs.
    - **Aggregated Transmission Bandwidth Configuration (ATBC)**: Specifies the total usable bandwidth across all CCs in the CA configuration.
2. **Purpose**:
    - Enables standardized descriptions of radio interface configurations.
    - Facilitates coordination between network elements and UEs for CA deployment.

Summary:

The **spacing, alignment, and terminology** associated with Carrier Aggregation ensure compatibility and efficiency in LTE-Advanced networks. By adhering to spacing multiples (300 kHz for contiguous CA) and leveraging grid alignment, CA configurations maximize spectral efficiency while minimizing receiver complexity. These principles, combined with expanded inter-band CA options in newer 3GPP releases, provide the foundation for enhanced broadband capabilities.

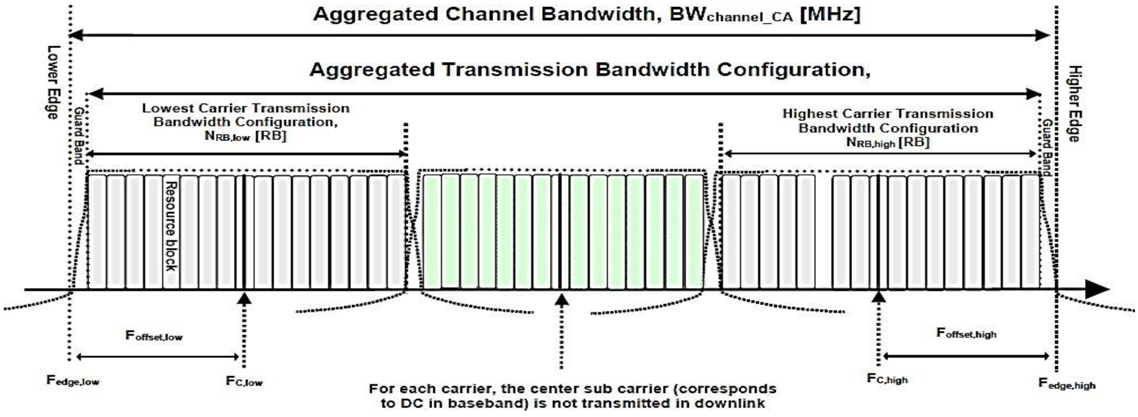


Figure 3.55: Definition of Aggregated channel bandwidth [3GPP R'14]

Intra-Band Contiguous Carrier Aggregation (CA) Overview

In **intra-band contiguous carrier aggregation**, the **Carrier Aggregation Bandwidth Class** for User Equipment (UE) is defined by:

1. The number of **Component Carriers (CCs)** the UE supports.
2. The **Aggregated Transmission Bandwidth Configuration (ATBC)** or **Number of Aggregated Resource Blocks (NRB_agg)**.

Bandwidth Classifications

- **Bandwidth Classes (A, B, C):**
  Defined in Releases 10 and 11 for CA configurations. These classes specify the supported aggregated bandwidth.
- **Future Expansions:**

Release 14 (3GPP R'14) introduced new bandwidth classes, expanding CA capabilities.

UE Reporting of CA Capabilities

During the **Evolved Packet System (EPS) bearer access process**, the UE communicates its CA capabilities to the network, including:

1. **Frequency Band Parameters**: DL and UL specifications for each band.
2. **CA Configuration Sets**:
    - Indicates the distribution of resource blocks across aggregated CCs.
    - For example, **CA_1C** specifies a UE's ability to operate on Band 1 with a maximum of **200 resource blocks** across two CCs.

Combination Sets for Carrier Aggregation

- **Intra-Band Combination Sets**:
  Defined by the **number of contiguous resource blocks** allocated to each CC.
- **Inter-Band Combination Sets**:
  Determined by the **channel bandwidth** occupied across different bands rather than the number of resource blocks.

Base Station Roles and Serving Cells

Serving Cells in Carrier Aggregation:

- **Primary Serving Cell (PCC)**:
    - Handles the **Radio Resource Control (RRC)** link for both DL and UL.
    - Manages critical operations such as NAS data transmission, security parameters, and **Physical Uplink Control Channel (PUCCH)** communications.
    - In idle mode, the UE monitors system information via the DL PCC.
- **Secondary Serving Cells (SCCs)**:
    - Correspond to additional CCs in both DL and UL.
    - Dynamically added or removed based on traffic requirements.
    - SCCs handle supplementary data transmission while the PCC retains primary control, except during handovers.

Impact of CA on Coverage:

- CCs across different frequency bands experience varying **path losses**.
    - Higher frequencies typically result in greater path losses and reduced coverage.
    - Lower frequency CCs provide wider coverage, while higher frequency CCs support localized high-capacity areas.
- **Coverage Scenarios**:
    - UEs may connect to different CCs based on their location.
    - For example, a UE outside the coverage of a higher-frequency CC will rely on

lower-frequency CCs for connectivity.

Illustrative Configuration of CA (Figure 3.56)

- **Multiple Serving Cells**:
  - Each CC acts as a serving cell with its coverage area.
  - Different UEs may utilize varying combinations of CCs depending on their location and the available coverage.
- **Example**:
  - **Black UE**: Connected to three CCs.
  - **White UE**: Falls outside the coverage of one CC (red) but remains connected via the other two CCs.

Key Takeaways

1. **Control and Management**:
   - The PCC is responsible for all primary control operations and NAS data management. SCCs supplement this by handling additional traffic.
2. **Dynamic Adaptation**:
   - SCCs are added or removed dynamically to optimize resource allocation.
3. **Coverage Optimization**:
   - Different frequency bands and CCs are leveraged to balance coverage and capacity.
   - Lower frequencies provide broader coverage, while higher frequencies offer localized high-capacity areas.

By integrating multiple serving cells and dynamically managing resources, **Carrier Aggregation** in LTE-Advanced maximizes bandwidth utilization and ensures efficient connectivity across varying network conditions.

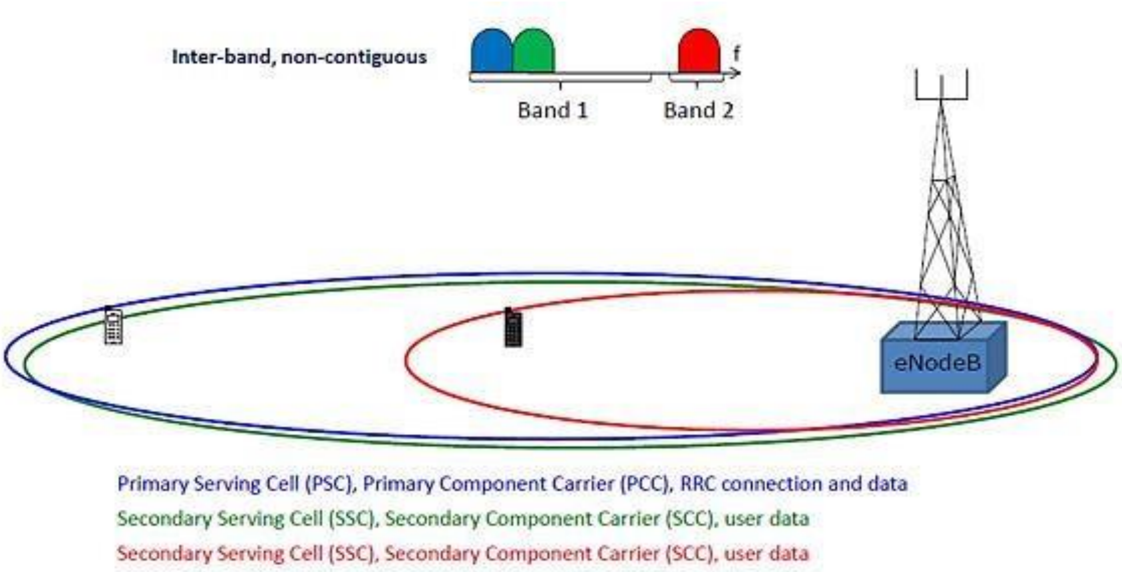
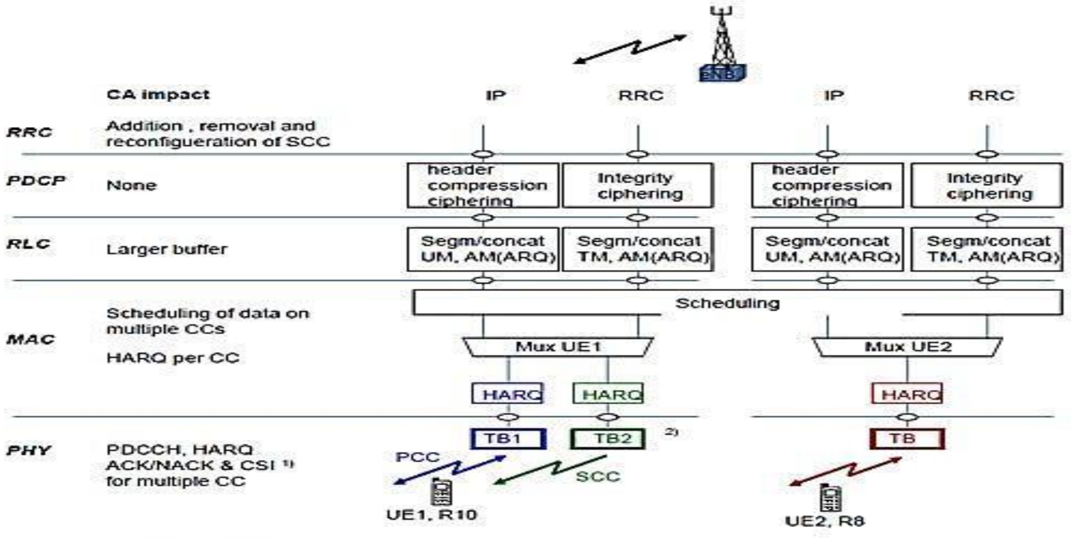


Figure 3.56: Primary and Secondary serving cells

Impact of carrier aggregations in signaling, MAC and scheduling

Additional RRC messages must be introduced in carrier aggregations to handle SCC; MAC scheduling is necessary to take use of CCs that affect the physical layer protocol and MAC [30, 34].



1) CSI = Channel State Information, provided on the UL by UE
2) There will be 1 TB per CC, unless spatial multiplexing is used.

Figure 3.57: Shows change of protocols due to CA

Signaling and Resource Management in Carrier Aggregation (CA)

Carrier Aggregation (CA) maintains compatibility with Release 8/9 (R'8/R'9) by minimizing signaling changes, as each Component Carrier (CC) is treated as an R'8 carrier. However, CA introduces enhancements to certain protocol layers, primarily in the **physical**, **medium access control (MAC)**, and **radio resource control (RRC)** layers.

Signaling Enhancements and Protocol Changes

1. **Physical Layer Modifications**:

   - **Downlink (DL)**:
      - Provides scheduling information for each CC.
      - Transmits **HARQ ACK/NACK** for individual CCs.
   - **Uplink (UL)**:
      - Acknowledges HARQ on a per-CC basis.
2. **Primary and Secondary Cells**:
   - **Primary Cell (PCC)**:
      - Manages the **NAS process**, key exchange, and mobility.
      - Facilitates signaling for resource scheduling on **secondary cells (SCCs)**.
   - **Secondary Cells (SCCs)**:
      - Viewed as additional resources for data transfer.
      - Controlled through PCC signaling, especially in cross-carrier scheduling scenarios.
3. **Protocol Transparency**:
   - **PDCP and RLC Layers**:
      - Unaffected by CA; signaling is transparent at these layers.
   - **RLC Buffer Modifications**:
      - Requires increased buffer capacity for higher data rates.
      - Buffer size specifications are outlined in **TS 36.306 (Table 2.5)**.
4. **MAC Layer**:
   - Adds support for multiple CCs, allowing multiplexing across aggregated carriers.
   - Each CC operates with its own **channel coding, HARQ process, modulation, and resource mapping**.

Resource Scheduling and Cross-Carrier Scheduling

1. **Same-Carrier Scheduling**:
   - Scheduling occurs on the carrier assigned to the UE.
   - Resources are managed independently for each CC.
2. **Cross-Carrier Scheduling** (optional, introduced in Release 10):
   - Enables the PCC to schedule resources on SCCs without a **PDCCH**.
   - Uses the **Carrier Indicator Field (CIF)** in the **Downlink Control Information (DCI)** to indicate the carrier handling the scheduling.
   - The PCC must send cross-scheduling information via its own PDCCH.
3. **PDCCH-Start**:
   - When cross-carrier scheduling is activated, this mechanism informs the UE of the number of **OFDM symbols** at the start of each subframe on SCCs.
   - Varies between **1 to 4 symbols** depending on CC bandwidth.

Implementation Scenarios for CA

1. **Intra-Band Contiguous CA**:
   - Aggregates CCs within a single operating band with adjacent frequencies.
   - Simplest configuration, processed as a single multicarrier signal by the UE.
2. **Intra-Band Non-Contiguous CA**:
   - Aggregates CCs within a single band but separated by gaps.
   - Requires enhanced signal processing to manage frequency gaps.
3. **Inter-Band CA**:
   - Aggregates CCs from different frequency bands, offering greater spectrum flexibility but increased complexity for UEs.
   - Requires separate processing for each carrier due to differences in propagation characteristics.

Inter-Band CA Implementation Options

1. **Low-High Band Aggregation**:
    - **Purpose**: Combines the coverage benefits of low-band frequencies with the capacity and throughput advantages of high-band frequencies.
    - **Example**: **CA_4A-12A**:
        - Combines Band 4 (high band) and Band 12 (low band) for up to 30 MHz bandwidth.
        - Band 12 ensures broader coverage, while Band 4 supports higher data rates.
    - **Challenge**:
        - Differences in **coverage and site density** between bands can limit efficiency.

Advantages of CA in Resource Allocation:

1. **Enhanced Data Rates**:
    - Aggregates bandwidth to achieve higher throughput.
2. **Efficient Spectrum Utilization**:
    - Combines fragmented spectrum resources, enabling flexibility in deployment.
3. **Dynamic Resource Allocation**:
    - Cross-carrier scheduling and SCC addition/removal optimize resource use.
4. **Compatibility with Existing Networks**:
    - Maintains compatibility with legacy systems while providing advanced CA capabilities.

LTE-Advanced: Achieving High-Capacity Broadband with Flexibility and Compatibility

LTE-Advanced strikes a balance between **backward compatibility** with earlier LTE standards and the demands for **high-capacity broadband performance**. This is achieved through the combination of the following key features:

1. Signaling Optimizations

- **Streamlined Control Signaling**:
    - Reduced signaling overhead improves efficiency, enabling faster data transmissions and reduced latency.
    - Optimizations in protocols like **RRC (Radio Resource Control)** and **MAC** ensure robust and adaptive communication.
- **Efficient Handover Mechanisms**:
    - Enhanced signaling for mobility management ensures seamless handovers between cells and technologies, even at high speeds.

2. Resource Scheduling Flexibility

- **Dynamic Resource Allocation**:
    - The MAC scheduler dynamically assigns resources based on real-time channel conditions, Quality of Service (QoS) requirements, and user demands.
- **Support for Diverse Use Cases**:
    - From low-latency applications to high-throughput services, flexible resource scheduling adapts to the specific needs of each use case.
- **Multi-User MIMO (MU-MIMO)**:
    - Efficient resource sharing among users through MU-MIMO enhances spectral efficiency, particularly in dense network environments.

3. Carrier Aggregation (CA) Configurations

- **Increased Bandwidth**:

  - By aggregating multiple carriers, LTE-Advanced supports bandwidths up to **100 MHz**, delivering higher data rates.
- **Backward Compatibility**:
  - Ensures interoperability with earlier LTE networks, allowing legacy devices to operate alongside LTE-Advanced users.
- **Diverse Configurations**:
  - CA supports both **contiguous** and **non-contiguous** spectrum allocation across frequency bands, maximizing spectrum utilization.

Conclusion

By integrating **optimized signaling**, **flexible resource scheduling**, and **advanced carrier aggregation**, LTE-Advanced provides a future-ready framework for broadband services. It delivers high data rates and low latency while maintaining seamless compatibility with earlier LTE technologies, supporting the evolution toward 5G and beyond.

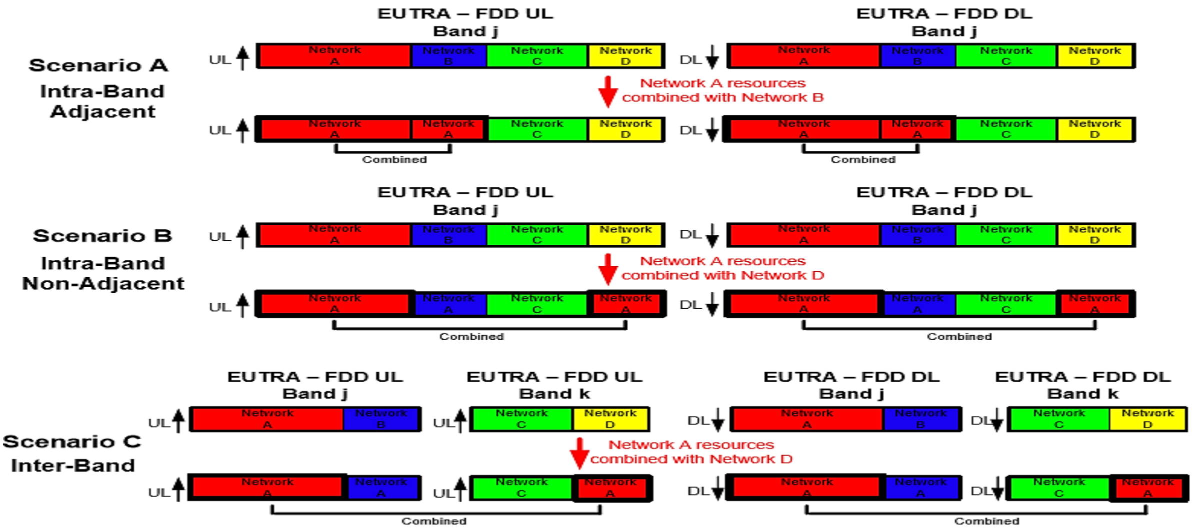


Figure 3.58: intra and inter CA

Frequency Band Considerations in Carrier Aggregation (CA)

Carrier Aggregation (CA) deployments must balance the trade-offs between **lower frequency bands** (e.g., 700 and 850 MHz) and **higher frequency bands** to optimize coverage, capacity, and efficiency.

Lower Frequency Bands

1. **Advantages**:
   - **Enhanced Coverage**:
     - Lower frequencies propagate further and penetrate obstacles better, providing extensive coverage in rural and indoor areas.
   - **Reliable Capacity**:
     - Though throughput and capacity are lower compared to higher frequencies, these bands remain consistent across varying cell sizes.

2. **Use Case**:
    - Ideal for broad coverage in less densely populated regions or as a fallback for network continuity.

Higher Frequency Bands

1. **Advantages**:
    - **High Throughput and Capacity**:
        - Higher frequencies offer significantly greater bandwidth, making them ideal for urban areas with high user density.
2. **Challenges**:
    - **Limited Coverage**:
        - Reduced propagation range and poor penetration capabilities necessitate additional base stations to achieve desired area coverage.
    - **Increased Hardware Complexity**:
        - Managing overlapping radio signals across multiple RF units demands sophisticated UE hardware, increasing:
            - Weight and dimensions.
            - Complexity and manufacturing costs.
    - **Interference Issues**:
        - Operating multiple transmitters and receivers simultaneously in close proximity can cause:
            - **Cross-Modulation**: Unwanted mixing of signals from different bands.
            - **Intermodulation**: Harmonics generated by nonlinearities in RF components.

Optimizing Frequency Spectrum Utilization

1. **Current Limitations**:
    - **Suboptimal Resource Usage**:
        - Existing CA implementations often fail to maximize combined band utilization.
        - Saturating a single band can deliver higher data rates compared to spreading resources thin across multiple bands.
2. **Recommended Strategies**:

- **Collaborative Planning**:
  - Partner with **RAN infrastructure providers** and **device/chipset manufacturers** to align deployment strategies with hardware capabilities.
- **Efficient Resource Allocation**:
  - Design CA solutions that dynamically prioritize underutilized resources while avoiding unnecessary hardware complexity.
- **Performance Assessment**:
  - Regularly evaluate resource utilization and throughput across aggregated bands to identify and address inefficiencies.

Conclusion

Balancing the strengths of lower frequencies (coverage) with those of higher frequencies (capacity) is essential for effective CA deployment. Collaboration among operators, infrastructure providers, and device manufacturers is critical to overcoming hardware complexities and achieving optimal spectrum utilization while maintaining cost efficiency.

3.2.1.4 MIMO in LTE-Advanced

Multiple-Input Multiple-Output (MIMO) technology utilizes multiple antennas at both the transmitter and receiver to enhance the spectral efficiency, throughput, and reliability of wireless communication systems. In LTE-Advanced, MIMO is a key enabler of high performance, supporting advanced configurations like **8x8 spatial multiplexing**.

Features of MIMO in LTE-Advanced

1. **Spectral Efficiency**:
   - LTE-Advanced achieves a peak **spectral efficiency of 30 bps/Hz** using 8x8 MIMO spatial multiplexing.
   - This level of efficiency is crucial for high-speed data transfer in modern wireless networks.
2. **Closed-Loop Pre-Coding**:
   - LTE-Advanced employs a **closed-loop pre-coding method** that optimizes the transmission based on channel feedback.
   - **Codebook-Based Pre-Coding**:
     - The pre-coding design uses a codebook tailored for **cross-polarized antennas**, improving performance under diverse channel conditions.
     - The codebook matrix is defined as the product of two matrices: W1W2W1W2
       - **W1W1**: Represents long-term, wideband channel characteristics.
       - **W2W2**: Represents short-term, frequency-selective channel characteristics.
3. **Codebook Elements**:
   - **α\alpha**: Phase difference between horizontal and vertical antenna groups in a cross-polarized array.
   - **bi**: Column vectors from an extended Fourier transform matrix.
   - **ej**: Selection vector with only one non-zero element, corresponding to the active column.

Advantages of MIMO in LTE-Advanced

1. **Enhanced Data Throughput**:
    - With 8x8 MIMO, LTE-Advanced doubles the peak data rates compared to earlier releases, such as Release 8.
2. **Improved Spectral and Energy Efficiency**:
    - Efficiently utilizes spectrum resources while reducing energy consumption.
3. **Better Cell Edge Coverage**:
    - MIMO improves signal quality for users at the edge of cells, ensuring reliable connectivity.
4. **Increased Channel Capacity**:
    - Supports higher numbers of simultaneous data streams, crucial for high-density networks.
5. **Advanced Channel State Information (CSI)**:
    - Facilitates precise channel estimation, allowing adaptive transmission strategies.

Technologies Complementing MIMO in LTE-Advanced

1. **Carrier Aggregation (CA)**:
    - Combines multiple frequency bands to expand bandwidth, complementing MIMO's throughput capabilities.
2. **Enhanced MIMO (eMIMO)**:
    - Increases efficiency by leveraging advanced antenna configurations and better CSI acquisition.

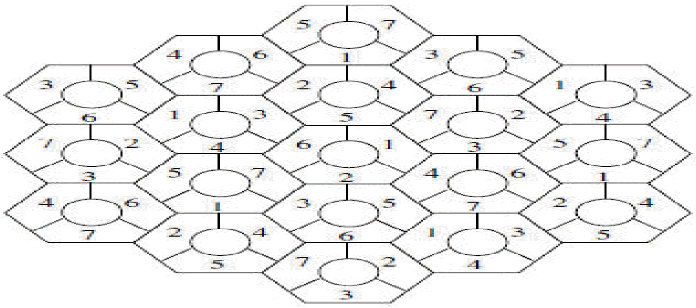
Impact of 8x8 MIMO in Release 10

- **Throughput Improvement**:
    - Achieves twice the peak data throughput compared to Release 8, making it suitable for bandwidth-intensive applications like video streaming and 5G precursor technologies.
- **Future Proofing**:
    - Sets the foundation for even more advanced MIMO techniques in subsequent LTE and 5G standards, ensuring scalability for future network demands.

Conclusion

By integrating **8x8 MIMO** with **codebook-based pre-coding** and complementary technologies like CA, LTE-Advanced achieves significant enhancements in capacity, coverage, and efficiency. This makes it a cornerstone of modern high-speed wireless communication systems.

Dynamic Radio Resource Management in 3GPP LTE



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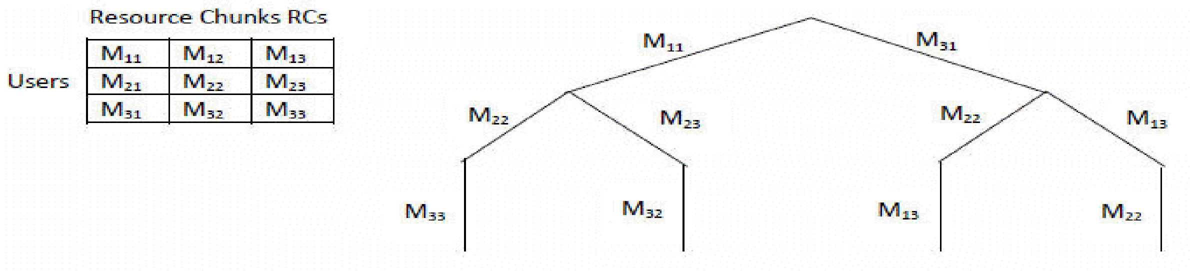
Comparison of channel dependent scheduling policies in LTE uplink



Resource Chunks RCs

Users			
	M_{11}	M_{12}	M_{13}
	M_{21}	M_{22}	M_{23}
	M_{31}	M_{32}	M_{33}

Figure 3.59: Analysis of different radio resource management and frequency reuse techniques in LTE

Evaluation of SC-FDMA Scheduling Strategies in LTE Uplink

This study examines three scheduling strategies for **Single-Carrier Frequency Division Multiple Access (SC-FDMA)** in the LTE uplink, highlighting their performance under varying conditions. The focus is on balancing throughput, fairness, and computational complexity.

1. Search-Tree Based Algorithm

- **Performance**:
    - Enhances performance by **0.5 to 1.2** units over other methods.
    - Ensures equitable bandwidth allocation for all users.
- **Key Feature**:
    - Allows for adjustable **computational complexity** by customizing the number of top branches retained during the search process.
    - Balances performance and resource efficiency.

2. Maximum Expansion Methods

- **First Maximum Expansion**:
    - Improves performance compared to the **Round Robin** approach.
- **Recursive Maximum Expansion**:
    - Similar benefits as the first method, with marginally better resource allocation efficiency.
- **Limitations**:
    - While these methods provide better throughput than Round Robin, they fall short in achieving fairness across users.

3. Round Robin Scheduling

- **Characteristics**:
    - Simple and fair allocation of resources to users in a sequential manner.
- **Drawback**:
    - Lags in throughput and efficiency compared to the more advanced scheduling algorithms.

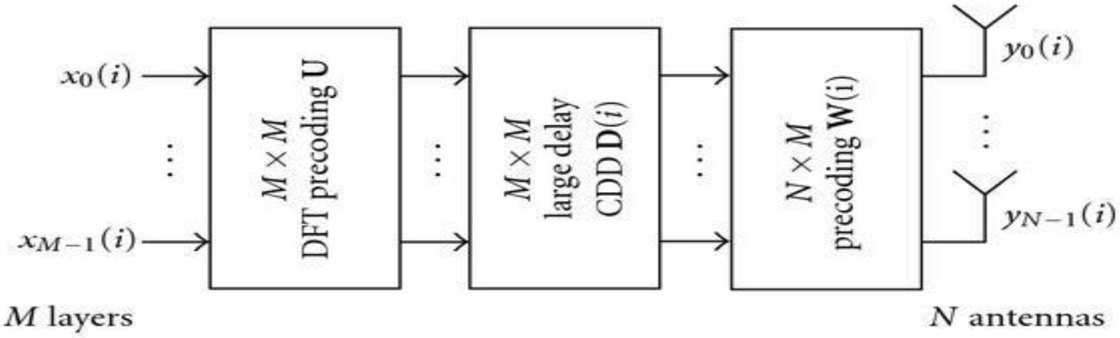
Comparison of Scheduling Strategies

Algorithm	**Performance**	**Fairness**	**Computational Complexity**
Search-Tree Based	High (0.5–1.2 improvement)	Excellent (equal bandwidth)	Adjustable
Maximum Expansion Methods	Moderate	Less Fair	Fixed
Round Robin	Low	Excellent	Low

Conclusion

The **Search-Tree Based Algorithm** stands out as the most versatile strategy, offering a superior trade-off between performance and fairness. Its ability to adjust computational complexity makes it suitable for diverse network conditions, ensuring an optimal balance between efficiency and equity in resource allocation.

MIMO Technologies in LTE-Advanced and 3GPP LTE



TEXT:

Figure 3.60: MIMO M layer

LTE and MIMO Technology: A Foundation for 4G Wireless Communication

LTE is widely regarded as the leading technology in the transition to 4G wireless communication, with key innovations like **Multiple Input Multiple Output (MIMO)** playing a pivotal role in achieving higher peak rates and improved system efficiency. These advancements enable future broadband wireless services by leveraging advanced antenna configurations and signal processing techniques.

Overview of MIMO Technology

1. **Development and Adoption**:
    - MIMO technology combines sophisticated signal processing with multiple antenna transmission methods.
    - Initially developed by wireless research institutions, MIMO has become integral to modern communication networks.

2. **Existing Deployments**:
    - Incorporated into **Wi-Fi standards** such as **802.11n**.
    - Standardized in UTRAN protocols for **WiMAX** and **3GPP Release 6/7 (HSPA)**.
    - Advanced MIMO techniques introduced with **3GPP Release 8 (LTE)** in 2009 and further explored in **Releases 9 and 10**.
3. **Importance in LTE**:
    - Supports technologies like **beamforming**, **transmit diversity**, and **spatial multiplexing**.
    - Crucial for achieving higher spectral efficiency and meeting the demands of broadband data services.

MIMO Modes in LTE-Advanced

LTE-Advanced employs multiple **Transmission Modes (TM)** to adapt multi-antenna configurations based on the radio environment and Signal-to-Interference-and-Noise Ratio (SINR).

Key Transmission Modes in LTE:

1. **Release 8 (TM1–TM7)**:
    - Introduced fundamental MIMO strategies for both **uplink (UL)** and **downlink (DL)**.
2. **Release 9 (TM8)**:
    - Enabled advanced multi-user MIMO (MU-MIMO) configurations.
3. **Release 10 (TM9)**:
    - Introduced **8x8 MIMO** for the downlink and **4x4 MIMO** for the uplink.
    - Allows dynamic switching between **Single User (SU-MIMO)** and **Multi User (MU-MIMO)**.

Transmission Modes in Detail:

Transmission Mode	Introduction	Description
TM1	R'8	Single antenna, basic reference transmission.
TM2	R'8 (UL in R'10)	Transmit diversity for improved robustness.
TM7	R'8	Beamforming for directional transmission.
TM8	R'9	MU-MIMO for simultaneous transmission to multiple users.
TM9	R'10	8x8 MIMO (DL), 4x4 MIMO (UL), and dynamic SU/MU transitions.

MIMO Benefits in LTE-Advanced

1. **Higher Data Rates**:
    - Enhanced spectral efficiency, achieving industry-leading peak rates.

2. **Improved SINR Utilization**:
    - Users with higher SINR gain significant advantages in data throughput and reliability.
3. **Dynamic Adaptation**:
    - Transmission modes enable networks to adapt to changing radio environments and user requirements.
4. **Reference Signals for Robust Communication**:
    - Used to combat fading and ensure signal integrity during demodulation.

Conclusion

MIMO technology, integrated into LTE and LTE-Advanced, has revolutionized wireless communication by combining cutting-edge antenna systems with adaptive transmission techniques. With advancements like **4x4 UL MIMO** and **8x8 DL MIMO**, LTE-Advanced delivers unparalleled performance, meeting the demands of modern broadband services while laying the groundwork for future wireless technologies.

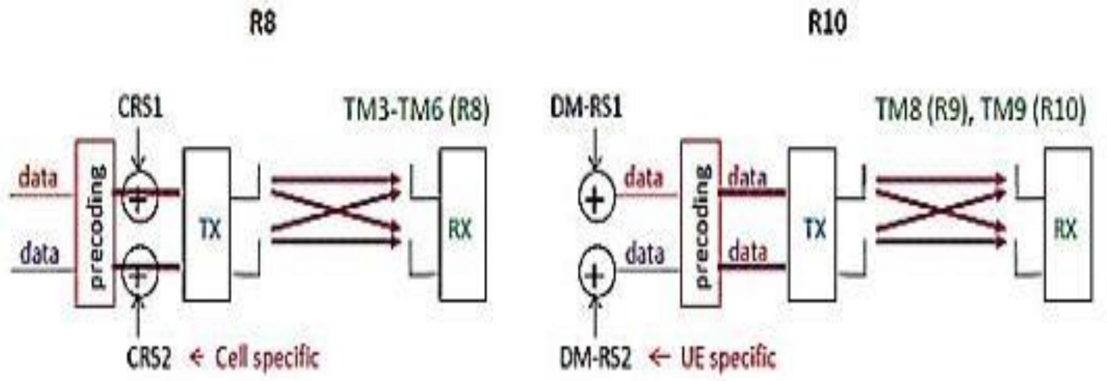


Figure 3.62: MIMO DL with pre-coding and RS for demodulation in R'8 and R'10

Advanced Features and Enhancements in LTE-Advanced

LTE-Advanced incorporates various techniques to improve spectral efficiency, capacity, coverage, and system reliability. Key aspects include advanced MIMO configurations, interference management strategies, and the integration of relays for efficient load balancing and extended coverage.

1. MIMO Enhancements in LTE-Advanced

Cell Reference Signals (CRS) and Demodulation Reference Signals (DM-RS):

- **CRS**: Unique to each cell or antenna, CRS is used by the UE to decode and demodulate signals by assessing channel impact.
- **DM-RS**: Added in Release 10 to assist in demodulating user-specific data streams in non-codebook-based pre-coding methods, providing insights into the combined effects of pre-coding and the radio channel.

Capabilities:

- **Downlink MIMO**: Supports up to **8 layers** (8x8 MIMO), achieving a peak spectral efficiency of **30 bps/Hz**.
- **Uplink MIMO**: Supports up to **4 layers** (4x4 MIMO), with a peak spectral efficiency of **15 bps/Hz**.
- **Interference Reduction**: Employs techniques like beamforming, spatial multiplexing,

and transmit diversity.

Challenges:

- **Antenna Integration**:
    - Constrained UE space limits the inclusion of multiple antennas, leading to signal correlation and interference with Bluetooth, Wi-Fi, and GPS antennas.
- **Solutions**:
    - Pattern diversity technologies for **2x4** and **4x4 MIMO** achieve minimal correlation and strong isolation between antennas.
    - Future designs may co-optimize LTE and WLAN RF components or strategically position multiple antennas with high isolation.

2. Enhanced Inter-Cell Interference Coordination (eICIC)

Inter-cell interference, a major capacity-limiting factor, is managed through frequency, time, and power domain techniques:

- **Frequency Domain**: Allocates specific resource blocks (RBs) to avoid overlap.
- **Time Domain**: Employs techniques like **Almost Blank Subframes (ABS)** to reduce interference.
- **Power Control**: Limits transmit power for cells with favorable channel conditions or lower throughput demands.

3.2.1.5 Cell Range Extension (CRE)

Purpose:

- Improves load balancing by offloading users from macro cells to smaller cells or relay stations.

Challenges:

- **SINR Reduction**:
    - UEs in extended ranges experience low SINR due to interference from macro base stations.
- **Performance Decline**:
    - Excessive range extension (>6 dB offset) can cause latency and reduce system capacity.

3.2.1.6 Relaying and Radio Repeaters

Types of Relay Stations (RS):

1. **Type I RS**:
    - Operates as a layer-3 RS with its own physical cell ID, managing **RRM, scheduling, and HARQ retransmissions**.
2. **Type II RS**:
    - Functions transparently, without its own cell ID, relying on the macro cell for control.

Benefits:

- **Coverage and Capacity**:
    - RSs close coverage gaps and enhance throughput, particularly at cell edges or shadowed regions.
- **Cost Efficiency**:
    - Lower operational costs and rapid deployment due to fewer regulatory restrictions.

Relay Operation:

- **Relay Backhaul (Un Interface)**:

    - Integrates the access and backhaul links, optimizing resource allocation.
- **Resource Allocation**:
    - Balances load between RS and macro eNodeB by reducing eNodeB transmit power and implementing biasing strategies.

Applications:

- **Dynamic Deployments**:
    - Events like conferences or large gatherings.
    - Addressing coverage "black holes" from construction or landscape changes.

Challenges:

- **Placement Sensitivity**:
    - Poor RS placement can waste investments and reduce expected benefits.
- **Traffic Variability**:
    - Requires adaptive resource distribution based on RS positioning and demand.

5. Combining MIMO, CA, and Relays

- **High-Frequency Bands**:
    - MIMO performs better in higher frequency bands (1700–2700 MHz) than lower bands.
- **Carrier Aggregation (CA)**:
    - Combining CA with MIMO amplifies performance, particularly in spectrum-constrained scenarios.

Conclusion

LTE-Advanced integrates cutting-edge technologies like MIMO, eICIC, CRE, and relaying to enhance network performance, capacity, and coverage. These innovations address the growing demand for broadband services, ensuring LTE-Advanced remains the cornerstone of 4G wireless communication and a foundation for 5G advancements.

3.2.1.7 Mobile Backhaul (MBH) in LTE-Advanced Networks

The increasing reliance on mobile networks to access remote content has driven significant growth in bandwidth demand, particularly in **Mobile Backhaul (MBH)** systems. These systems connect the **Radio Access Network (RAN)** at cell sites to the **core network**, enabling high-capacity technologies like LTE-A to meet performance benchmarks. With advancements such as HetNet, Carrier Aggregation (CA), MIMO, and Coordinated Multipoint (CoMP), the importance of robust MBH has become critical, especially in dense urban environments.

Key Backhaul Technologies

1. Fiber Backhaul

Fiber is the most efficient backhaul option due to its **virtually unlimited capacity, low latency, and scalability**.

- **Technologies Used**:
    - **MSAG-PON FTTH/B/C**: Multiplexing using passive optical networks.
    - **CWDM & DWDM**:
        - **Coarse Wavelength Division Multiplexing (CWDM)** and **Dense Wavelength Division Multiplexing (DWDM)** enable multiple signals

on the same strand using different light wavelengths.

    - DWDM supports **up to 160 channels**, each capable of **10 Gbps**, achieving a potential capacity of **1.6 Tbps per fiber**.

- **Advantages**:
    - High throughput and redundancy.
    - Scalable to accommodate future demands with minimal physical changes.
    - Reliable for critical macro cell backup using secondary links.
- **Challenges**:
    - High initial costs for deployment and installation.
    - Breakeven time of **18–20 years**, making it less attractive as a standalone business case for mobile operators.

2. Wireless Backhaul

Wireless solutions are an alternative where fiber deployment is infeasible, such as remote locations or dense urban areas.

- **Technologies Used**:
    - **Microwave (MW)**: Reliable for short to medium distances.
    - **E-band Point-to-Point (PTP)**: High capacity over a limited range.
    - **Point-to-Multipoint (PMP)**: Cost-effective and efficient in urban environments.
- **Advantages**:
    - Quick deployment and lower upfront costs compared to fiber.
    - PMP systems are more affordable, with fewer radios and links required.
    - Compact equipment and area-wide spectrum licenses simplify urban deployments.
- **Challenges**:
    - Limited capacity compared to fiber, especially as cell density increases.
    - Susceptible to weather and environmental conditions.

Choosing Between Fiber and Wireless Backhaul

Backhaul Type	Advantages	Disadvantages
Fiber	High capacity, low latency, redundancy.	High initial cost, lengthy breakeven period.
Wireless	Lower cost, faster deployment, flexible.	Limited capacity, weather-dependent.

Advancements in Backhaul Efficiency

1. **Wavelength Division Multiplexing (WDM)**:
   - Combines multiple signals with different wavelengths on a single fiber.
   - **Dense WDM (DWDM)**: Enhances capacity by closely spacing channels, reducing the need for additional fibers.
2. **Future-Proofing Fiber**:
   - Operators can expand capacity by multiplexing new wavelengths or using existing conduits for additional fiber strands.
   - This ensures scalability without significant infrastructure changes.

Backhaul and LTE-Advanced Enhancements

1. **HetNet Integration**:
   - Backhaul solutions must support heterogeneous networks, including small cells, macro cells, and relay nodes.
   - **PMP systems** excel in urban HetNet deployments due to their cost efficiency and ease of installation.
2. **Carrier Aggregation (CA) and MIMO**:
   - Combining CA with high-order MIMO increases spectral efficiency, requiring robust backhaul solutions to prevent bottlenecks.
3. **Latency and Synchronization**:
   - Low latency and accurate synchronization are critical to meeting 4G KPI standards and supporting future 5G services.

Conclusion

The growth in bandwidth demand has elevated the importance of **Mobile Backhaul (MBH)** within LTE-Advanced networks. Fiber remains the gold standard for capacity and scalability, while wireless backhaul provides flexible, cost-effective alternatives in challenging deployment scenarios. Advanced techniques like **DWDM** and spectrum-efficient wireless solutions ensure that backhaul systems can meet the needs of both current and future networks. Combining fiber and wireless backhaul strategically is key to achieving high performance and cost efficiency in LTE-Advanced and beyond.

Pros and Cons of Backhaul Frequency Bands

Different frequency bands are used in mobile backhaul solutions, each with its own advantages and disadvantages. Here, the **sub-6 GHz licensed** and **microwave (MW)** bands are compared based on their suitability for small-cell backhaul.

1. Sub-6 GHz Licensed Band

Pros:

- **Non-Line-of-Sight (NLOS) Capability**:
    - Ideal for locations where Line of Sight (LOS) is unavailable, such as urban environments with obstacles.
- **Ease of Integration**:
    - Enables combining eNodeB and backhaul into a single enclosure, simplifying deployment.
- **PMP Architecture**:
    - Point-to-Multipoint (PMP) is widely adopted, offering broad coverage for multiple nodes.

Cons:

- **Limited Spectrum Availability and High Costs**:
    - Sub-6 GHz bands are expensive and often limited to narrow channels, restricting capacity.
- **Capacity Limitations**:
    - PMP architecture shares available capacity among network cells, exacerbating bandwidth constraints.
    - **Lower Efficiency Compared to PTP**:
        - Point-to-Point (PTP) designs provide higher capacity in the same spectrum by packing multiple lines within a single coverage area.

Use Case:

- Suitable for operators with sufficient licensed spectrum access, particularly in small-cell edge deployments with lower capacity needs.

2. Microwave (MW) Bands

Pros:

- **Wide Adoption and Proven Technology**:
    - Frequently used for cellular backhaul, with a long history of reliable performance.
- **Cost-Effective**:
    - Prices continue to decrease, making it an accessible solution for many operators.
- **Extended Range**:
    - Supports long-distance connections, making it suitable for rural small-cell deployments.

Cons:

- **Requires Line of Sight (LOS)**:
    - Deployment is limited to areas with unobstructed paths, reducing flexibility in dense urban environments.
- **Competition in Small-Cell Market**:
    - Faces challenges from higher-frequency bands like 60 GHz and E-band, which offer smaller antennas, higher capacities, and lower spectrum costs.

Use Case:

- Best suited for rural or suburban deployments where LOS is achievable, and long-range connections are required.

Comparison

Feature	Sub-6 GHz Licensed Band	Microwave (MW) Bands
Line-of-Sight (LOS)	Not required (NLOS capable)	Requires LOS
Integration	Combines eNodeB and backhaul	Typically separate components
Cost	High spectrum costs	Cost-effective, declining equipment prices
Capacity	Limited (narrow channels, PMP sharing limitations)	Moderate to high (long-range, proven tech)
Range	Limited	Extended range (ideal for rural deployments)
Deployment	Urban environments, lower-capacity edge networks	Rural or LOS-friendly suburban environments

Conclusion

- **Sub-6 GHz licensed bands** excel in NLOS conditions but are constrained by high costs and capacity limitations, making them suitable for niche applications like edge deployments in small-cell networks.
- **Microwave bands** are a reliable and cost-effective choice for LOS backhaul, especially in rural and suburban areas, but face growing competition in urban markets from higher-frequency options like 60 GHz and E-band.

Table 3.11: The benefits and drawbacks of bands for wireless BH solutions

Backhaul(BH) and small cells: According to a recent evaluation on small-cell backhaul, backhaul throughput requirements are often around 100 Mbps; this figure rises if small cells incorporate other air-interface modules (3G, Wi-Fi) in addition to LTE-A [45].

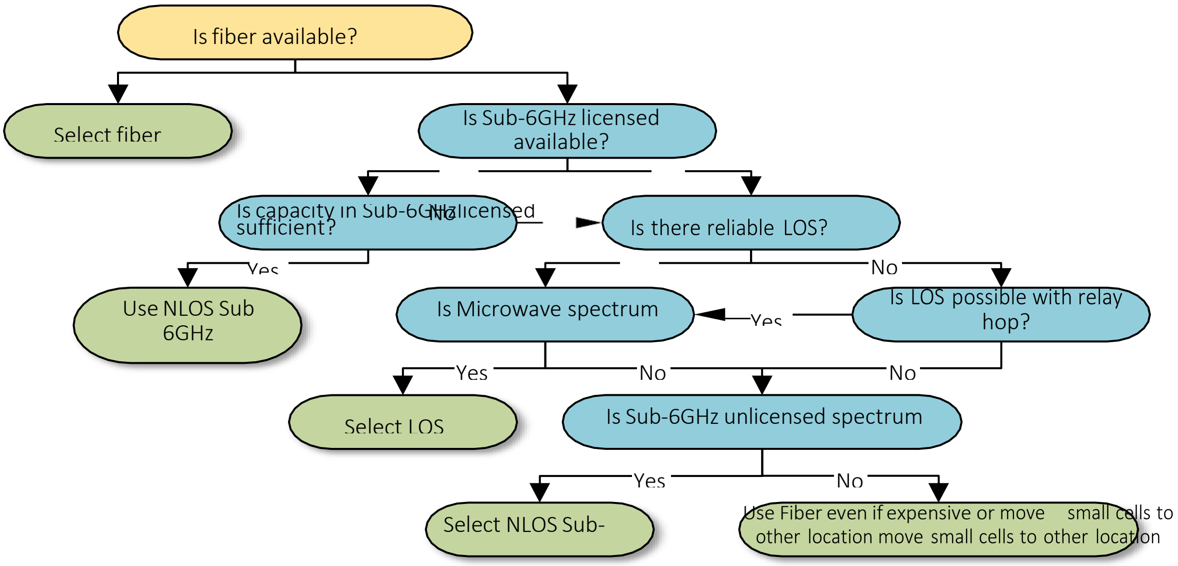


Figure 3.63: Small-cell backhaul decision tree [Redesigned from 45]

Small-Cell Backhaul Solutions

Small-cell deployments are critical in addressing network demands in high-density environments. However, no single backhaul technology can comprehensively fulfill the diverse requirements of these deployments. A combination of solutions is often necessary, depending on the deployment scenario.

Preferred Backhaul Options

1. **Fiber**:
    - **Advantages**:
        - Provides **superior bandwidth** and **low latency**, making it the ideal choice for small-cell backhaul.
    - **Limitations**:
        - Impractical in outdoor settings or locations where fiber installation is costly or time-consuming.
2. **Wireless Backhaul Solutions**:
    - Essential for scenarios where fiber is unavailable or infeasible.
    - **Examples**:
        - **Microwave Technology**: Effective for line-of-sight (LOS) communication, such as connecting a small cell to an aggregated macro cell.
        - **Cable Modems**: Useful in areas with pre-existing infrastructure, providing reliable, moderate-bandwidth connectivity.

Deployment Scenarios and Challenges

1. **High-Density Environments**:
    - **Examples**: Hotels, conference centers, stadiums.
    - **Requirement**: Reliable, high-bandwidth connections to support multiple users and devices simultaneously.
    - **Challenges**: Interference, congestion, and structural limitations.
2. **Outdoor Deployments**:
    - **Examples**: Urban streetscapes, remote areas.
    - **Requirement**: Line-of-sight communication between small cells and macro cells.
    - **Challenges**: Physical barriers, environmental conditions, and limited infrastructure.

Complementary Backhaul Solutions

- Backhaul technologies often work in **complementary roles** rather than as competitors, addressing specific challenges in combination.
- For instance:
    - Fiber can serve as the primary backhaul in indoor or urban settings.
    - Wireless solutions like microwave can extend connectivity to areas where fiber is impractical.

Decision Framework

- **Figure 2.22 (Referenced)**:
    - Illustrates a **decision tree** for selecting the most suitable backhaul option based on factors like:
        - Deployment type (indoor vs. outdoor).
        - Availability of existing infrastructure (fiber or cable).
        - Bandwidth and latency requirements.
        - Cost considerations.

Conclusion

The selection of small-cell backhaul solutions must be tailored to specific deployment scenarios, leveraging the strengths of both **fiber-based** and **wireless technologies**. By employing complementary approaches, network operators can ensure reliable, high-performance connectivity in diverse environments.

3.2.1.8 Self-Optimizing Network (SON)

Self-Optimizing Networks (SON) play a pivotal role in modern mobile network deployments, enabling efficient management of resources and maintaining optimal performance. SON capabilities are especially critical in addressing challenges associated with deployment, scalability, and backhaul connectivity.

Key Features of SON

1. **Automation**:
    - SON automates network management tasks, such as configuration, optimization, and troubleshooting.
    - Reduces reliance on manual interventions, minimizing operational complexity and costs.
2. **Real-Time Optimization**:
    - Continuously monitors network conditions to dynamically adjust parameters.
    - Ensures optimal performance for coverage, capacity, and quality of service (QoS).
3. **Interoperability with Backhaul Solutions**:
    - Facilitates seamless integration of various backhaul options, ensuring a reliable, high-bandwidth connection.
    - Supports **complementary backhaul solutions**, including fiber, microwave, and satellite links, depending on the deployment scenario.

Selecting Backhaul Solutions with SON

In deployment planning, SON aids in determining the most appropriate backhaul solution by leveraging a **decision tree framework** (e.g., as depicted in Figure 2.22). This framework evaluates multiple factors:

1. **Network Requirements**:
    - Bandwidth demand, latency tolerance, and reliability requirements.
2. **Deployment Environment**:
    - Urban, suburban, or rural settings.
    - Physical constraints like terrain and building density.
3. **Cost and Scalability**:
    - Initial deployment and operational costs.
    - Ability to scale with growing user demands.
4. **Technology Suitability**:
    - **Fiber**: Offers high capacity and low latency but may be costly for remote areas.
    - **Microwave**: Provides flexibility and cost-effectiveness in areas where fiber deployment is challenging.
    - **Satellite**: Suitable for remote or underserved regions with minimal infrastructure.

Advantages of SON in Backhaul Optimization

- **Dynamic Traffic Management**: Adapts to fluctuating user demands by reallocating resources in real-time.
- **Fault Detection and Recovery**: Identifies and resolves backhaul issues quickly to prevent service degradation.
- **Energy Efficiency**: Minimizes power consumption through intelligent resource allocation.

Conclusion

Self-Optimizing Networks enhance the deployment and operational efficiency of LTE and 5G systems. By integrating SON with a decision tree-based framework for backhaul selection, operators can ensure reliable connectivity and optimize costs. This synergy between SON and backhaul solutions is essential for addressing modern network challenges and delivering high-quality user experiences.

3.2.2 Technologies innovations in 5G

The development of **5G** represents a transformative phase in wireless communication, building on the advancements introduced by LTE and LTE-Advanced. While still under development during the rollout of 4G, emerging ideas for 5G represent both **evolutionary extensions** of existing technologies and **revolutionary departures** from traditional network paradigms. Below are some of the **key innovations** shaping the future of 5G:

Key Technological Innovations in 5G

1. **Small, Compact Base Stations with Nanotechnology**:
    - Leveraging **nanotechnology**, base stations are becoming smaller and more energy-efficient.
    - These compact designs facilitate dense network deployments, crucial for urban environments with high data demands.
2. **Advanced Multicarrier Modulation Methods**:
    - Introduction of new modulation schemes to improve spectral efficiency and reduce interference.
    - Enables the transmission of higher data rates with lower latency.
3. **Centralized Radio Access Technology (RAT)**:
    - A **centralized approach** to radio access simplifies network management and enhances resource allocation.
    - Facilitates coordination across different radio technologies and frequency bands.
4. **Abandonment of Traditional Cell-Based Concepts**:
    - Transition to **collaboration and coordination-based network structures**.
    - Moves away from fixed, cell-centric designs to more dynamic, user-centric architectures.
5. **Spectrum Fragmentation**:
    - Efficient utilization of fragmented spectrum resources across different frequency bands.
    - Enables seamless communication despite the increasing complexity of frequency allocations.
6. **Integration of Cloud Computing**:
    - Networks leverage **cloud computing** for scalable and flexible resource management.
    - Supports edge computing for real-time processing and low-latency applications.
7. **Application of Nanotechnology**:
    - Nanotechnology enhances materials and devices used in network components, improving performance and reducing costs.
    - Enables innovations in antenna design, energy storage, and signal processing.
8. **Flexible, Low-Latency Frame Structures**:
    - Design of adaptive frame structures to minimize latency, critical for applications like autonomous driving and IoT.
    - Offers flexibility to support diverse service requirements, from high-speed broadband to ultra-reliable low-latency communication (URLLC).
9. **Spectrum Pooling and Cognitive Radio Technologies**:
    - **Spectrum pooling** allows shared use of frequency bands among different operators or applications.
    - **Cognitive radio** dynamically adapts to spectrum availability, optimizing usage in real-time.
10. **Enhanced Resource Allocation Mechanisms**:
    - Advanced algorithms improve the efficiency of resource distribution, ensuring fair allocation and better network performance.
    - Particularly useful in managing massive device connectivity in IoT ecosystems.

Impact of These Innovations

- **Higher Data Rates and Capacity**:
    - Supports increasing demands from applications like virtual reality, AI, and IoT.
- **Improved Network Efficiency**:
    - Lowers energy consumption and operational costs.
- **Reduced Latency**:
    - Enables real-time services, critical for autonomous systems and remote healthcare.
- **Scalable Architecture**:
    - Prepares networks for exponential growth in connected devices.

Conclusion

The innovations driving 5G signify a leap in wireless communication technology. By integrating concepts like **nanotechnology**, **cognitive radio**, and **cloud computing**, 5G aims to deliver a **flexible, high-capacity, low-latency** network capable of supporting future digital ecosystems. These advancements not only extend the capabilities of LTE-Advanced but also redefine network design, paving the way for next-generation connectivity.

3.2.3 LTE-Advanced and 5G Toolbox

LTE-Advanced networks, with their robust components and advanced technologies, are positioned to significantly contribute to the evolution of **5G networks**. Their existing capabilities will address many 5G requirements while supporting the development of complementary technologies.

Key Contributions of LTE-Advanced to 5G

1. **Access Technologies**:
    - **OFDMA (Orthogonal Frequency Division Multiple Access)** for downlink and **SC-FDMA (Single Carrier Frequency Division Multiple Access)** for uplink.
    - These technologies are highly efficient in delivering data, ensuring high throughput, and reducing interference, making them well-suited to meet 5G's stringent requirements.
2. **Continuity in Radio Network Access**:
    - The **user access mechanisms** in LTE-Advanced are likely to carry forward into 5G with minimal changes.
    - This continuity ensures backward compatibility, simplifying the transition to next-generation networks.

Need for Frame Structure Modifications

Although the fundamental access technologies in LTE-Advanced are sufficient for many 5G objectives, **frame structure adjustments** will be necessary to address specific challenges:

1. **Latency Reduction**:
    - 5G demands ultra-low latency for applications like autonomous driving, virtual reality, and industrial automation.
    - Modifications to LTE-Advanced frame structures will further minimize transmission delays.
2. **Flexible Frame Designs**:
    - Adapting frame structures to accommodate diverse 5G use cases, such as **enhanced Mobile Broadband (eMBB)**, **Ultra-Reliable Low-Latency**

Communications (URLLC), and **Massive Machine-Type Communications (mMTC)**.

Role of Complementary Technologies

In addition to LTE-Advanced, emerging technologies will complement its capabilities to fulfill 5G requirements:

1. **Massive MIMO**:
    - Expands on LTE-Advanced's MIMO systems by incorporating large-scale antenna arrays for higher spectral efficiency and capacity.
2. **Dynamic Spectrum Sharing**:
    - Allows simultaneous use of LTE and 5G in the same spectrum band, enhancing spectrum utilization.
3. **Network Slicing**:
    - Segments the network to meet the specific demands of diverse applications, building on LTE-Advanced's QoS features.

Conclusion

The technologies underpinning LTE-Advanced provide a solid foundation for the development and deployment of 5G. While **OFDMA/SC-FDMA** access methods will likely remain central, adjustments to frame structures are essential to meet 5G's latency and flexibility goals. By leveraging LTE-Advanced as a stepping stone, 5G networks can achieve seamless integration and enhanced performance for future wireless ecosystems.

CHAPTER THREE
LTE - ADVANCED OPTIMIZATION ANALYSIS AND JUSTIFICATIONS IN SELECTED TRENDS OF CELLULAR NETWORKS

2.1 Analysis result and justifications for selected trends of LTE - advanced cellular networks

Deployment Preference Features: Technology and Demography

In **LTE-A radio frequency planning**, multiple implementation factors such as modulation schemes, antenna configurations, and spectrum selection need to be carefully evaluated. As highlighted in [8], **Carrier Aggregation (CA)** stands out as a key feature in LTE-A, enabling enhanced utilization of spectrum resources. Studies reveal that 57% of the available bands in Frequency Division Duplex (FDD) mode utilize the **1800 MHz** frequency, while the **2.3 GHz** band is commonly employed in Time Division Duplex (TDD) mode. Additionally, **3GPP TR 36.814 V9.0.0** recommends several frequency bands for LTE-A, including **450 MHz**, **UHF (698–960 MHz)**, **2.3 GHz**, and **C-band (3.4–4.2 GHz)** [58,59,61].

CA is highly versatile, as it allows spectrum resources to be combined both within and across frequency bands, thereby enhancing bandwidth and capacity [29,59,66]. This flexibility supports the simultaneous provision of multiple services, such as unicast data for web browsing alongside high-rate broadcast programming, ultimately improving user experience.

Frequency Band Characteristics

- **Lower bands** (e.g., 450 MHz, 698–960 MHz): Offer better coverage.
- **Higher bands** (e.g., 1.7–2.7 GHz, 3.4–4.2 GHz): Provide greater bandwidth but require more cells due to propagation limitations.

MIMO Support and Limitations;

To further boost data rates, **MIMO (Multiple Input Multiple Output)** technology is essential, operating across all LTE bands. However, its performance is generally:

- **Superior** in higher bands (1.7–2.7 GHz).
- **Inferior** in lower bands due to propagation characteristics.

Implementing high-order MIMO on the **uplink (UL)** poses challenges, particularly in user devices, as the size and battery life constraints make it difficult to incorporate multiple antennas. Larger devices, such as tablets, are better suited for high-order MIMO. Nevertheless, LTE-A achieves significant improvements with just **two transmit antennas**. By integrating MIMO with CA, operators can achieve substantial performance gains, including increased data rates and reduced **CAPEX (Capital Expenditure)** and **OPEX (Operational Expenditure)**, especially in regions with high spectrum costs.

Advanced Techniques for System Enhancement

1. **Coordinated Multiple Point (CoMP):**
   Introduced in **3GPP Release 11**, CoMP allows base stations to synchronize radio resources, improving performance and **Signal-to-Interference-plus-Noise Ratio (SINR)** for both uplink and downlink.
   - **Joint Processing (JP):** Offers the greatest system gain through coherent transmission but depends on SINR distribution and traffic load predictability.
   - Challenges include:

- Delays and quantization errors in transmitting large **Channel State Information (CSI)** over the X2 interface.
- Extended round trip times for ACK/NACK acknowledgments.

2. **Enhanced Inter-Cell Interference Coordination (eICIC):**
   In scenarios involving nodes with varying transmission power sharing the same frequencies, **eICIC** is crucial for managing rapid fluctuations in traffic loads effectively.

In increasingly complex deployment environments, these advanced techniques significantly enhance system reliability, reduce interference, and optimize resource utilization. By leveraging technologies like CA, MIMO, CoMP, and eICIC, LTE-A networks can better meet the demands of diverse demographic and technological scenarios.

Factors Influencing Operator Decisions and Strategies for User Retention

Operators face several challenges when deciding whether to update their systems, including elevated tariffs, device costs, and expenses associated with inter-network switching. To retain users and reduce churn rates, providing incentives to legacy network users is crucial.

Pricing Strategies for LTE-A Services

Charging higher rates for LTE-A services compared to existing mobile data plans can help ensure service quality. However, this approach is less effective in attracting users than more flexible pricing models, such as **"pay-for-what-you-use"**, where users are billed based on their actual data consumption.

Availability and Affordability of LTE-A Devices

Leading smartphone manufacturers, including **Samsung, Apple, Huawei, and Nokia**, are producing LTE-A-compatible devices in large volumes. Research conducted in **Addis Ababa** indicates that while some devices meet LTE-A requirements, affordability remains a major barrier for most market participants.

Solutions to Enhance LTE-A Device Accessibility

1. **Affordable Bundled Packages:**
   Offering LTE-A smartphones bundled with additional services could make them more accessible.
2. **Support for Local Manufacturing:**
   Implementing government policies to support local smartphone manufacturers can reduce the cost burden for users.
3. **Tax and Import Fee Reductions:**
   Reducing import taxes and fees on LTE-A devices or providing targeted subsidies could lower terminal costs.
4. **Incentivizing Local Content Development:**
   Encouraging the creation of **e-government initiatives**, **e-applications**, and **local internet content** in regional languages could increase the perceived value of LTE-A services for users.

These strategies not only make LTE-A services more appealing to users but also address cost-related barriers, promoting greater adoption while supporting regional economic growth.

Role and management of vendors

Vendors in the telecom industry can be classified into four primary categories based on their responsibilities, providing network equipment, software, management tools, maintenance services, and employee training [62]:

1. ***Strategic Suppliers:***
   Vendors with a high level of dependence and cost exposure, requiring organizations to collaborate closely to drive growth.

2. ***Emerging Vendors:***
   Vendors with a limited initial presence but significant potential for future expansion.
3. ***Tactical Vendors:***
   Vendors characterized by low costs and limited visibility, often focused on specific, less critical tasks.
4. ***Legacy Suppliers:***
   Long-established vendors that are not considered strategic but remain relevant due to their historical presence.

Vendor Management (VM) Trends and Practices

Recent trends show that complex organizations, such as telecom operators, often distribute vendor management responsibilities across multiple departments. For companies aiming to upgrade their infrastructure, adopting a systematic approach to virtual machines is essential to ensure comprehensive vendor oversight and to identify potential gaps or redundancies [62].

This systematic approach involves:

- ***Risk Mitigation:*** *Focusing on vendors supporting critical business processes and applications to minimize risks.*
- ***Capability Assessment:*** *Understanding the organizational skills needed for effective vendor management and identifying gaps.*
- ***Best Practices Implementation:*** *Ensuring vendor management practices are applied across the organization so that staff have the necessary expertise.*
- ***Cautious Decision-Making:*** *Operators dependent on vendors must carefully evaluate technology choices, ensuring requirements are met and compliance is verified.*

By aligning these practices, telecom operators can optimize their vendor relationships, enhance operational efficiency, and support long-term growth.

Both the number of mobile subscribers and data traffic are constantly rising

The number of mobile subscribers continues to grow steadily. Projections from [55,74] estimate that mobile broadband users will increase from ***7.5 billion in 2016*** *to over* ***9 billion by 2022****, with approximately* ***5 billion users adopting LTE/LTE-A****. Even if each smartphone generates over* ***10GB of traffic per month****, the total data traffic for this period is expected to reach* ***70 exabytes (EB)****, up significantly from* ***8.8EB in 2016*** *[54, 55, 58].*

The Case of Ethiopia

Emerging markets, such as Ethiopia, play a pivotal role in Sub-Saharan Africa's mobile growth. Ethiopia was among the top five countries globally for net mobile user additions in ***Q4 2017****, as noted in [55]. Current data from Ethiopian Telecom indicates:*

- ***61.81 million mobile subscribers*** *(over 50% of the population).*
- ***243,000 LTE users****.*

  This segment generates ***87% of Ethiopian Telecom's revenue****, highlighting its critical importance [3].*

Economic Impact of Mobile Broadband

According to [57], broadband connections hold transformative potential for a country's economic growth and job creation, provided that regulators, policymakers, and stakeholders establish appropriate rules and guidelines. Similarly, mobile broadband can catalyze economic development and employment growth, making it a vital tool for national progress [5, 57]. These trends underscore the significance of mobile broadband not only as a driver of technological adoption but also as a cornerstone for economic and societal development.

2.2 Techno-Economic Evaluation (TEA) and Market Analysis Study

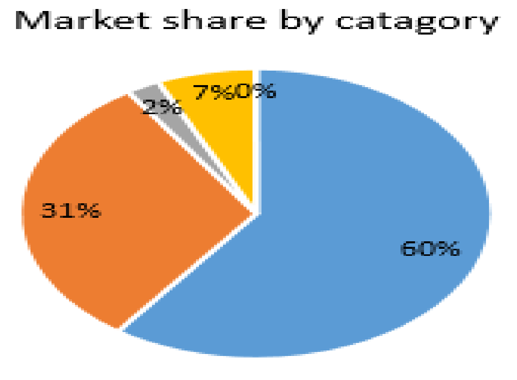
Technical Assessment Using TEA Tools

The technical evaluation of LTE-A deployment was carried out over a study period of six years. Key factors included the services to be offered, market penetration rates, the target number of subscribers during the evaluation period, and the availability of LTE-A-compatible devices.

- **Revenue Estimation:**
  Annual revenues were calculated by analyzing market share, subscriber numbers, and the **Average Revenue Per User (ARPU)** for each year.
- **Network Components and Costs:**
  Network components required to deliver services were determined through **network dimensioning**, with costs obtained from:
  - Vendor data,
  - Insights from previous Ethiopian Telecom LTE projects,
  - Relevant literature sources.
- **Operating Costs:**
  The total **OPEX** (Operating Expenditures) accounted for expenses related to:
  - Power consumption,
  - Computational resources,
  - Administration, maintenance, and operation (O, A&M).
- **Economic Evaluation:**
  A newly developed TEA tool was used to assess:
  - **Economic Assets:** Including earnings, costs, and cash flows.
  - **Economic Indicators:** Key metrics such as:
    - **Discounted Cash Flow (DCF),**
    - **Net Present Value (NPV),**
    - **Internal Rate of Return (IRR),**
    - **Payback Period.**

The evaluation employed a **10% discount rate** to calculate these financial indicators, providing a comprehensive understanding of the project's financial viability.

(ii). Smartphone Penetration



Smartphone Penetration and LTE-A Adoption

Smartphone penetration plays a pivotal role in determining the success of LTE-A adoption. The analysis conducted in **Addis Ababa** focused on **LTE-A-compatible devices** to evaluate current penetration levels and their influence on user adoption.

1. Smartphone Penetration Analysis

1. **Rising Device Availability**:
   - **Figure 4.1** and **Table 2.5** indicate a steady increase in the availability of LTE-

A-capable devices in the market.
    - The shift toward a **multi-device era** is evident, with users likely to own complementary gadgets such as tablets and mobile Wi-Fi routers.
2. **Affordability and Accessibility**:
    - Affordability remains a critical factor influencing LTE-A smartphone adoption.
    - The availability of budget-friendly devices can accelerate adoption, particularly in price-sensitive markets like Addis Ababa.

2. Factors Influencing LTE-A Adoption

1. **Deployment Strategy**:
    - The impact of LTE-A rollout on users is closely tied to Ethiopian Telecom's **deployment strategy**, including coverage areas and marketing approaches.
2. **Value-Added Services**:
    - Offering services such as streaming bundles, personalized data plans, and rewards for loyal users can drive adoption.
3. **ARPU Growth Opportunities**:
    - Increased smartphone penetration directly correlates with higher **Average Revenue Per User (ARPU)** through greater data consumption.

3. Recommendations for Ethiopian Telecom

1. **Focus on Affordability**:
    - Partner with device manufacturers to introduce affordable LTE-A-compatible smartphones.
    - Offer financing options or bundled discounts to reduce upfront costs for users.
2. **Promote Value-Added Services**:
    - Introduce attractive **data plans** and service packages tailored to different user segments.
    - Enhance customer experience with features like flexible billing and data rollover options.
3. **Target Multi-Device Users**:
    - Capitalize on the trend toward multi-device ownership by promoting LTE-A services compatible with tablets, routers, and IoT devices.

Conclusion

The increasing availability of LTE-A-compatible smartphones, combined with effective deployment strategies and affordability measures, will drive user adoption and market expansion in Addis Ababa. Ethiopian Telecom must capitalize on these trends to expand its customer base and enhance ARPU, ensuring the success of its LTE-A rollout and future 5G upgrades.

(iii). Market Partition

This analysis evaluates the adoption and market share projections of LTE-A in both global and regional contexts, with a focus on Sub-Saharan Africa and Ethiopia. The findings draw from industry reports, white papers, and projections, highlighting trends in mobile broadband (MBB) adoption and the potential growth of LTE-A.

Global LTE-A Market Trends

- **Projected Market Share**:
    - LTE-A is anticipated to capture **50% of the global mobile market**, driven by

    - advancements in MBB bandwidth and enhanced network capabilities.
- **Impact on ARPU (Average Revenue Per User)**:
    - **Emerging Markets**: Enhanced MBB bandwidth through LTE/LTE-A is expected to significantly boost ARPU, especially in regions with growing demand for broadband services.

LTE-A Adoption in Sub-Saharan Africa

1. **Initial Market Share**:
    - LTE-A held a **4% market share** in Sub-Saharan Africa in 2017, reflecting its nascent stage of adoption.
2. **Growth Projections**:
    - Forecasts indicate substantial growth:
        - **12% market share** by 2020.
        - **29% market share** by 2025.
3. **Driving Factors**:
    - Increasing affordability of LTE-A-enabled devices.
    - Growing demand for high-speed internet and data-centric services.

Ethiopian Market Dynamics

1. **Subscriber Growth**:
    - Ethiopia is experiencing **exponential growth** in mobile network subscribers.
    - As of recent reports, **60% of the population** owns mobile phones, creating a fertile ground for MBB adoption.
2. **Data Consumption Trends**:
    - Rapidly rising data consumption highlights the demand for enhanced network performance and LTE-A capabilities.
3. **Operator Contributions**:
    - Ethiopian Telecom is driving LTE-A adoption through strategic investments in infrastructure and services, catering to the country’s burgeoning mobile population.

Conclusions

- **Global Market**: LTE-A is poised to dominate the global mobile market, significantly enhancing MBB bandwidth and ARPU in emerging regions.
- **Sub-Saharan Growth**: LTE-A's adoption trajectory in Sub-Saharan Africa reflects a shift towards high-speed mobile broadband, with market share expected to grow sevenfold from 2017 to 2025.
- **Ethiopian Opportunity**: With a large, rapidly growing mobile user base and increasing demand for data, Ethiopia represents a key market for LTE-A expansion, aligned with broader regional trends.

This analysis underscores the transformative potential of LTE-A in driving connectivity, economic growth, and digital inclusion in emerging markets.

(iv). The cost of CAPEX and OPEX

Cost of CAPEX and OPEX in Network Deployment

The costs associated with **Capital Expenditures (CAPEX)** and **Operational Expenditures (OPEX)** for deploying and maintaining a telecommunications network are integral to the planning and rollout process. These costs are determined through **network dimensioning**, leveraging insights from vendor reports, data-driven models, and recent academic and industry literature.

1. Understanding CAPEX and OPEX

1. **CAPEX (Capital Expenditures)**:
    - Represents the upfront costs of acquiring, installing, and upgrading network infrastructure.
    - Key components include:
        - **Base Stations**: Macro cells, small cells, and associated equipment (e.g., antennas, RF systems).
        - **Backhaul Infrastructure**: Fiber, microwave, or other transmission systems.
        - **Core Network Upgrades**: Includes EPC (Evolved Packet Core) or transitioning to 5G cores.
        - **Licensing Fees**: For spectrum acquisition and regulatory compliance.
2. **OPEX (Operational Expenditures)**:
    - Refers to recurring costs incurred during the network's operation and maintenance.
    - Key components include:
        - **Power Consumption**: Energy costs for running base stations and data centers.
        - **Maintenance**: Hardware servicing, software updates, and repairs.
        - **Leasing Costs**: For tower space, land, or fiber links.
        - **Employee Salaries**: Costs for staff managing operations, maintenance, and customer service.

2. Network Dimensioning for Cost Estimation

1. **Process**:
    - Network dimensioning calculates the required infrastructure to meet projected **subscriber demand** and **data traffic** while ensuring quality of service (QoS).
2. **Inputs**:
    - Vendor reports providing equipment costs.
    - Data-driven models estimating network load, subscriber growth, and bandwidth requirements.
    - Literature insights for cost trends and technology benchmarks.
3. **Outputs**:
    - **CAPEX Projections**: Based on the quantity of base stations, backhaul links, and core upgrades.
    - **OPEX Projections**: Derived from estimated power needs, maintenance intervals, and staffing requirements.

3. Factors Influencing CAPEX and OPEX

1. **Technology Choice**:
    - LTE-A and 5G networks require advanced technologies such as **MIMO**, **Carrier Aggregation**, and **HetNets**, which impact both CAPEX (initial setup) and OPEX (operational complexity).
2. **Geographical Conditions**:

  - Urban areas may need dense small-cell deployments, increasing CAPEX, while rural areas with macro cells may incur higher OPEX due to power and maintenance challenges.
3. **Energy Efficiency**:
  - Deploying energy-efficient hardware can lower OPEX but may increase CAPEX due to higher upfront costs.
4. **Vendor Selection**:
  - Costs vary significantly depending on vendor pricing, scalability of solutions, and support services.

Conclusion

By integrating vendor reports, data-driven assumptions, and current literature, network dimensioning provides accurate estimations for **CAPEX** and **OPEX**. This enables operators to design cost-effective deployment strategies while ensuring the scalability and sustainability of their networks. A detailed cost-benefit analysis ensures optimal resource allocation, balancing long-term operational savings with upfront investments.

2.3 Dimensioning of capacity

Capacity dimensioning needs: The goal of capacity dimensioning is to determine how many sites can satisfy the capacity demand. The following is the fundamental capacity dimensioning procedure.

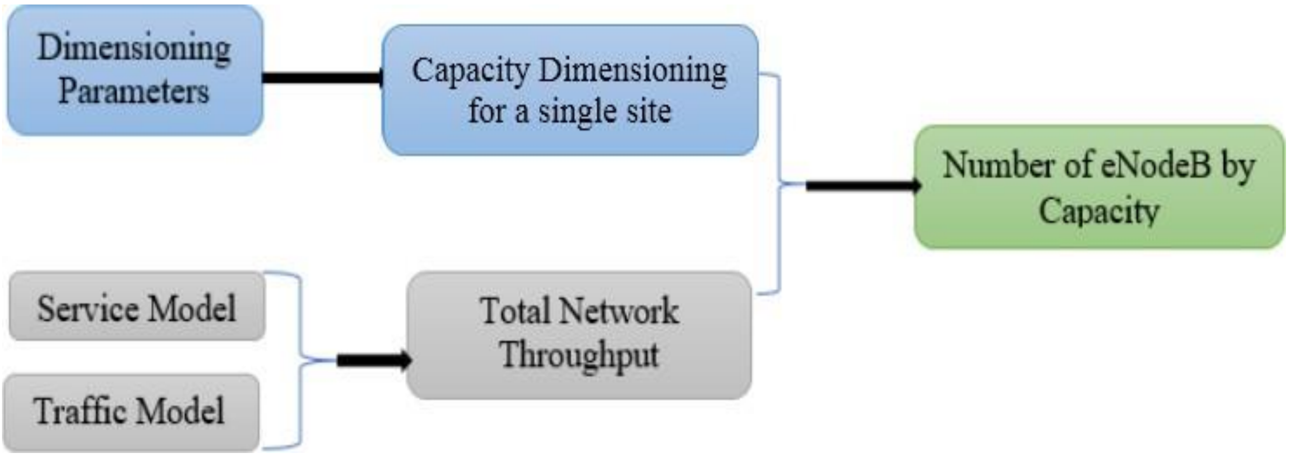


Figure 4.2: Procedure of capacity dimensioning

Capacity dimensioning is a critical step in LTE and LTE-A network planning, aimed at determining the number of eNodeBs required to meet both traffic and coverage demands. This involves a systematic evaluation of throughput, site capacity, and network requirements to ensure a balance between capacity and coverage, while meeting quality-of-service (QoS) targets.

1.3.1 LTE Capacity Planning Process

The capacity dimensioning process follows a structured approach:

1. **Total Network Throughput Calculation**:

  - Determined using traffic and service models.

- Traffic volume is estimated based on user behavior and service demands.

2. **Single-Site Capacity Evaluation**:
    - Depends on factors like bandwidth, modulation type, antenna configurations, and duplex mode.
    - Resource block (RB) utilization in uplink (UL) and downlink (DL) determines the throughput.
3. **Site Count Estimation**:
    - Total traffic volume is divided by the capacity of a single site to calculate the required number of eNodeBs.
    - Site requirements are validated against coverage estimates and adjusted as necessary.

1.3.2 Determining Total Sites and Single-Site Capacity

1. **LTE Frame Structure**:
    - Each LTE frame consists of **20 time slots (10 ms)**, with **7 OFDMA symbols per subframe (1 ms)**.
    - A **20 MHz channel** supports **100 resource blocks**, each containing **12 subcarriers (180 kHz)** and **7 symbols** per 0.5 ms.
2. **Capacity Factors**:
    - **Modulation Type**: Higher-order modulations (e.g., 64 QAM) increase capacity.
    - **Antenna Configurations**: Use of MIMO enhances throughput.
3. **Cell Edge Throughput Requirements**:
    - Minimum throughput targets:
        - **8 Mbps for DL**.
        - **2 Mbps for UL**, suitable for streaming services.

1.3.3 LTE-A Radio Network Capacity and Coverage Dimensioning

1. **Capacity Dimensioning**:
    - Incorporates carrier aggregation (CA) for increased bandwidth and capacity.
    - Enhanced planning for advanced features like SC-FDMA and OFDMA ensures efficient spectrum utilization.
2. **Coverage Dimensioning**:

    - Uses link budgets and propagation models (e.g., COST 231-Hata) to estimate the required number of eNodeBs.
    - Adjustments are made when coverage does not meet capacity requirements.

1.3.4 Propagation Model

The **COST 231-Hata model** is employed to analyze propagation loss:

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

Where:

- d: Cell radius (km).
- f: Carrier frequency (MHz).
- hBS : Base station height (m).
- hUE: User equipment height (m).
- Co: Correction factor (0 dB for suburban, 3 dB for dense urban/urban).

1.3.5 Power Output and Receiver Sensitivity

1. **Transmitter Power**:
    - eNodeB power: **46 dBm**.
    - UE power: **23 dBm**.
2. **Receiver Sensitivity**:
    - Calculated as: $Rxsensitivity=SINR+NF+NP+10\log(15000)$
    - Where:
        - SINR: Demodulation threshold.
        - NF: Noise figure.
        - NP: Thermal noise power density (−174 dBm/Hz).

1.3.6 Interference Margin and Coverage-Driven eNodeBs

1. **Interference Margin**:
    - Accounts for load-based noise growth.
    - Mitigates intra-cell interference (via OFDM) and inter-cell interference in UL and DL.
2. **Coverage-Driven Site Estimation**:

- Number of eNodeBs:
  #eNodeBcoverage=Site Area (km*km)/Total Area (km*km)
- Site area is determined using hexagonal cell geometry:
  Site Area = 1.5*sqrt{3}* R^2
- Where R represents DL/UL cell range.

1.3.7 Addis Ababa Case Study

- **Total Area**: 779.95 km², divided into:
  - **Dense Urban (DU)**: 40% of 240.82 km².
  - **Urban (U)**: 60% of 240.82 km².
  - **Suburban (SU)**: 539.13 km².

Conclusion

The **capacity dimensioning process** ensures that the number of eNodeBs aligns with traffic and coverage requirements, meeting QoS targets. Using detailed propagation models, power budgets, and throughput targets, LTE-A planning addresses both capacity and coverage demands. In Addis Ababa, integrating traffic data, user density, and environmental factors enables tailored network deployment to optimize performance and scalability.

2.4 Spectrum dimensioning

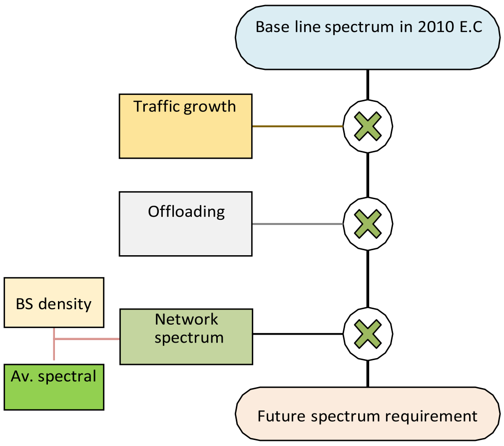


Figure 4.3: Future spectrum prediction [79]

Spectrum Planning and Re-Farming for LTE-A

The International Telecommunication Union (ITU) encourages operators to assess spectrum demand systematically to prepare for future network expansions. Ethiopian Telecom has implemented a methodology, illustrated in Figure 4.4, to forecast future spectrum requirements for both macro and small cells, aligning with ITU guidelines.

Spectrum Allocation Summary

- Current Allocations:
    - Ethiopian Telecom's existing spectrum allocations for 2G, 3G, and LTE networks are detailed in Figure 6.6.
    - The summary includes an analysis of frequency bands and their utilization for current technologies.
- Re-Farming Opportunities:
    - The spectrum re-farming process identifies available slots that can be transitioned from older technologies to support LTE-A deployments.

Spectrum Utilization Updates for LTE-A

1. Current Bandwidth Utilization (SU):
    - Presently, 71 MHz of spectrum is allocated and utilized across various services.
2. Future Bandwidth Utilization (SUN):
    - After re-farming and updates, 89 MHz of spectrum will be available for LTE-A.
    - This expansion ensures sufficient bandwidth to meet the growing demands for high-speed broadband and enhanced network capacity.

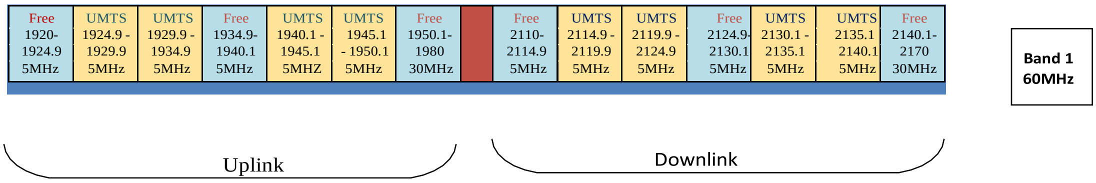
Strategic Importance of Re-Farming

- Optimized Resource Utilization:
    - Re-farming reclaims underutilized spectrum from legacy networks (e.g., 2G or 3G) and reallocates it for advanced technologies like LTE-A.
- Enhanced Network Performance:
    - Expanding spectrum for LTE-A supports higher throughput, better spectral efficiency, and reduced congestion.
- Future-Ready Infrastructure:
    - Ensures the network is scalable and capable of accommodating increased traffic from new applications, such as IoT and 5G.

Conclusion

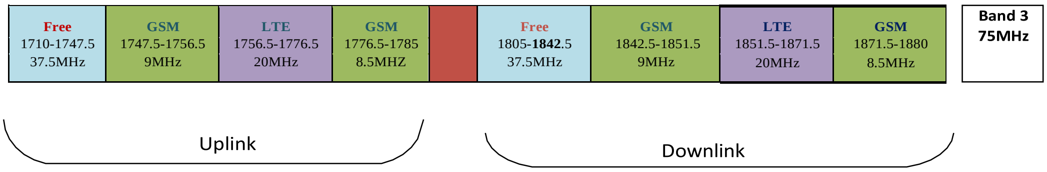
Ethiopian Telecom's approach to spectrum forecasting and re-farming demonstrates a forward-looking strategy to optimize existing resources while preparing for LTE-A network expansions. By transitioning 71 MHz to an updated utilization of 89 MHz, the operator positions itself to meet future demands for broadband services effectively.

2100MHz

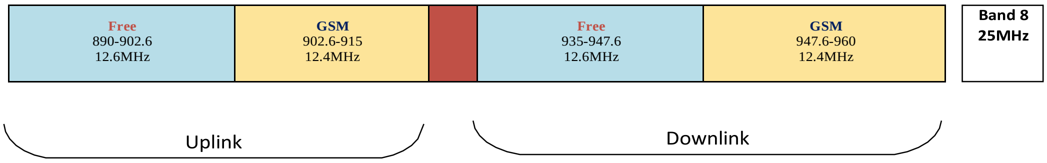


Free 1920-1924.9 5MHz	UMTS 1924.9 - 1929.9 5MHz	UMTS 1929.9 - 1934.9 5MHz	Free 1934.9-1940.1 5MHz	UMTS 1940.1 - 1945.1 5MHZ	UMTS 1945.1 - 1950.1 5MHz	Free 1950.1-1980 30MHz	🟥	Free 2110-2114.9 5MHz	UMTS 2114.9 - 2119.9 5MHz	UMTS 2119.9 - 2124.9 5MHz	Free 2124.9-2130.1 5MHz	UMTS 2130.1 - 2135.1 5MHz	UMTS 2135.1 2140.1 5MHz	Free 2140.1-2170 30MHz

1800MHz



900MHz



800MHz

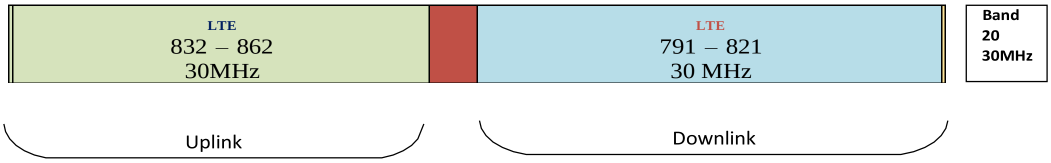


Figure 4.4: ethio telecom frequency usage all band are FDD [3]

Traffic Growth and Spectrum Efficiency in Sub-Saharan Region

The Sub-Saharan region is experiencing notable **traffic expansion**, driven by increasing demand for mobile broadband services. Operators are leveraging advanced technologies to address this growth while optimizing spectrum utilization.

Offloading Factor and Its Impact

- **Definition**:
    - The **offloading factor** ranges from 0 to 1 and represents the proportion of mobile traffic diverted from the cellular network to other systems, such as Wi-Fi.
- **Variability**:
    - A lower offloading factor indicates greater reliance on cellular networks, whereas a higher factor implies significant traffic offloading to alternative networks.

Spectrum Efficiency and LTE-A

1. **Technology-Driven Efficiency**:
    - Spectrum efficiency, measured in **bps/Hz/cell**, depends on the technology deployed.
    - **LTE-A (LTE-Advanced)** achieves up to **30 bps/Hz**, making it one of the most efficient wireless technologies available.
2. **Calculation of Spectrum Efficiency**:

  - Using the inputs specified in **Equation (6.12)**, the computed spectral efficiency is **22.5 bps/Hz**, slightly below the theoretical maximum but still indicative of excellent performance.

Key Factors Influencing Spectral Efficiency

1. **Traffic Load**:
   - Increasing network traffic can reduce spectral efficiency due to congestion and interference.
2. **Network Configuration**:
   - Efficiency depends on configurations such as **carrier aggregation (CA)**, **MIMO deployment**, and **interference mitigation**.
3. **Offloading Practices**:
   - High offloading reduces cellular network load, indirectly boosting spectral efficiency for remaining traffic.

Conclusion

While the theoretical spectral efficiency of LTE-A reaches **30 bps/Hz**, practical scenarios often yield lower values, such as the **22.5 bps/Hz** calculated here. This result highlights the importance of network optimization and strategic offloading to maximize the performance of mobile broadband in the growing Sub-Saharan region market.

2.5 Spectrum valuation

International Mobile Telecommunications (IMT) and the International Telecommunication Union's Radio Communication Sector (ITU-R)

1. What does IMT stand for?

IMT stands for *International Mobile Telecommunications*. Within the ITU community, IMT refers to broadband mobile systems, encompassing IMT-2000, IMT-Advanced, and IMT-2020. These standards facilitate the global deployment of mobile broadband networks, including 3G, 4G, and 5G. The ITU-R, working with its 189 Member States and various sector members, develops and adopts these international standards and regulations.

2. What are IMT-2000, IMT-Advanced, and IMT-2020?

IMT standards underpin all major mobile broadband systems (3G, 4G, 5G):

- **IMT-2000**: Established in 2000, this enabled the first 3G installations.
- **IMT-Advanced**: Released in 2012, it represents the 4G wireless cellular technology currently deployed worldwide.
- **IMT-2020**: Encompasses 5G technology standards, initially trialed in 2018 and formalized by 2020, setting the framework for future mobile broadband connections.

3. What are ITU Regions?

The ITU divides the world into three zones to manage and classify global radio spectrum use:

- **Region 1**: Includes Europe, Africa, the Middle East, and parts of Asia.
- **Region 2**: Covers the Americas and Greenland.
- **Region 3**: Includes Oceania and much of Asia.

Each region has specific frequency allocations, determining the spectrum used for 4G, 5G, and LTE.

Administrative Regions of the ITU:

The ITU also defines five administrative regions based on member states:

- **Region A**: Americas (35 Members)
- **Region B**: Western Europe (33 Members)
- **Region C**: Eastern Europe and Northern Asia (21 Members)
- **Region D**: Africa (54 Members)
- **Region E**: Asia and Australasia (50 Members)

4. What role does the ITU play in IMT?

The ITU-R is responsible for developing and regulating the use of the radiofrequency spectrum through the *Radio Regulations (RR)*, updated every four years at the ITU World Radiocommunication Conference (WRC). These regulations ensure global harmonization of the IMT spectrum, supported by ITU-T Recommendations for IMT core networks and ITU-R Recommendations for radio interfaces. These efforts involve academia, industry, governments, and regulators to advance mobile broadband systems like 3G, 4G, and 5G.

Telecommunication Services Licensing in the Ethiopian Communications Authority (ECA)

The ECA is tasked with licensing and monitoring communications services in Ethiopia, managing individual and class licenses for various telecom services:

1. **Unified Telecommunications Services License**: Permits the design, operation, and maintenance of mobile, fixed networks, and other electronic communications nationwide.
2. **Internet Exchange Point (IXP) License**: Authorizes physical infrastructure enabling traffic exchange between internet networks.
3. **Radio Frequency Spectrum**: Oversees efficient spectrum use, minimizing interference, and supports broadcasting, telecommunications, and public safety.

The ECA is also responsible for:

- Managing Ethiopia’s *National Frequency Allocation Table (NFAT)*.
- Approving telecommunications equipment for compliance with health, safety, and technical standards.
- Assigning IP addresses and domain names, including the .et domain.
- Administering public safety spectrum for emergency services like police and EMS.

Licensed vs. Unlicensed Spectrum Bands

Wireless technologies use the airways (spectrum) to transmit and receive data. These bands are divided into:

- **Licensed Spectrum**: Exclusively allocated to operators, offering benefits like reduced congestion, better performance, and enhanced efficiency. However, it incurs high licensing and equipment costs.
- **Unlicensed Spectrum**: Open for general use under legal restrictions (e.g., power limits). Benefits include availability, cost-efficiency, and simplicity, though it may face congestion and regulatory constraints.

Comparison:

- **Licensed Spectrum**: Better for large-scale, interference-sensitive applications, typically used by major operators.
- **Unlicensed Spectrum**: More accessible for smaller providers and WISPs,

suitable for cost-sensitive deployments.

Applications of the Radio Frequency Spectrum in Ethiopia

ECA manages spectrum use for broadcasting, telecommunications, and private radio services. It regulates and licenses equipment like antennas, routers, and mobile terminals, ensuring compliance with international standards. Public safety spectrum is prioritized for critical communications, while unlicensed bands (e.g., 2.4 GHz, 5 GHz) are reserved for Wi-Fi and RFID devices.

Importance of Spectrum Management:

Effective spectrum use minimizes interference, boosts efficiency, and supports socioeconomic activities like healthcare, education, and law enforcement.

2.6 Literature result reviews for LTE, LTE-advanced and NR cellular network optimizations

Literature #1: "LTE Radio Access Network Dimensioning by Particle Swarm Optimization"

This study, conducted by Addis Ababa University, focuses on dimensioning the LTE Radio Access Network (RAN) for coverage in Addis Ababa. Key aspects include:

- Estimating the number of eNodeBs required for optimal capacity and coverage.
- Using empirical propagation models to calculate coverage links and signal quality.
- Addressing coverage gaps (black holes) in densely urban and suburban areas through HetNet configurations of macro and small cells.

Observations:

Optimizations in LTE, LTE-Advanced, and NR networks significantly enhance:

- Coverage and capacity.
- User Equipment (UE) category complexity and Quality of Service (QoS).
- Strategic supply-demand alignment for operators to improve user satisfaction.

Review Highlights:

- The LTE dimensioning process evaluates factors like maximum path loss, cell radius, and area coverage. For Addis Ababa, characterized by dense urbanization over 129 km², outdoor planning tools and empirical models (e.g., Cost-231) were used.
- Simulations considered signal strength (-95 dBm) and medium signal margins (-98 dBm for VoLTE indoor penetration loss).
- Parameters such as azimuths, mechanical/electrical tilts, and antenna power were optimized to achieve good RSRP and reduce inefficiencies in coverage.

Literature #2: "Techno-Economic Investigation of LTE-Advanced Deployment for Addis Ababa, Ethiopia"

This research explores the techno-economic aspects of deploying LTE-Advanced in Addis Ababa over a six-year period.

Key Observations:

Optimizations in LTE-Advanced and NR networks improve:

- Coverage, capacity, cost-efficiency, revenue generation, QoS, and market penetration.

Review Highlights:

- Revenue estimation was based on annual market share, subscriber growth, ARPU, and device availability.

- Costs, including CAPEX (network components) and OPEX (operations, administration, and maintenance), were calculated using Ethiopian telecom project data, vendor information, and published reports.
- The analysis employed metrics like DCF, NPV, IRR, and payback periods, incorporating a 10% discount rate.
- A newly developed Techno-Economic Analysis (TEA) tool was used to model profits, costs, and cash flows effectively.

Literature #3: "Design Optimization of Tracking Area in LTE Networks Using Clustering Techniques"

This study analyzes the optimization of tracking areas (TAs) in LTE networks using clustering techniques to improve signaling efficiency.

Key Observations:

Enhancements through LTE, LTE-Advanced, and NR optimizations include:

- Improved capacity and traffic volume management.
- Efficient location management signaling (e.g., Tracking Area Updates (TAU)).
- Strategic densification and digitalization of telecom networks.

Review Highlights:

- TA optimization using two heuristic techniques (K-means and HDBSCAN clustering) significantly reduced signaling overhead in Addis Ababa's LTE network:
    - K-means clustering reduced overhead by 49.51% (from 6.08E+08 to 3.07E+08 messages).
    - HDBSCAN clustering achieved a 59.54% reduction (to 2.46E+08 messages).
- Indoor small cells were analyzed, identifying seven hotspots grouped into clusters based on building density and KPI reports. Notable areas include:
    - **Cluster 1:** Bole, Olympia, Airport.
    - **Cluster 2:** Legehar, Stadium, Mexico.
    - **Cluster 3:** Megenagna, G. Sholla.
    - **Cluster 4:** Sarbet, Old Airport.
- In scenarios, 1240 small cells (all clusters) and 709 small cells (selected clusters) were recommended to handle traffic volumes (1000–4000 GB DL, 200–1000 GB UL).

General Observations Across All Studies

1. **Coverage and Capacity Enhancements:**
    - Proper dimensioning and TA optimization are critical for addressing urban density and reducing signaling overhead.
    - HetNet approaches (macro and small cells) are instrumental in mitigating coverage gaps and enhancing user satisfaction.
2. **Cost and Revenue Analysis:**
    - Detailed techno-economic evaluations ensure cost-efficient network deployments.
    - Optimizations align with subscriber growth, ARPU trends, and device capabilities.
3. **Clustering Techniques and Traffic Analysis:**
    - Clustering methods, such as K-means and HDBSCAN, enable precise TA configurations to minimize overhead and maximize efficiency.

  - Data-driven models help forecast traffic demands and guide resource allocation.

These studies collectively highlight the transformative potential of LTE, LTE-Advanced, and NR optimizations in improving network performance, user experience, and economic viability in urban areas like Addis Ababa.

CHAPTER FOUR

RESULTS, DISCUSSIONS, RECOMMENDATIONS AND CONCLUSSIONS

5.1 RESULT

5.1.1 LTE optimization analysis results

1. Multipath Fading Mitigation:

- LTE employs **OFDMA** (Orthogonal Frequency Division Multiple Access) for downlink transmissions to tackle multipath fading, a significant issue in earlier technologies like UMTS. However, OFDMA's high **Peak-to-Average Power Ratio (PAPR)** makes it less efficient for uplink.
- To address this, LTE uses **SC-FDMA (Single Carrier Frequency Division Multiple Access)** for uplink transmission, which offers:
  - **Lower PAPR:** Reduces power consumption and extends battery life for user equipment (UE).
  - **Improved Power Amplifier Efficiency:** At the cost of a more complex base station receiver.

2. Scheduling Techniques in LTE

Downlink Scheduling Algorithms and Limitations:

- **Round Robin (RR):** Simple but inefficient, as it ignores instantaneous channel conditions, reducing system capacity.
- **Proportional Fairness (PF):** Balances fairness and throughput but isn't suitable for real-time traffic due to a lack of QoS consideration.
- **Earliest Deadline First (EDF):** Focuses on delay-sensitive tasks but performs poorly in channel-quality variations.
- **Max C/I:** Maximizes throughput but neglects users with poor channel conditions, like those at the cell edge.

Improved Downlink Scheduling Solutions:

- **M-EDF-PF:** Combines EDF's delay-sensitive scheduling with PF's channel-aware approach, balancing throughput, fairness, and QoS provisioning.

Uplink Scheduling Algorithms and Limitations:

- **LC-Delay:** Accounts for channel contiguity and end-to-end delay constraints.
- **PF-Delay:** Similar to LC-Delay, considers delay requirements and channel conditions.
- **Maximum Throughput (MT):** Maximizes overall throughput but is unfair to cell-edge users.
- **Frequency-Time Expanded (FME):** Expands scheduling to time and frequency domains, ensuring fair resource distribution without over-prioritizing users with high Channel Quality Indicators (CQI).

3. SC-FDMA in Uplink:

- SC-FDMA, chosen for uplink in 3GPP LTE and explored in LTE-Advanced, combines single-carrier modulation with frequency-domain equalization.
  - **Advantages:**
    - Simplified transmitter design for UEs.
    - Lower PAPR, enhancing energy efficiency.
    - Power savings and battery life extension.
  - **Challenges:**

    - Increased receiver complexity (manageable since the receiver is in the base station).

4. PAPR and BER Performance Evaluation:

Key Metrics:

- **Peak-to-Average Power Ratio (PAPR):** Indicates envelope variance in multi-carrier signals. Lower PAPR is desirable for efficiency.
- **Bit Error Rate (BER):** Reflects transmission accuracy; lower BER indicates better performance.

Performance Observations:

- **Interleaved OFDMA (I-OFDMA):**
    - Performs better than localized OFDMA (L-OFDMA) in minimizing PAPR.
    - Achieves acceptable BER levels, making it more efficient overall.
- **Modulation Techniques:**
    - **Quadrature Phase Shift Keying (QPSK):** Lower BER compared to 16QAM, preferred for reliability.
    - **16QAM (16-ary Quadrature Amplitude Modulation):** Offers higher data rates but slightly higher BER.

SC-FDMA vs. OFDMA Performance:

- **QPSK:** SC-FDMA outperforms OFDMA, especially for uplink due to its lower PAPR and better power efficiency.
- **16QAM:** OFDMA slightly outperforms SC-FDMA in high-speed scenarios due to better spectral efficiency.

5. Vehicular Channel Performance (ITU Vehicular-A):

- **Least Mean Square Error (MMSE) Equalization:**
    - Reduces error in both SC-FDMA and OFDMA systems.
- **Mapping Methods:**
    - **Interleaved Mapping:** Superior performance compared to localized mapping.
    - **Localized Mapping:** Performs adequately but exhibits higher PAPR and lower efficiency than interleaved mapping.

Summary:

LTE's optimization strategies leverage advanced multiple-access schemes and sophisticated scheduling techniques to balance efficiency, fairness, and QoS. SC-FDMA’s advantages in uplink transmission make it ideal for mobile devices, while OFDMA dominates in scenarios requiring high spectral efficiency. Proper modulation schemes (e.g., QPSK) and scheduling algorithms (e.g., M-EDF-PF, LC-Delay) further enhance system performance, ensuring robust, fair, and efficient LTE network operations.

5.1.2LTE - advanced optimization analysis results

5.1.2.1 Identified system problems

The **LTE-Advanced** network faces several critical challenges that impact its performance and scalability, particularly in terms of interference, capacity, and load management. These issues stem from the architecture and operational mechanisms of LTE-Advanced and require strategic enhancements to meet user demands and IMT-Advanced specifications.

1. Inter-Cell Interference (ICI):

- **Nature of the Problem:**

  - LTE-Advanced uses a **frequency reuse ratio of 1**, meaning all subcarriers operate with the same transmission intensity across the entire cell.
  - This creates significant interference, especially for **cell-edge users**, as they experience overlap from neighboring cells.
  - Unlike WCDMA, which mitigates interference with **macro diversity**, LTE-Advanced struggles with efficient ICI management.
- **Impact:**
  - **Reduced throughput** for cell-edge users.
  - High data rates are only achievable near the **cell center**.
- **Current Solutions and Limitations:**
  - Tools like **Interference Rejection Combining (IRC)**, **Fractional Power Control (FPC)**, and **Fractional Frequency Reuse (FFR)** aim to manage interference.
  - However, these techniques are less effective compared to the advanced mechanisms available in the LTE-Advanced **toolbox**.

2. Capacity and Coverage Challenges:

- **Data Transmission Growth:**
  - The rise in mobile data demand leads to **capacity bottlenecks**, particularly in densely populated urban areas.
  - Coverage gaps exacerbate the challenges, particularly for **HetNets** with multi-cell deployments.
- **Interference as a Double-Edged Sword:**
  - While some interference can improve system performance if managed well, uncontrolled interference degrades SINR (Signal-to-Interference-plus-Noise Ratio) and overall quality of service.

3. Load Balancing Issues:

- **Problem Description:**
  - Effective **load balancing** involves redistributing heavy users to smaller cells (e.g., controlled by Layer 3 Relay Stations) to prevent congestion in macro cells.
  - Current implementations are suboptimal, leading to inefficient utilization of small cell resources.
- **Impact:**
  - Underutilization of smaller cells.
  - Overloading of macro cells, resulting in degraded user experiences and increased call drop rates.

4. Spectrum Efficiency Concerns:

- **Importance of Spectrum Efficiency:**
  - LTE-Advanced needs to meet the **IMT-Advanced specification** for high spectral efficiency.
  - Current deployment struggles to achieve this goal due to interference and suboptimal resource allocation.
- **Future Challenges:**
  - Poor SINR levels may persist in **5G networks** unless significant enhancements are made to LTE-Advanced.

Summary of Key Challenges:

1. **Inter-cell interference (ICI):** Affects throughput and disproportionately impacts cell-edge users.
2. **Capacity and coverage limitations:** Strain system resources due to rising data demands.

3. **Load balancing inefficiencies:** Lead to uneven distribution of traffic and underutilization of small cells.
4. **Spectrum efficiency shortfalls:** Threaten to limit LTE-Advanced's ability to meet user expectations and IMT-Advanced standards.

Recommendations for Mitigation:

1. **Advanced ICI Management:**
    - Implement **Coordinated Multi-Point (CoMP)** and **enhanced FFR** to improve interference handling.
    - Optimize power control settings to better balance signal strength across cell-edge users.
2. **Improved Load Balancing:**
    - Develop dynamic load redistribution mechanisms to balance traffic effectively between macro and small cells.
    - Use machine learning-based algorithms for predictive load management.
3. **Spectrum Efficiency Enhancements:**
    - Increase deployment of **massive MIMO** and adaptive modulation schemes to maximize spectral utilization.
    - Refine resource scheduling techniques to prioritize SINR improvements.
4. **Capacity and Coverage Expansion:**
    - Integrate **small cells** more effectively into HetNet architectures to offload macro cells.
    - Use advanced planning tools to optimize the placement and configuration of cells.

These enhancements will help LTE-Advanced overcome its current challenges and provide a more robust foundation for future **5G** networks.

Generally

Inter-Cell Interference (ICI):

- The frequency reuse ratio of 1 in LTE-Advanced leads to significant ICI, particularly affecting cell-edge users who face interference from neighboring cells.
- This results in reduced throughput for cell-edge users, while high data rates are primarily achievable near the cell center.

Key Challenges:

- Managing interference: Tools like Interference Rejection Combining (IRC), Fractional Power Control (FPC), and Fractional Frequency Reuse (FFR) help but are not as effective as the newer solutions in the LTE-Advanced toolkit.
- **Load Balancing:** Heavy users are moved to smaller cells using relay stations, but spectrum efficiency and SINR (Signal-to-Interference-plus-Noise Ratio) challenges persist.

HetNet (Heterogeneous Network) Deployment Challenges:

- Interference management between macro and small cells is crucial to enhancing system performance.
- Backhaul limitations, regulatory constraints, and high operational costs hinder small cell deployment.

5.1.2.2 Modulation, coding, BEC, frequency offset adjusting and interference minimization

Proposed Time Domain Windowing Technique:

- **Advantages:**
    - Reduces Inter-Carrier Interference (ICI) and prevents error propagation in OFDM signals.

  - Offers superior Bit Error Rate (BER) performance compared to traditional OFDM without equalization.
  - Demonstrates better tolerance to frequency offset and reduces spectral spreading.
- **Performance Comparison:**
  - Achieves over 10 dB gain at normalized frequency offset of 0.15 and BER of 10^{-3} or 10^{-3} compared to traditional OFDM.
  - Outperforms self-cancellation and correlative coding methods under significant frequency offsets.

5.1.2.3 Dimensioning of small cells or hotspots and macro cells

Challenges in HetNet Deployment:
The increasing demand for indoor traffic has made it essential to deploy efficient, cost-effective, and on-demand small cells to complement macro cells. Effective traffic planning involves identifying the locations, quantities, and scalability of cells to accommodate growing demands. However, deploying HetNets faces numerous challenges, including:

- **Interference:** A major concern, degrading system performance, and requiring strategies to minimize interference between small and macro cells, as well as among small cells.
- **Backhaul Limitations:** Wired options like fiber are expensive, while wireless options face issues such as interference, jitter control, line-of-sight (LOS), and clock synchronization.
- **Power Supply:** Small cell power requirements add operational costs.
- **Site Availability:** Securing suitable locations for small cells is difficult.
- **Centralized Management:** Essential to reduce costs associated with isolated management of small cells.

To improve user experience and enable seamless handovers, careful planning, design, and preemptive measures are necessary for deploying, optimizing, maintaining, and managing small cells.

Cell Dimensioning for Macro and Small Cells:
Currently, mobile broadband traffic is heavily concentrated indoors, with buildings, malls, enterprises, and residences accounting for 89% of mobile usage. To meet this demand, it is recommended to deploy a network overlay of hotspots or small cells (e.g., metro/micro, pico, and femto cells) within macro cell coverage areas with high data traffic.

Benefits of Small Cells:

- Adapt to spatial-temporal traffic variations.
- Offload data from macro cells.
- Increase frequency reuse and provide higher capacity.
- Utilize dynamic interference management strategies, including HetNets, cross-carrier scheduling, Coordinated Multipoint (CoMP), and enhanced Inter-Cell Interference Coordination (eICIC).

Relying solely on macro cells to maintain high Quality of Service (QoS) is inefficient in high-demand environments. Strategies like cell densification and HetNet deployment are critical to improve QoS.

Cost and Complexity:
While these approaches enhance network performance, they increase costs due to:

- Network complexity.
- Efficiency demands.
- Optimal backhaul requirements (e.g., 100–200 Mbps per small cell and up to 1 Gbps per macro base station).

Deployment Needs:

- Sparse deployment suffices in low-density areas.

- Denser deployments are needed in high-traffic regions, as guided by [3GPP TR 36.932]. The number of small cells depends on demand, capacity, and cost considerations.

Example for Addis Ababa:
Many commercial spaces, malls, and stores are underutilized in HetNets. For example, not all buildings are equipped with hotspots. Assuming 40 service users per floor daily over a six-year period, small cells, each supporting 32–64 users (32 being optimal), can be deployed.

Formula for Small Cell Calculation:
SmallIndoor=Number of Subscribers (NS)/Small Cell Capacity

NS Calculation:
$NS=BC\cdot U\cdot f\cdot CA$
Where:

- **NS** = Number of baseline subscribers.
- **BC** = Baseline coefficient.
- **U** = Number of users.
- **f** = Floors.
- **CA** = Cluster area.
- **SmallIndoor** = Users per indoor small cell.

Subscriber growth over the study period is forecasted using a linear model, with a 10% annual growth rate reflecting urbanization, city expansion, and advancements in applications and services.

Generaly

HetNet Deployment for Indoor Traffic:

- Small cells are deployed to handle the increasing indoor traffic, supplementing macro cells.
- Strategies include hotspot overlays, which offload data from macro cells and improve frequency reuse and capacity.

Key Considerations:

- Optimal placement of small cells to minimize interference and maximize coverage.
- **Backhaul Challenges:**
    - Fiber-based options are costly, and wireless alternatives face issues like interference, jitter, and clock synchronization.
- **Cost and Scalability:**
    - Small cells must balance cost, energy efficiency, and node capacity, with scalability for future demand.

Small Cell Dimensioning Formulae:
SmallIndoor=Number of Subscribers (NS)/Small Cell Capacity
Where:
$NS=BC\cdot U\cdot f\cdot CA$

- **BC:** Building count.
- **U:** Users per floor.
- **f:** Floors per building.
- **CA:** Cluster area.

5.1.2.4 Small cell band selection type

Indoor Performance Challenges in Cellular Networks
Over 50% of calls and more than 70% of data services occur indoors, yet signals from traditional macro cell installations often struggle to penetrate buildings due to issues like **penetration loss**. Various solutions have been explored to address these limitations, including:

- Advanced modulation and coding techniques.

- Multi-antenna systems.
- Capacity expansion through new radio spectrum.
- Network densification, achieved by adding sectors per base station (BS) or deploying additional macro BSs.

However, these methods prove insufficient in densely populated areas and cell edges, where performance often declines, and costs and complexity increase.

Adoption of HetNets

Heterogeneous Networks (HetNets), which integrate small, low-power cells with existing macro BSs, offer an effective alternative. Small cells provide:

- Improved network capacity and coverage.
- Enhanced quality with lower power consumption.
- Greater deployment flexibility and reduced CAPEX/OPEX.

While small cells share operational characteristics with macro cells, including resource usage, their **coverage area and capacity** differ, making effective resource allocation critical to avoiding interference.

Small Cell Band Selection Methods

Small cells can operate using two main band selection strategies:

1. **In-Band Deployment**
    - Small cells operate in the same frequency band as macro cells.
    - Advantages: Reduced investment costs.
    - Challenges: Requires advanced interference management techniques, such as enhanced Intercell Interference Coordination (eICIC), to maintain service quality.
2. **Out-Band Deployment**
    - Small cells operate in a separate frequency band from macro cells.
    - Advantages: Increases system capacity and efficiency.
    - Challenges: Higher investment costs compared to in-band solutions.

The choice between in-band and out-band depends on several factors, including:

- Backhaul requirements.
- Traffic and signal management needs.
- Monitoring capabilities.
- Seamless handover capabilities.

Optimal LTE-A System for Small Cells

A robust and cost-effective LTE-Advanced (LTE-A) system incorporating both macro and small cells is necessary to balance these factors effectively. Vendor considerations are also crucial during system planning and deployment.

Deployment Scenarios and LTE-A Advantages

Developing scalable deployment scenarios involves using **uncertainty matrices** to address key uncertainties and additional factors to guide analysis and data collection. LTE-A offers several advantages:

- Meets IMT-Advanced requirements for true 4G networks (500 Mbps UL and 1 Gbps DL).
- Enhances spectrum efficiency beyond standard LTE capabilities.

The transition from LTE to LTE-A is both a physical-layer enhancement and a paradigm shift in network design. LTE-A retains technical compatibility with LTE in areas like:

- Channels.
- Radio Resource Management (RRM).
- Other specifications, while incorporating advanced features for superior performance.

Generally

- Over 70% of mobile data usage occurs indoors, but macro cell installations often fail to penetrate buildings efficiently.

- **HetNet Strategy:**
    - Deploy low-power small cells (e.g., pico, femto cells) to improve capacity and coverage.
- **In-Band vs. Out-Band Deployment:**
    - **In-Band:** Uses the same frequency as macro cells but requires advanced interference coordination (eICIC).
    - **Out-Band:** Increases capacity and efficiency but incurs higher costs.

5.1.2.5 Deployment scenario matrixes

The following key uncertainties have been identified as central to deployment choices and are further analyzed for techno-economic evaluation. Current trends indicate that most LTE-Advanced deployments utilize HetNet configurations of macro cells and small cells (e.g., metro or micro cells). Advanced technologies and features play a crucial role in achieving high data rates and improving network efficiency, including:

- **Carrier Aggregation (CA)** and **MIMO antenna arrays/ports**.
- **Higher-order adaptive modulations** such as QPSK, 16QAM, and 64QAM, based on link decibel (dB) signal quality and power management.
- **Higher-order multiplexing/demultiplexing** techniques (FFT/DFT/IFFT/IDFT) for OFDM and SC-FDMA.
- Advanced coherent and non-coherent detection mechanisms, including high-efficiency data rate entropy, input symbol coding/decoding, phase and symbol bit quantization.
- Advanced Radio Resource Management (RRM) scheduling.

These technologies enhance overall network performance and efficiency while supporting high data throughput.

Deployment Considerations:

Deployment decisions hinge on the balance between resource allocation, CAPEX, OPEX, and user demand. LTE deployment can follow two approaches:

1. **Progressive Deployment:**
    - Lower costs for infrastructure and devices.
    - Gradual expansion that accommodates limited initial budgets.
    - However, this approach may lead to degraded quality of service (QoS) as users transition between LTE-Advanced covered and non-covered areas.
2. **Full Deployment:**
    - Ensures end-user demands are fully met and overcomes coverage limitations.
    - Comes with significantly higher CAPEX and OPEX.

When deploying LTE-Advanced, strategies must include optimizing mobile broadband (MBB) adoption, utilizing spectrum and base stations efficiently, managing backhaul and core network resources, and developing tariff models that attract users while generating revenue.

Outdoor Small Cells:

Strategically positioned outdoor small cells in high-traffic zones can boost a macro cell's capacity by up to 400% with the addition of four metro outdoor small cells per macro cell. However, placing small cells too close to the center of a macro cell may cause competition among them, reducing effectiveness. To maximize return on investment (ROI), hotspots must be optimally positioned.

For outdoor small cells, a dedicated carrier is recommended:

- This avoids interference with macro cells, providing broader coverage.
- Reduces CAPEX expenses, optimizes total cost of ownership (TCO), and diverts more traffic from macro networks.

Based on these factors and the 3GPP technical standards for outdoor small cells ([3GPP TR 36.932]), it is generally accepted that deploying two metro cells per macro cell is an optimal configuration.

Generally

- Carrier Aggregation (CA) enables bandwidth aggregation for improved efficiency:
    - **Intra-Band CA:** Aggregates contiguous carriers within the same band.
    - **Inter-Band CA:** Aggregates carriers across different bands (e.g., Band 1, 3, 7, 20).

Addis Ababa LTE-Advanced Deployment:

- Uses **3GPP R'14 specifications** for intra-band and inter-band CA.
- A maximum of 50 MHz aggregated bandwidth is achieved using:
    - Intra-band CA: Up to 20 MHz from refarmed GSM (1800 MHz) or 3G DCS (2100 MHz).
    - Inter-band CA: Bands 3 (20 MHz), 7 (20 MHz), and 20 (10 MHz).
- Band combinations are chosen based on throughput demands, such as Bands 3 and 20 for macro cells, and Bands 1 and 7 for small cells.

5.1.2.6 Achieved optimization system techniques and RRM scheduling

To meet LTE-Advanced system requirements, several advanced methodologies have been introduced, including:

- **Cell Range Expansion (CRE):** Extends the coverage area of small cells.
- **Enhanced Inter-Cell Interference Coordination (eICIC):** Reduces interference between macro and small cells.
- **Carrier Aggregation (CA):** Combines multiple frequency bands to enhance data throughput.
- **Heterogeneous Networks (HetNet):** Integrates small cells with macro cells for improved capacity and coverage.
- **Relaying:** Enhances signal quality and coverage in challenging environments.
- **Coordinated Multi-Point Transmission/Reception (CoMP):** Improves signal quality and data rates through coordination among cells.
- **Self-Optimizing Networks (SON):** Automates network management and optimization.
- **Advanced MIMO Systems:** Increases spectral efficiency and data rates with higher-order antennas.

Innovative Small Cell Technologies

Manufacturers also provide innovative small cell solutions for cost-effective coverage enhancements:

- **Radio Dot System (RDS):** Developed by Ericsson, it delivers high-performance coverage in areas like parking lots, underground basements, and buildings unsuitable for traditional base stations.
- **Hardened Radio Dot (HRD):** Designed for challenging environments like stadiums and outdoor events. HRD supports LTE-A features such as 256QAM, D-MIMO, and CA.

Deployment Scheduling and Transmission Processing

CoMP deployment involves two main options:

1. **Centralized Control (Option 1):**
    - Combines macro/high-power RRH in Scenarios 1 and 2.
    - Utilizes a centralized eNodeB that connects multiple remote radio equipment (RRE) using optical fiber.
    - The eNodeB manages radio resources with minimal propagation delay but faces increased processing loads and higher optical cable capacity requirements as RRE

count rises.

2. **Autonomous Distributed Control (Option 2):**
    - Involves independent eNodeBs in Scenarios 3 and 4, combining macro and low-power RRH setups.
    - Signals are exchanged over wired channels, but varying propagation distances can cause delay discrepancies.

Downlink (DL) and Uplink (UL) CoMP Classifications

Downlink CoMP Techniques:

- **Joint Processing (JP):**
    - Multiple cells transmit data to a single UE simultaneously to improve signal quality and throughput.
    - Subcategories:
        - **Coherent Transmission:** Uses phase combining at the receiver and pre-coding between cells.
        - **Non-Coherent Transmission:** Utilizes soft combining of the OFDM signal.
    - Hybrid configurations allow some cells to transmit data using JP while others use Coordinated Beamforming and Scheduling (CBS).
- **Coordinated Beamforming/Scheduling (CBS):**
    - Data is sent from one cell to a UE using a single channel, with beamforming and scheduling coordinated to minimize interference to other cells.

Uplink CoMP Techniques:

- **Joint Reception:**
    - Signals transmitted by the UE are received simultaneously by multiple points or cells to enhance signal quality.
- **Coordinated Scheduling and Pre-Coding (CBS):**
    - Coordination among points determines user scheduling and pre-coding, but the information is directed to a single point.

A distinct feature in UL CoMP is the use of Virtual Cell IDs (VCID), which differentiate broadcast and reception points. For example, a device may receive uplink via a small cell and downlink via a macro cell depending on interference conditions, though the UE remains unaware of the multi-cell reception.

Generally

Optimization Techniques:

- **Cell Range Expansion (CRE):** Expands the effective range of small cells.
- **Enhanced Inter-Cell Interference Coordination (eICIC):** Reduces interference between macro and small cells.
- **Carrier Aggregation (CA):** Combines multiple carriers to enhance bandwidth.
- **Coordinated Multi-Point (CoMP):** Improves signal quality through coordinated transmissions.
- **Self-Optimizing Networks (SON):** Automates network performance adjustments.

Deployment Scheduling:

- Two CoMP deployment options:
    - **Centralized Control:** Uses high-power remote radio heads (RRH) for efficient resource allocation.
    - **Distributed Control:** Involves independent eNodeBs, accommodating propagation delay differences.

5.1.2.7 Ethio telecom's advanced deployment option, LTE (Addis Ababa)

The LTE-Advanced deployment option for Addis Ababa employs carrier aggregation (CA) for macro and small cells, chosen based on performance, cost considerations, and current trends. The carrier aggregation setup leverages both re-farmed unused band slots and newly available bands following the 3GPP Release 14 specifications.

Spectrum and Bandwidth Allocation

From the available spectrum resources, a maximum aggregated bandwidth of 50 MHz is achievable using:

- **Intra-Band CA:** Aggregating three component carriers (3CC) from selected bands.
- **Inter-Band CA:** Combining carriers from bands 1 (5 MHz), 3 (20 MHz), 7 (20 MHz), and 20 (10 MHz).

As a minimum, **10 MHz bandwidth** is achievable using intra-band CA. Depending on the carrier configuration (1CC, 2CC, or 3CC), bandwidths between **5 MHz and 50 MHz** are attainable through either intra-band or inter-band carrier aggregation.

For better efficiency, **intra-band CA** is preferred if sufficient bandwidth is available to support LTE-A. However, this depends on network and UE capabilities, as UEs must decode and modulate up to three non-contiguous component carriers (CCs).

Band Re-Farming

- **GSM Spectrum:** Re-farming the 1800 MHz band yields a 20 MHz bandwidth using intra-band CA across the eNodeB sectors or cells.
- **3G DCS Spectrum:** Re-farming the 2100 MHz band provides a 5 MHz bandwidth using intra-band CA across the eNodeB sectors or cells.

By combining bands 3, 7, and 20, a total inter-band aggregated bandwidth of **50 MHz** is obtained. Similarly, using single CC or 2CC configurations for either intra-band or inter-band CA across bands 1, 3, 7, and 20, bandwidths ranging from **5 MHz to 40 MHz** are available for uplink operations.

Deployment Scenarios

Considering the higher throughput requirements for LTE-Advanced, optimized combinations of bandwidth and bands are utilized:

- **Macro Cells:** Bands 3 and 20 are prioritized for macro cell deployments.
- **Small Cells:** Bands 1 and 7 are used for small cell deployments.

This approach ensures enhanced performance and efficient use of spectrum resources while addressing network complexity and user equipment (UE) capabilities.

Generally

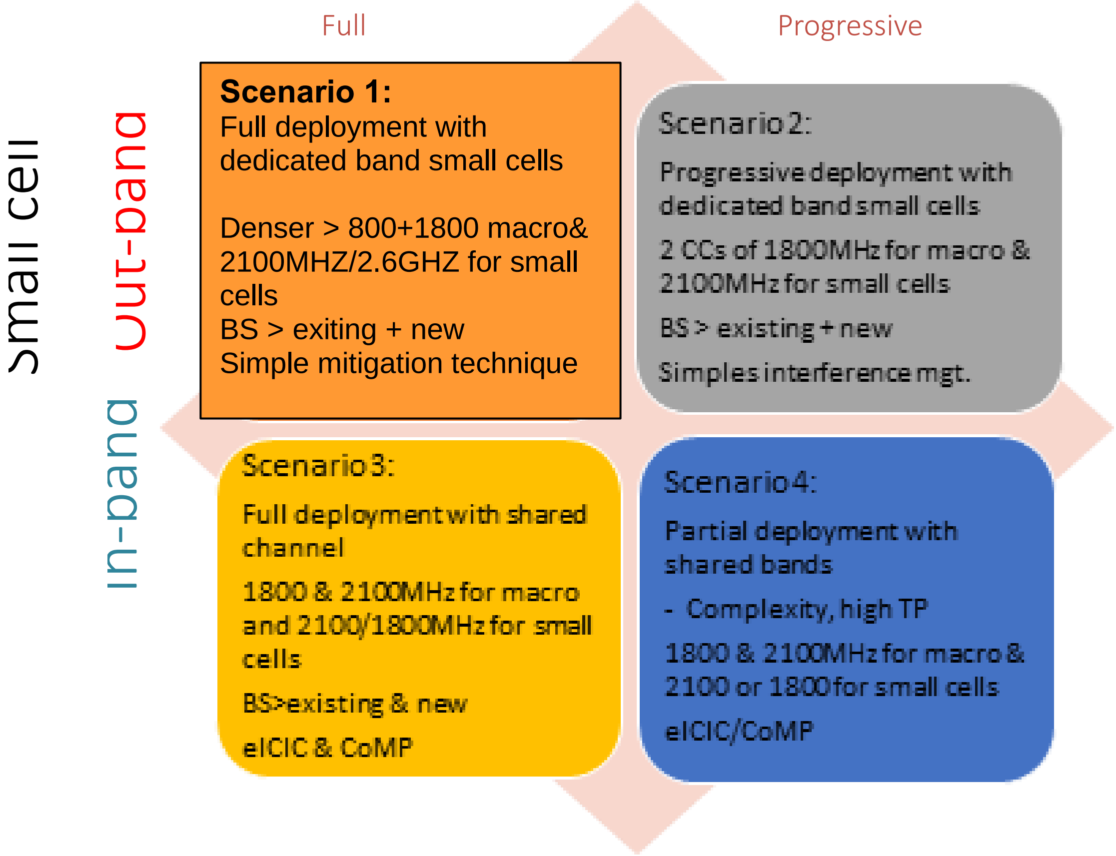
- Deploys macro and small cells using intra-band and inter-band CA for bandwidth up to 50 MHz.
- Optimized band combinations for specific scenarios:
    - Macro cells: Bands 3 and 20.
    - Small cells: Bands 1 and 7.
- Strategically places small cells in high-traffic areas to offload macro cells, ensuring higher throughput and better QoS.

The LTE-Advanced deployment in Addis Ababa incorporates advanced technologies like CA, HetNets, and CoMP to overcome challenges like ICI and limited indoor coverage. Optimization techniques focus on improving spectral efficiency, enhancing QoS, and ensuring cost-effective scalability for future demands.

Summary:

The following scenario matrix are selected as the LTE - advanced deployment option for Addis Ababa. Carrier aggregation for macro and small cells is selected for LTE-A deployment based on the discussed trends, performance and cost. The carrier aggregation combination is performed by re-farming the existing unused band slots and also based on new bands using 3GPP R’14 specifications. From the available spectrum resources, maximum of 50MHz aggregated bandwidth is obtainedusing intra-band CA of 3CC from the selected bands or inter-band CA of 3 component carriers from the list band 1(5MHZ), 3(20MHZ), 7(20MHZ) & 20(10MHZ), and as minimum as 10MHz using intra-band carrier aggregation respectively, from this, using 1CC, 2CC& 3CC a BW of 5-50MHZ is possible using either intra or inter band carrier aggregations. For better efficiency, usingintra-band carrier aggregation is preferable if the operator has required bandwidth for LTE-A and in parallel includes network and UE complexity; as UEs has to decode, modulate up to three non-contiguous CCs. By re-farming the existing GSM spectrum band, 20MHz bandwidth is obtained using intra-band carrier aggregation from the component carriers of 1800MHz band on either of the eNodeBs sectors or cells. And also by re-farming the existing 3G DCS spectrum band, 5MHz bandwidth is obtained using intra-band carrier aggregation from the component carriers of 2100MHz band on either of the eNodeBs sectors or cells. Consequently, a combination of band 3, 7 and 20 provide 50MHz inter band aggregated bandwidth. In the same scenarios from either single CC or 2CC of inter or intra band carrier aggregation of band 1,3,7&20, from 5 up to 40MHZ bandwidth is activated and used in the uplink. Considering higher throughput requirements for LTE-A, a combinationof higher bandwidth is taken for the succeeding scenarios using band 3 and 20 for macro while band 1 and 7 for small cells.

Deployment options of carrier aggregations for full and progressive scenarios is as following:



5.1.2.8 Optimization analysis result of survey data collection, case of ethio telecom

Optimization Analysis Results of Survey Data Collection: Case of Ethio Telecom

The survey data collection and analysis for Ethio Telecom's LTE and LTE-Advanced network reveal critical insights into the network's configurations, performance, and limitations. Below are the findings and their implications:

1. Radio Frequency Bands and Carrier Aggregation (CA):

- **Radio Frequency Bands Used:**
    - **2600 MHz** (Band 7), **800 MHz** (Band 20), **1800 MHz** (Band 3), and **2100 MHz** (Band 1).
    - Licensed and available carrier bandwidths range from **10 MHz to 75 MHz**, depending on the band.
- **Carrier Aggregation (CA):**
    - **Downlink Configurations:** 1CC, 2CC, or 3CC combinations of **5, 10, 20, 40, or 50 MHz**.
    - **Uplink Configurations:** 1CC or 2CC with bandwidths up to **40 MHz**.
- **Deployment Characteristics:**
    - **2600 MHz** and **2100 MHz** are primarily used in **indoor environments**, high-density areas, and transportation hubs for their high capacity and throughput over short ranges.
    - **800 MHz** and **1800 MHz** support **macro cells**, offering broader coverage and stable throughput.
- **CA Challenges:**
    - CA is more effective within the same or nearby eNodeBs but is rarely implemented across distant macro eNodeBs due to:
        - Coverage and signal strength limitations.
        - Resource shortages.
        - Architectural constraints.

2. MIMO Configurations and Theoretical Throughput:

- **Channel Configurations and Bandwidth:**
    - Example for **50 MHz** bandwidth:
        - **250 RBs** produce **42 million symbols/second (MSps)**.

        - Using **64-QAM (6 bits/symbol)** and **4x4 MIMO**, the theoretical maximum throughput is **756 Mbps (after accounting for 25% signaling overhead)**.
    - Example for **40 MHz** bandwidth:
        - **200 RBs** produce **33.6 MSps**, leading to **604.8 Mbps (uplink)** after applying signaling overhead.
- **Practical Constraints:**
    - Theoretical throughputs are rarely achieved due to:
        - Signal strength variations.
        - Mobility challenges during handovers.
        - Limited adaptive modulation utilization under weak signal conditions.

3. CoMP and HetNet Deployments:

- **Current State:**
    - CoMP is limited in macro eNodeBs due to:
        - High distance between sites.
        - Insufficient resource coordination and signal strength.
    - Macro cells are more stable than small cells, but they face challenges in supporting advanced CoMP HetNet configurations.
- **Challenges:**
    - Movable User Equipment (UE) often experiences signal degradation, resulting in:
        - High call drop rates.
        - Congestion and reduced throughput.

4. LTE-Advanced and LTE-Pro Deployment:

- Ethio Telecom’s LTE-Advanced deployment provides **0.5–1 Gbps average data rates** for users but is limited to **45–50 MHz channel capacity**.
- To support the theoretical maximum of **100 MHz channel bandwidth**, the network requires:
    - **License activations** for additional spectrum.

  - Advanced administrative configurations.
  - Cost amendments for upgrades and resource optimization.

Key Recommendations for Ethio Telecom:

1. **Enhance Carrier Aggregation and Spectrum Utilization:**
    - Activate licenses and reconfigure systems to support **100 MHz channel capacity** for LTE-Advanced and LTE-Pro.
    - Expand spectrum availability through re-farming and acquiring additional licenses for higher data rates and throughput.
2. **Improve CoMP and HetNet Deployments:**
    - Invest in small cell backhaul and resource coordination to enhance CoMP HetNet configurations.
    - Focus on deploying CoMP in areas where macro cells cannot fully address congestion and coverage gaps.
3. **Optimize MIMO and Modulation Techniques:**
    - Maximize **adaptive modulation** and MIMO configurations by improving network architecture and signal strength.
    - Use advanced scheduling techniques to ensure stable connections for moving UEs.
4. **Upgrade Network Management Tools:**
    - Utilize sophisticated planning tools to optimize RF configurations, such as Atoll or WinProp, for real-world scenarios.
5. **Strategic Investments in LTE-Pro to 5G Transition:**
    - Plan for cost-effective transitions to **5G-ready technologies**, leveraging LTE-Pro components like massive MIMO, HetNets, and low-latency access methods.

Summery:

While Ethio Telecom’s LTE-Advanced network offers robust coverage and capacity, challenges remain in achieving theoretical throughput and fully utilizing advanced features like CoMP. Strategic upgrades in licensing, resource optimization, and small cell deployments can significantly improve performance and prepare the network for a seamless transition to 5G.

Optimization survey data collection analysis result

Thesis data collection survey is performed from ethio telecom for collecting; radio frequency, spectrum band, carrier aggregation, cell structure, channel configurations, modulation types, multiplexing structures, MIMO types, CoMP configurations, Channel bandwidth architecture, data bandwidth or data rate, throughput, infrastructures, … According to the survey assessment, ethio telecom uses four radio frequencies bands: 2600MHZ in band 7, 800MHZ in band 20, 1800MHZ in band 3 & 2100MHZ in band 1. From this bands a carrier aggregation of three bands having a total of 10MHZ to 50MHZ channel bandwidth from the three sectors in eNodeB, from different band cell carriers of a sector of eNodeB or and from different bands of a sector of eNodeB. The eNodeB cells have a channel of only 10MHZ from the available carrier bandwidth of 30MHZ band 20(**832 – 862 MHZ in Uplink and 791 – 821MHZ Down link**) in 800MHZ radio frequency, 20MHZ from the available carrier bandwidth of 75MHZ band 3(**1710 – 1785 MHZ in Uplink and 1805 – 1880MHZ in Down link**) in 1800MHZ radio frequency, 20MHZ from the available carrier bandwidth of 70MHZ band 7(**2500 – 2570MHZ in Uplink and 2620 – 2690MHZ in Down link**) in 2600MHZ radio frequency, 5MHZ from the available carrier bandwidth of 60MHZ band 1(**1920 – 1980MHZ in Uplink and 2110 – 2170MHZ in Down link**) in 2100MHZ radio frequency. These four available radio frequency are available and licensed by the international telecommunication unions **(ITU)**. In the NR 5G networks there are licensed and unlicensed radio frequencies available for enhancing the bandwidth and throughput of the cellular networks. The sites (eNodeBs) with three sectors (1800MHZ with 100% coverage, 2600MHZ and 2100MHZ with 50% coverage and then 800MHZ with about 29% coverage). Radio frequency 2600MHZ and 2100MHZ is mostly used for eNodBs for indoor, garage, rood ways, buildings, malls, rail ways, airports and dense areas with small range coverage for high capacity and throughput comparatively with the 800& 1800 MHZ RFs. Radio frequency 800& 1800 MHZ are deployed for macro cells for long coverage and high throughput. And also there are different band configurations available and activated in ethio telecom such as; 1CC (5,10 or 20MHZ), 2CC (5+10, 5+20, 10+20, 20+20 MHZ) or 3CC (5+10+20, 5+20+20, 10+20+20MHZ) carrier aggregations in the downlink. In the uplink a CA of 1CC or and 2CC of 5,10,15, 20, 25, 30, 35 and 40MHZ available as the same configurations in the downlink scenario. The existing free GSM 1800MHZ and UMTS 2100MHZ radio frequency is re-farmed and used in the LTE-advanced or LTE-pro system. The carrier aggregation is used from the same or different macro eNodeB and from different small cells with the coordinated multi point(CoMP) E-UTRAN CA configurations. But the CA is may not usually used from many different macro eNodeBs in the CoMP scenarios because of distance, resource shortage, signal strength and architectural and areal not comfortable. It has also different types of MIMO configurations. So ethio telecom customers can enjoy with high bandwidth data throughput from the carrier aggregation, MIMO, adaptive modulations and radio frequency radio resource scheduling. A frame has 10 sub frames (20 slots) of 10 milliseconds. For the BW of 50MHZ, there is 50MGZ/180KHZ=250 RB. Each RB in a 1millisecond sub frame has 12*7*2=168 symbols per milliseconds in normal cyclic prefix (CP) modulations. For 250 RB, 250*168=42000 symbols per milliseconds or 42000000 symbols per seconds or 42MSps (mega symbols per second). For very strong signaling scenario a maximum modulation is used of 64 QAM means 6 bits per symbol. Then 42*6=252 Mbps. Using 4x4 MIMO, 252*4=1008Mbps and finally removing 25% overhead used for signaling (1008-1008*25%) will give a theoretical throughput 756Mbps in the download. The average capacity of eNodeB or three sectors, there is 2268Mbps (2.268Gbps). And for BW of 40MHZ, there is 200 RB and 200*168 = 33,600 symbols per milliseconds or 33,600,000 symbols per seconds or 33.6MSps (mega symbols per second). Using 4x4 MIMO, 33.6*6= 201.6Mbps and 806.4Mbps. Removing 25% overhead used for signaling (806.4-806.4*25%) = 604.8Mbps for the uplink. But due to signal strength conditions, CoMP like macro cell HetNets, adaptive modulation configuration may not fully utilize, it is not possible to get the theoretical throughput exactly.

In ethio telecom there is limitation of areal architecture, resources and frequency spectrum carrier aggregation with HetNets and CoMP E-UTRAN configurations for the macro eNodeBs case. Due to the coverage, capacity and site distribution conditions; CoMP is not implemented within E-UTRAN from the macro eNodeBs and hence there is limitations of durable, efficient and effective service usages. This is because of macro cells have high durability and stability than small cells (due to interruptions of power or transmission multimedia). A movable UE during call is probability not getting strong signals from more sites (eNodeBs) and then bearer transaction within more sites is difficult during call or there is more congestions and call drop rate and then week throughput. Also in ethio telecom, LTE-advanced and LTE-pro deployments are considered to provide services for users about averagely 0.5 - 1Gbps data rate and carrier aggregation is implemented within 45 or 50Mhz channel capacity (not implemented for maximum of 100Mhz channel capacity) in the downlink. Hence LTE-advanced or LTE-pro in ethio telecom needs license activations and high level administration configuration to support 100MHZ. As consequently upgrade of solutions needs licenses and cost amendments for maximum resource utilization optimizations.

5.2 Discussions

5.2.1 LTE optimization discussions

This thesis explored the **Bit Error Rate (BER)** and **spectral efficiency** of **SC-FDMA** systems over fading channels, providing a detailed comparative analysis with OFDMA. The study focused on mathematical modeling, statistical evaluation, and deriving performance metrics for SC-FDMA transmissions under various conditions. Below are the key discussions and contributions:

1. Contributions of the Thesis

a. Statistical Evaluation of Enhanced Noise in Frequency Domain

- **Focus:**
    - Analyzed noise amplification introduced during linear frequency-domain equalization in both OFDM and SC-FDMA systems.
    - Investigated how noise affects signal detection in fading environments like Rayleigh and AWGN channels.
- **Key Outcome:**
    - Computed the density function of the noise random variable, offering insights into its statistical distribution.

b. BER Analysis for SC-FDMA and OFDMA in Fading Channels

- **Focus:**
    - Derived closed-form equations for BER in SC-FDMA transmissions, specifically with **Zero Forcing Frequency Domain Equalization (ZF-FDE)** and **Minimum Mean Square Error Equalization (MMSE-FDE)**.
    - Assumed independence among subcarriers for analytical simplicity.
- **Key Outcome:**

    - Provided closed-form BER results for ZF-FDE and lower-bound estimates for MMSE-FDE in SC-FDMA systems.
    - Highlighted performance advantages or disadvantages compared to OFDMA under the same channel conditions.

c. SC-FDMA Spectral Efficiency Analysis

- **Focus:**
    - Extended BER analysis to study spectral efficiency for SC-FDMA transmissions over adaptively modulated Rayleigh fading channels.
    - Derived closed-form spectral efficiency formulas for both ZF and MMSE equalization schemes.
- **Key Outcome:**
    - Demonstrated the achievable spectral efficiency for realistic channel models, including **Extended Vehicular A (EVA)** and **Extended Typical Urban (ETU)**.
    - Identified scenarios that yield the lowest performance in SC-FDMA systems.

2. Key Findings and Discussions

Performance Comparisons Between OFDM and SC-FDMA

- **Noise Amplification:**
    - SC-FDMA experiences less noise enhancement at the detection stage compared to OFDM, owing to its single-carrier structure.
- **BER Performance:**
    - SC-FDMA generally outperforms OFDM in terms of BER in fading channels, particularly when ZF-FDE is used.
    - MMSE-FDE offers better BER performance than ZF-FDE due to its ability to minimize error through noise-power weighting, although it introduces complexity.
- **Spectral Efficiency:**
    - While OFDM demonstrates slightly higher spectral efficiency due to its multi-carrier nature, SC-FDMA provides better energy efficiency and lower PAPR, making it ideal for uplink transmission.

Implications for Fading Channels

- In Rayleigh and AWGN fading channels:
    - SC-FDMA offers consistent performance with reduced BER and efficient spectrum usage.
    - Noise effects are more predictable and manageable in SC-FDMA systems.

ZF vs. MMSE Equalization

- **ZF-FDE:** Provides simplicity and sufficient performance under ideal conditions but suffers in noise-dominated environments due to unbounded noise amplification.
- **MMSE-FDE:** Balances noise and interference, delivering robust BER and spectral efficiency, albeit with greater computational requirements.

3. Practical Implications

SC-FDMA for Uplink Transmission

- **Energy Efficiency:** SC-FDMA’s low PAPR ensures longer battery life for UEs, which is crucial for mobile devices.
- **Complexity Management:** While SC-FDMA requires more complex receivers, this is manageable at the base station level, which has fewer power constraints than mobile devices.

Realistic Channel Models (EVA and ETU):

- The spectral efficiency analysis under these models highlights SC-FDMA’s resilience in realistic propagation scenarios, making it a suitable choice for uplink transmissions in LTE and LTE-Advanced systems.

Future Considerations:

- The derived BER and spectral efficiency formulas can be used for further optimization in 5G and beyond, especially for low-PAPR transmission techniques like SC-FDMA.

4. Summery

This thesis provides valuable insights into the performance of SC-FDMA systems over fading channels, emphasizing its advantages in BER and energy efficiency compared to OFDMA. The derived formulas and statistical models offer a foundation for further research into optimizing uplink transmissions in current and future wireless communication systems.

5.2.2 LTE - advanced optimization discussions

Effective optimization and planning are critical to balancing the trade-offs between **Quality of Service (QoS)** and cost in LTE-Advanced (LTE-A) networks, particularly in environments like Addis Ababa, where demand for mobile data is rapidly increasing. The study underlines key aspects such as **resource management**, **deployment scenarios**, and **techno-economic considerations** in designing a scalable, efficient LTE-A network.

1. Deployment Planning and Scenarios

Progressive Rollout vs. Full Deployment

- **Progressive Rollout:**
  - Features gradual implementation to minimize initial costs and manage resource allocation incrementally.
  - However, it may result in uneven QoS in areas not yet covered by LTE-A, leading to user dissatisfaction.
- **Full Deployment:**
  - Offers comprehensive coverage and enhanced QoS from the outset.
  - Comes with higher upfront **CAPEX** and **OPEX**, making it resource-intensive.

Feasibility Applications Framework

- The study evaluates deployment options using criteria such as:
  - **Coverage:** Ensuring consistent and widespread signal availability.
  - **Capacity:** Meeting current and future user demand efficiently.
  - **Spectrum Dimensioning:** Optimizing the allocation of available spectrum while planning for future needs.
  - **Small Cells:** Addressing capacity demands in high-density areas.
  - **Techno-Economic Factors:** Balancing costs, revenues, and resource constraints.

2. Case of Ethio Telecom: Traffic Growth and Infrastructure Challenges

Traffic Growth and Demand Trends

- Mobile data demand in Addis Ababa is increasing exponentially, driven by urbanization and the proliferation of high-bandwidth applications.
- Existing network infrastructure struggles to meet the growing demand for **coverage**, **capacity**, and **throughput**, highlighting the need for LTE-A upgrades.

Key Insights from the Analysis

- **Network Evolution:**
  - LTE-A's advanced features, including carrier aggregation (CA) and small cells, make it suitable for addressing Addis Ababa's traffic demands.

  - Spectrum repurposing and backhaul upgrades are pivotal to ensuring scalability.
- **Resource Assessment:**
  - **Spectrum:** Current resources are underutilized in some bands, while new bands are recommended for dense indoor environments.
  - **Base Stations:** LTE base stations are upgradeable, with options to add new sites where required.
  - **Backhaul:** Existing infrastructure can support LTE-A but may need enhancements in specific scenarios.

3. Optimization and Resource Management

Spectrum Dimensioning

- **Predictive Planning:**
  - Spectrum demand is forecasted on a six-year basis, accounting for population growth, urbanization, and technological advancements.
- **Reallocation:**
  - Repurposing unused bands (e.g., from legacy GSM or 3G networks) provides additional bandwidth for LTE-A.
- **New Bands for Small Cells:**
  - Targeted deployment of new spectrum in high-traffic indoor areas ensures efficient network performance.

Small Cell Deployment

- Small cells address localized capacity challenges, particularly in:
  - Crowded metropolitan areas.
  - Indoor environments like malls and office buildings.
- **Benefits:**
  - Offloading traffic from macro cells.
  - Enhancing frequency reuse and QoS.
- **Challenges:**
  - Ensuring robust backhaul connectivity and managing interference with macro cells.

Backhaul Enhancements

- Adequate backhaul is critical to supporting the increased data flow in LTE-A networks.
- The study emphasizes:
  - Leveraging existing backhaul infrastructure with targeted upgrades.
  - Exploring both wired and wireless backhaul options based on cost and feasibility.

4. Scenario Planning and Analytical Techniques

Local Context and Uncertainties

- The study employs **scenario planning** and **PESTLE analysis** to address uncertainties in the local context.
- Trends such as urban population growth, technological adoption, and regulatory policies influence the choice of deployment strategies.

Techno-Economic Metrics

- Viability assessments incorporate both technical and economic parameters:
  - **Technical:** Coverage, capacity, and QoS metrics.
  - **Economic:** CAPEX, OPEX, and return on investment (ROI).

5. Conclusions and Recommendations

Key Observations

- Mobile data traffic in Addis Ababa is expected to grow significantly, necessitating a robust and scalable LTE-A network.
- Effective planning and optimization must address spectrum management, resource allocation, and infrastructure upgrades.

Recommendations for Ethio Telecom

- **Progressive Rollout:** Begin with high-demand areas, gradually expanding coverage to balance costs and QoS.
- **Spectrum Strategy:** Focus on repurposing existing bands and deploying new bands strategically for small cells.
- **Small Cell Deployment:** Use hotspots and indoor environments to manage traffic density and improve QoS.
- **Backhaul Investments:** Enhance existing backhaul while exploring cost-effective wireless solutions.
- **Analytical Framework:** Continuously assess technical and economic viability to adapt to evolving market demands.

By addressing these areas, Ethio Telecom can establish a future-proof LTE-A network that meets Addis Ababa’s growing mobile data needs efficiently and sustainably.

5.3 Conclusions

5.3.1 LTE conclusions

LTE Conclusions on Uplink Transmission and PAPR Performance

Coverage Expansion and Efficiency:

Reducing the uplink signal’s peak power by just a few dB significantly enhances the coverage area, addressing the challenges of uplink transmission in scenarios where battery usage is a limiting factor. This efficiency leads to **notable deployment cost savings**, as SC-FDMA systems—particularly with **DFDMA** (Distributed FDMA) and **LFDMA** (Localized FDMA)—require fewer base stations than OFDMA to serve rural areas.

SC-FDMA as a Key Technology:

SC-FDMA, adopted in **3GPP LTE and LTE-Advanced**, is a superior uplink transmission technology and a strong candidate for **IMT-Advanced standards** due to its low Peak-to-Average Power Ratio (PAPR).

Simulation Study Findings:

The study compared the PAPR of **SC-FDMA (DFDMA and LFDMA)** and **OFDMA** uplink signals, with key findings:

1. **DFDMA vs. LFDMA vs. OFDMA**:
   - LFDMA has a higher PAPR than DFDMA but a lower PAPR than OFDMA.
   - This demonstrates that **DFDMA outperforms LFDMA** in leveraging SC-FDMA's low-PAPR advantage.
2. **Pulse Shaping Effects**:
   - Adding pulse shaping using a **raised-cosine filter** increases PAPR.
   - **DFDMA** shows progressive performance improvement with increased roll-off factors, whereas **LFDMA** shows minimal improvement.
3. **Modulation and PAPR**:
   - Higher-order modulation techniques (e.g., 64-QAM) tend to increase PAPR in SC-FDMA while slightly reducing it in OFDMA.
   - **SC-FDMA retains a lower overall PAPR** compared to OFDMA across all modulation schemes, making it suitable for uplink.

Recommendations for Uplink Transmission:

- To minimize PAPR at the user end, **lower-order modulation schemes** like BPSK, QPSK, and 16-QAM are preferred for uplink transmission.
- Optimizing **DFDMA subcarrier mapping** and fine-tuning the roll-off factor of pulse-shaping filters can further improve performance.

Conclusion:

The adoption of SC-FDMA in LTE uplink systems provides significant advantages in terms of PAPR, coverage, and energy efficiency, particularly for rural deployments. Adaptive modulation strategies and careful resource allocation remain critical for achieving optimal performance and meeting the stringent requirements of LTE and LTE-Advanced networks.

5.3.2 LTE-advanced conclusions

Heterogeneous Networks (HetNets):

- **Benefits**:
  HetNets enhance user signal strength in areas with good coverage, increase user throughput, and optimize overall network capacity. These networks achieve this through **network densification**, using a variety of small cells to:
  - Expand coverage areas.
  - Transfer loads to improve service quality.
  - Boost network capacity.
- **Challenges**:
  The addition of small cells from various tiers can result in **interference**, particularly when co-channel bandwidth is used.
  - LTE-A introduces advanced features like **Almost Blank Subframes (ABS)** and **enhanced Inter-Cell Interference Coordination (eICIC)** to reduce interference and improve user throughput.
- **Theoretical vs. Practical Applications**:
  Current HetNet studies often rely on **idealized models** (e.g., full buffer, hexagonal cells) for mathematical simplicity.
  - While these models showcase the **upper bounds** of HetNet capabilities, they may **overestimate performance** in real-world deployments.
  - To bridge this gap, realistic traffic models are required to **accurately predict user throughput** and **Signal-to-Interference-plus-Noise Ratio (SINR)** using practical indicators, aiding better network planning and enhancing user experiences.

Enhanced Coordinated Multi-Point (CoMP):

- **Improvements**:
  CoMP techniques are shown to significantly enhance the experience of **cell-edge users**, addressing interference in both homogeneous and heterogeneous networks.
- **Real-World Feasibility**:
  - The feasibility of deploying CoMP is improving with advancements in:
    - **Backhaul connectivity**.
    - **Cost-effective radio nodes**.
    - **Faster processing units** at base stations and user terminals.
  - Enhanced **beam shaping** and innovative carrier types can further reduce interference, making CoMP a practical solution in HetNet environments.
- **Growing Interest**:
  As novel network topologies like HetNets and geographically distributed antennas

become prevalent, demand for **interference mitigation solutions** like CoMP will increase.

Massive MIMO (Multiple-Input, Multiple-Output):

- **Functionality**:
  Massive MIMO involves the use of many antennas at base stations to:
  - Increase speed, capacity, and efficiency in cellular networks.
  - Employ **multi-user spatial division** to create unique narrow beams for each user, allowing simultaneous data transfer with spatial isolation.
- **Performance**:
  - System throughput can improve **dozens of times** through spatial isolation.
  - **Theoretical capacity** increases as user channels become orthogonal with a rising number of antennas.
  - In practical networks:
    - Single-user link performance improves by ~10x.
    - System capacity increases by 4–8 times, even with limited configurations like 64T64R antennas.
- **Challenges**:
  - Massive MIMO requires significant resources for:
    - **Pilot-channel estimation**.
    - **Air-division calculations**.
    - **Large-scale antenna deployments**.
  - While theoretically promising, early massive MIMO systems were commercially unviable due to these high demands.
- **Current Feasibility**:
  Advancements in technology have made **commercial deployment** more practical, particularly for systems with fewer active multi-antennas. This allows massive MIMO to play a transformative role in modern LTE-Advanced and future 5G networks.

Summary:

LTE-Advanced leverages **HetNets**, **CoMP**, and **Massive MIMO** to address challenges like interference and capacity limitations while enhancing coverage and throughput. Practical deployment of these technologies requires advancements in hardware, realistic modeling, and efficient resource management to unlock their full potential.

LTE advanced Conclusions on the technologies innovations in 5G

Many **LTE-Advanced: Innovations Shaping 5G Technologies**

While the deployment of 4G LTE is still ongoing, several advancements and innovative concepts emerging from **LTE-Advanced** are paving the way for 5G. These innovations, whether as extensions of LTE or entirely new directions, are set to transform mobile networks. Key technologies and their potential impact on 5G include:

1. Small and Compact Base Stations via Nanotechnology

- Nanotechnology enables the development of **miniature and highly efficient base stations**, crucial for increasing network densification.
- These compact stations improve coverage and capacity while reducing energy consumption and deployment costs.

2. Enhanced Multicarrier Modulation Scheme

- Advanced modulation schemes build on LTE’s OFDMA and SC-FDMA to provide

higher spectral efficiency and better resilience against interference, enabling more reliable and high-speed data transmission.

3. Centralized Radio Access Technology (RAT)

- Centralizing radio access management allows for:
    - **Dynamic resource allocation** across multiple cells.
    - Improved coordination, leading to reduced interference and enhanced network efficiency.

4. End of the Cell Concept (Coordination/Collaboration)

- Moving away from traditional cell-based architecture:
    - Encourages coordination between base stations and users.
    - Enables seamless communication and higher throughput without rigid boundaries.

5. Spectra Fragmentation

- Techniques to efficiently manage fragmented spectrum:
    - Allow dynamic aggregation of non-contiguous frequency bands.
    - Maximize the use of available spectrum resources.

6. Cloud Computing

- **Cloud-based architectures** bring scalability, flexibility, and cost-effectiveness to network operations.
- Facilitate **centralized processing** for managing large volumes of data in real-time, critical for IoT and edge computing.

7. Nanotechnology Applications Beyond Base Stations

- Innovations in **nano-scale antennas** and **materials** promise breakthroughs in performance, energy efficiency, and device miniaturization.

8. Versatile Low-Latency Frame Structure

- Low-latency frame structures are key to meeting 5G requirements for real-time applications, including:
    - Autonomous vehicles.
    - Remote healthcare.
    - Industrial automation.

9. Spectrum Pooling and Cognitive Radio

- **Spectrum pooling** allows multiple operators to share spectrum dynamically, improving spectral efficiency.
- **Cognitive radio** technologies enable devices to detect and utilize underutilized spectrum, optimizing network capacity.

10. Optimized Resource Allocation Mechanisms

- Enhanced algorithms for resource allocation ensure efficient management of network resources:
    - Reducing congestion.
    - Prioritizing critical applications.
    - Boosting overall user experience.

11. Further Enhanced Self-Optimizing Networks (eSON)

- LTE-Advanced’s Self-Optimizing Networks evolve into **eSON** for 5G:

    - Adaptive configurations for traffic and interference management.
    - Autonomous network adjustments to maintain optimal performance under dynamic conditions.

Summery

These innovations—stemming from LTE-Advanced—represent a critical foundation for 5G, driving advancements in **network architecture**, **resource efficiency**, and **latency reduction**. By integrating technologies like **nanotechnology**, **cloud computing**, and **cognitive radio**, 5G is set to provide unprecedented levels of connectivity, speed, and scalability, meeting the demands of next-generation applications and services.

Conclusions: Case of Ethio Telecom LTE and LTE-Advanced Networks

Ethio Telecom's **LTE and LTE-Advanced network assessments** reveal the following key features and challenges in deploying and optimizing carrier aggregation (CA) and coordinated multipoint (CoMP) technologies:

Carrier Aggregation (CA):

- **Current Band Configurations:**
    - The network supports up to **three component carriers (CC)** with **non-contiguous** bandwidths of **20+20+10 MHz**.
    - **Two component carriers (20+20 MHz)** are also supported, either in **contiguous** or **non-contiguous** configurations, from the same eNodeBs.
- **Technological Diversity:**
    - Ethio Telecom employs **adaptive modulation**, **multiplexing coding**, and **MIMO antenna systems** to maximize spectrum utilization and throughput.

Challenges in CoMP and HetNet Deployments:

- **CoMP HetNet Limitations:**
    - Effective **CoMP HetNet coordination** among multiple macro eNodeBs is limited by factors such as:
        - **Coverage distances** between macro cells.
        - **Signal strength variations** across different edge ends.
- **Customization Requirements:**
    - According to discussions with Ethio Telecom teams, the network requires **customizations and configuration updates** to enable full CoMP HetNet carrier aggregation across macro eNodeBs.
- **Small Cell Potential:**
    - While **small cells** with large capacity can support CoMP HetNets, they face challenges such as:
        - Limited **coverage area** compared to macro cells.
        - Constraints in **transmission power stability**.
        - Increased dependency on reliable backhaul connections.

Recommendations for Optimization:

1. **Enhanced Configurations for CoMP HetNet Support:**
    - Invest in advanced **network planning tools** and algorithms to improve inter-cell coordination and enable full CoMP functionality across macro and small cells.
2. **Expansion of Small Cell Deployments:**
    - Strategically deploy small cells to address gaps in coverage and enhance capacity, while optimizing backhaul and power stability.
3. **Dynamic Resource Allocation:**

- Leverage enhanced **adaptive modulation and coding** techniques to better manage spectrum and mitigate signal variations across edge ends.

4. **Collaboration with Vendors:**
    - Work with equipment vendors to develop **custom solutions** that address Ethio Telecom's unique coverage and capacity challenges, ensuring scalability and interoperability of network components.

Summary:
Ethio Telecom's LTE and LTE-Advanced networks demonstrate strong foundational capabilities in carrier aggregation and adaptive technologies. However, limitations in **CoMP HetNet coordination** across macro eNodeBs, as well as challenges with small cell deployments, highlight areas for improvement. Strategic investments in **custom configurations**, **small cell expansions**, and **dynamic resource management** are critical to unlocking the full potential of these advanced network features.

5.4 Future works

5.4.1 LTE - future work

Although the project has achieved its primary objectives—optimizing throughput, bandwidth, core and radio resources, capacity, coverage, cost, and quality of service—there remain numerous opportunities for deeper exploration and refinement. The following suggestions for future work offer avenues for advancing LTE research and practical implementations:

1. Subcarrier Correlation Analysis

- Current studies often assume subcarriers are independent. Future research should:
    - Examine the effects of **correlation** between subcarriers to develop models that account for more general scenarios.
    - Extend findings from **Zero-Forcing Frequency Domain Equalization (ZF-FDE)** in OFDM to evaluate **Bit Error Rate (BER)** performance in SC-FDMA under diverse fading channels.

2. Impact of Restricted CQI Feedback

- Investigate the influence of **restricted Channel Quality Indicator (CQI) feedback** on the spectral efficiency of SC-FDMA and OFDMA.
- This will enable a **fair comparison** of these technologies under limited feedback scenarios, potentially refining **channel-state-dependent scheduling algorithms**.

3. Signal-to-Quantization Noise Ratio (SQNR) Improvements

- Explore ways to mitigate high PAPR effects in uplink signals:
    - Use **raised-cosine roll-off factors** to reduce the impact on SQNR after amplitude clipping.
    - Optimize clipping and shaping techniques to enhance system robustness.

4. Integration of MIMO Techniques

- Incorporate **Multiple-Input Multiple-Output (MIMO)** techniques into models:
    - Evaluate the combined effects on BER, spectral efficiency, and system performance.
    - Use realistic configurations to analyze practical implications.

5. Error Correction and Demodulation Enhancements

- Investigate **Forward Error Correction (FEC)** to address challenges in channels with high subcarrier counts.

- Conduct a comprehensive analysis of demodulation design for scenarios requiring large correlation windows:
    - Implement **Maximum Likelihood Sequence Detection (MLSD)** techniques to improve BER performance.

6. Bandwidth Efficiency vs. Complexity Trade-offs

- Study the balance between **bandwidth efficiency** and **demodulation complexity** in OFDM systems:
    - Evaluate how higher-order correlation windows reduce out-of-band power and impact complexity.
    - Combine **time-domain windowing** with advanced equalization techniques to address residual errors in dispersive channels.

7. Adaptive Cyclic Prefix Lengths

- Optimize the length of the **Cyclic Prefix (CP)** based on real-time radio environment conditions:
    - Shorter CPs in low-dispersion environments to increase spectrum efficiency.
    - Longer CPs in highly dispersive channels to minimize inter-symbol interference (ISI).

Summary of Potential Applications

The outcomes of this research and future extensions can be applied to:

- **Scheduling algorithms** that utilize mathematical models of random variables simulating SNR at the receiver.
- Designing systems that account for **imperfect synchronization**, including effects of ISI and ICI.
- Enhancing spectral efficiency and system robustness through **time-domain equalization** and **adaptive modulation techniques**.

These directions aim to refine LTE's performance while preparing for more complex and realistic scenarios, paving the way for innovations that can transition into future wireless standards such as **5G and beyond**.

5.4.2 LTE - advanced future works

This study has laid a foundation for exploring LTE-A rollout options in **Addis Ababa**, focusing on addressing mobile data demand. Several avenues for future research and development are identified to expand on these findings:

1. Enhanced Framework Development and Analysis

- **Refinement of TERA Framework**:
    - Carefully examine all deliverables of the **TERA (Technical, Economic, Radio Access)** framework.
    - Improve the modified framework to refine **Technical-Economic Analysis (TEA)** results and provide more precise insights.
- **VoLTE Integration**:
    - Explore the **feasibility of integrating voice services and VoLTE** into LTE-A.
    - Assess its impact on LTE-A dimensioning, coverage, capacity, and the resulting TEA findings.

2. Advanced Radio Network Dimensioning and Planning

- Utilize diverse tools for LTE-A network dimensioning to improve planning accuracy:
    - **Planning Tools**: Tools like **WinProp** and **Atoll** can be used to simulate real-world deployment scenarios.

  - **Simulation Tools**: **Matlab**, **Python**, and **Java** can provide robust environments for analyzing:
    - Network performance under varying conditions.
    - The interaction between small cells and macro cells.
    - Overall system performance improvements through small cell integration.

3. Small Cell and Macro Cell Interaction

- Investigate the influence of **small cells** on macro cells in terms of:
  - Coverage optimization.
  - Load balancing and capacity enhancement.
  - Impact on interference management and overall system throughput.

4. Graphical User Interface (GUI) Development

- Develop a **user-friendly GUI** for the improved TEA methodology:
  - Make the analysis tool accessible for a broader audience, including researchers and network planners.
  - Enable interactive exploration of TEA findings and facilitate related studies.

Potential Impact of Future Work

- **Improved Decision-Making**: Refined tools and frameworks will enable more accurate assessments of LTE-A deployment strategies.
- **VoLTE Readiness**: Exploring voice integration ensures alignment with future demands for unified communication services.
- **Enhanced Planning Tools**: Incorporating advanced simulation and planning tools improves network dimensioning, particularly in complex urban environments like Addis Ababa.
- **Usability**: A GUI-based TEA tool fosters adoption by simplifying analysis and making the framework adaptable to various studies.

By pursuing these research directions, LTE-A rollouts can better meet the growing demand for mobile data while addressing voice integration, network dimensioning, and system optimization challenges.

5.5 LTE-advanced recommendation

1. RF Planning Recommendations

Incorporating advanced planning techniques and tools can significantly improve the precision of **RF planning** for LTE-Advanced deployments, particularly in complex environments like Ethiopia, including **Addis Ababa**:

- **Utilize Advanced Mapping Tools**:
  - Include **digital maps**, **building files**, **clutter maps**, and **population density maps** in RF planning.
  - These tools allow for accurate modeling of signal propagation for **macro**, **indoor**, and **outdoor cells**, improving network dimensioning.
- **Adopt Multi-Layer Cellular Configurations**:
  - Deploy **multi-band**, **multi-modulation**, **multi-MIMO**, **multi-carrier**, and **multi-sector** technologies.
  - Use a combination of **macro**, **micro**, **pico**, **femto**, and **indoor/outdoor cells** to optimize LTE sites for varying traffic patterns and geographic needs.
- **Address Uneven Traffic Distribution**:
  - Tailor solutions for cities like Addis Ababa where traffic distribution is highly uneven.

  - Leverage **small cells** in high-density areas and **macro cells** for broader coverage in less congested zones.

2. LTE-Advanced and 5G Toolbox Recommendations

- **Extend the Role of LTE-Advanced in 5G Evolution**:
  - LTE-Advanced will remain a vital technology in the transition to **5G**.
  - Future research should focus on **cooperative methods** to enhance **liquid capacity**, allowing resources to be dynamically shared and allocated.
- **Optimize Radio Access Technologies**:
  - Continue utilizing **OFDMA** and **SC-FDMA** for their proven resilience in data delivery and adaptability to varying user demands.
  - These technologies ensure a seamless evolution path for users transitioning to 5G.
- **Enhance Frame Structures**:
  - Improve the **radio access methods' frame structure** to further reduce latency, a critical requirement for 5G applications such as real-time communication and IoT.

Conclusion and Future Considerations

The integration of **RF planning best practices**, advanced tools, and multi-layered network configurations will ensure LTE-Advanced continues to deliver robust performance while supporting 5G aspirations. Enhancing the efficiency of existing LTE-Advanced technologies, particularly in **radio access and latency management**, will provide a solid foundation for realizing the full potential of next-generation mobile networks.

Recommendations for Ethio Telecom

To optimize Ethio Telecom's network performance and align with evolving technological demands, the following recommendations are proposed:

1. Scheduling and System Optimization

- **Regular Surveys and Updates**:
  - Implement a **scheduling plan** to systematically survey and optimize resource utilization.
  - Incorporate updates such as **releases**, **modules**, **patches**, and **new innovations** into the network infrastructure.
- **Efficient Resource Utilization**:
  - Ensure that resource allocation methods are continuously evaluated for efficiency.
  - Leverage advanced tools and analytics to identify bottlenecks and opportunities for improvement.

2. Deployment of Advanced Technologies

- **Massive MIMO**:
  - Deploy massive MIMO systems to increase capacity, spectral efficiency, and user throughput.
  - Utilize its ability to handle high traffic volumes and improve coverage in dense urban environments.
- **Heterogeneous Networks (HetNets)**:

  - Incorporate HetNets with macro, micro, pico, and femto cells to optimize coverage and capacity.
  - Use small cells in high-demand areas to offload traffic from macro cells and improve overall efficiency.
- **Coordinated Multi-Point (CoMP)**:
  - Deploy CoMP for **interference mitigation** and to enhance the experience of users at cell edges.
  - Integrate CoMP across HetNet layers to maximize its benefits in dense network environments.
- **Adaptive Radio Resource Management (RRM)**:
  - Use adaptive RRM techniques to dynamically allocate resources based on real-time traffic and channel conditions.
  - Optimize modulation schemes and power levels to improve efficiency and reduce operational costs.

3. Research and System Recommendations

- **Technical Research Opportunities**:
  - Use Ethio Telecom's deployment as a **case study** to research optimal resource utilization methods.
  - Analyze data traffic patterns and customer demands to suggest tailored solutions for system optimization.
- **Technical Documentation**:
  - Document findings and methodologies in the form of a **thesis or technical report**.
  - Provide detailed descriptions of the deployed systems, configurations, and technical lessons learned.

Summery

By adopting advanced technologies like **massive MIMO**, **HetNets**, **CoMP**, and **adaptive RRM**, Ethio Telecom can enhance its network performance while addressing customer demands cost-effectively. Regular system optimizations and the integration of new innovations will position the network to meet future challenges and establish Ethio Telecom as a leader in efficient telecom resource management. This effort will also contribute valuable insights and technical expertise to the broader field.

CHAPTER FIVE
REFERENCES, LIBRARY AND ACCESSORIES

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