

**Designing a Dynamic Spectrum Sharing Algorithm Between
DCS and LTE in the 1800 MHz Band:
a case study of a mobile telecommunication operator in
Zimbabwe**

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for the degree of

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Abstract

In recent years, there has been remarkable growth in the wireless devices and networks market, leading to the proliferation of numerous wireless services and applications. Consequently, regulatory agencies around the world have allocated licensed spectrum chunks to different wireless services to meet the increasing demand. Despite technological advancements such as Multiple Input Multiple Output (MIMO) communications, heterogeneous networks, and cooperative communications, spectrum scarcity continues to pose a challenge for regulatory agencies worldwide. Facing this challenge, Dynamic Spectrum Sharing (DSS) has emerged as a promising remedy. As a facet of frequency spectrum management, DSS aims to bolster spectrum utilization efficiency and elevate the end-user experience by introducing greater flexibility in the usage of spectrum resources.

This Dissertation has substantiated DSS as a viable solution to the challenge of spectrum scarcity. It assessed the effectiveness and suitability of dynamic spectrum sharing within a conventional mobile network setting, concentrating on intra-operator scenarios encompassing Digital Cellular System (DCS), also recognized as GSM1800, and LTE radio technologies. Monte Carlo-style system-level simulations were conducted using Atoll, utilizing raster traffic maps provided by the Mobile Network Operator (MNO). These simulations served two main purposes: firstly, to benchmark the simulator's performance with actual network performance data collected from the MNO, and secondly, to validate the impact of DSS on the network by contrasting it with the current fixed spectrum sharing method employed by the MNO in urban and suburban settings, thus offering a realistic analysis. Key Performance Indicators (KPIs) on LTE, such as Downlink Throughput, Physical Resource Block (PRB) Utilization, and Evolved Radio Access Bearer (ERAB) Establishment, were evaluated, along with consideration of the impact on 2G metrics like voice call drops, total carried traffic, and receiver (Rx) signal quality.

The simulations revealed a substantial surge in LTE throughput, averaging 62% across both clusters, resulting in an overall increase in LTE traffic by 34%, thanks to DSS implementation. Remarkably, this enhancement in LTE performance was achieved while ensuring minimal adverse effects on DCS performance. Notably, DSS's impact on the DCS network was more pronounced in urban areas, leading to a 7% reduction in voice traffic attributed to heightened interference in shared spectrum zones, leading to increased SINR. As a result, there was a 6% drop in DL quality samples (DL Rq), resulting in a 0.16% increase in voice call drops post-DSS activation. In suburban regions, both DSS and Fixed Spectrum Allocation (FSA) exhibited nearly identical DCS performance, with negligible impact, as indicated by a slight 1.7% decline in received signal quality compared to the urban cluster. To further optimize DCS performance within the DSS

framework, future strategies suggest reducing the transmit power of resource elements in shared spectrum zones to mitigate interference with DCS channels.

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This dissertation signifies the culmination of my journey through the Master of Engineering in Telecommunications program at the University of Cape Town. It has been a challenging yet immensely rewarding experience, encompassing nearly three years of dedication and hard work. Reflecting on the effort invested in this dissertation, I am profoundly grateful for the invaluable insights it has provided me.

The successful completion of this dissertation owes much to the steadfast support of my wife, daughters, and colleagues, who stood by me every step of the way throughout the research period. Their encouragement and understanding were pivotal in overcoming the obstacles encountered along this journey. I am eternally grateful for their steadfast belief in me.

Although the path has been arduous at times, the experience and knowledge gained throughout this process are truly priceless. Each challenge presented an opportunity for growth and learning, shaping me into the professional I am today.

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As I transition into the next chapter of my life, I bring along the wisdom and memories accumulated throughout my time at the University of Cape Town. This dissertation signifies not only an academic accomplishment but also a significant personal milestone that I will always hold dear.

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Definitions of Acronyms

Table 1: Acronyms

Acronyms	Definitions	Acronyms	Definitions
BCCH	Broadcast Control Channel	MIMO	Multiple Input Multiple Output
CA	Carrier Aggregation	MNO	Mobile Network Operator
CR	Cognitive Radio	OFDMA	Orthogonal Frequency Division Multiple Access
CSON	Centralized Self-Organizing Node	QoE	Quality of Experience
DCS	Digital Cellular System	QoS	Quality of Service
DSS	Dynamic Spectrum Sharing	RAN	Radio Access Network
EDGE	Enhanced Data Rates for Global Evolution	RAT	Radio Access Technology
EMS	Element Management System	RSRP	Reference Signal Received Power
FCC	Federal Communications Commission	RxLev	Received signal strength in GSM
FDD	Frequency Division Duplex	SIMO	Single Input Multiple Output
GSM	Global System for Mobile Communications	SINR	Signal-to-Interference-plus-Noise Ratio
GPRS	General Packet Radio System	SDR	Software Defined Radio
GERAN	GSM EDGE Radio Access Network	SU	Secondary User
ITU-R	International Telecommunications Union- Radio communications sector	SS	Spectrum Sensing
LTE	Long Term Evolution	TCH	Traffic Channel
MAIO	Mobile Allocation Index Offset	TDD	Time Division Duplex
MCS	Modulation and Coding Scheme	UMTS	Universal Mobile Telecommunications System

1. INTRODUCTION

According to Cisco [1], the last decade has witnessed a remarkable transformation in mobile services, delivering significant benefits to human lives. These services rely on networks that employ multiple Radio Access Technologies (RATs) across various dedicated licensed spectrum bands. With the mobile economy contributing nearly 5% to the global GDP [2], it has seen substantial growth over the past forty years, witnessing a surge in the number of wireless system users [3]. This upward trajectory is anticipated to persist, especially with the advent of the Internet of Things (IoT) era. As the consumption of Internet bandwidth continues its exponential rise [4], spectrum usage density also escalates, highlighting spectrum as the most critical resource for wireless technology operators.

The scarcity and costliness of spectrum significantly influence the cost implications associated with deploying new radio access technologies such as 4G and 5G. Consequently, many operators are turning to 'frequency refarming' from existing RATs like Universal Mobile Telecommunications System (UMTS) and Global System for Mobile Communications (GSM) [5, 6] or purchasing entirely new spectrum blocks. However, frequency refarming can reduce capacity and degrade user experience on existing technologies. Studies conducted by the FCC [7] have highlighted high levels of spectrum underutilization in these dedicated spectrum blocks across various RATs, leading to spectrum inefficiency and hindering the growth of wireless applications.

Since the year 2000, there has been a significant rise in research endeavours concentrating on dynamic spectrum sharing as a method to boost spectrum efficiency while enhancing user experience [8]. As stated by Sharma et al. [9], this approach is motivated by the recognition that a substantial portion of licensed radio spectrum remains underutilized in both spatial and temporal domains. Dynamic spectrum sharing endeavours to reconcile the paradox between spectrum scarcity and underutilization. Numerous approaches have surfaced, encompassing centralized and distributed spectrum sharing, spectrum overlay or underlay access, and cooperative and non-cooperative spectrum sharing techniques, all of which will be elaborated on in the dissertation.

Furthermore, recent advancements in software-defined radio, advanced digital processing techniques, and wideband transceivers have rendered dynamic spectrum access feasible by augmenting the utilization of radio frequencies in a flexible and adaptive manner. The impetus for the dissertation originates from the practical application and efficacy of dynamic spectrum sharing in typical, realistic mobile

networks. The subsequent section will outline the research motivation, trailed by the delineation of the formulated research questions.

1.1 Rationale for Research

There is a widespread acknowledgment that wireless spectrum stands as a highly coveted resource, serving as a catalyst for innovation on a global scale. However, its availability is limited, and acquisition costs are exorbitant [10]. This reality was starkly illustrated by the European UMTS auction in 2000, which saw spectrum fetching approximately 90 billion Euros [11]. For many operators, this auction proved to be financially crippling, posing insolvency risks [12].

In addition to the challenges posed by costly and limited wireless spectrum, there is the compounding issue of the exponential surge in demand for mobile data. Recent research by Cisco[1] forecasts a Compound Annual Growth Rate (CAGR) of at least 14% in mobile subscriptions in Europe and North America from 2014 to 2019, indicating a doubling of demand. The Ericsson Mobility Report in November 2017[13] further attributes this surge in mobile data traffic to a substantial rise in smartphone subscriptions. Smartphones enable users to access higher-resolution video content, leading to increased data consumption per subscriber. As illustrated in Figure 1, mobile broadband subscriptions reached approximately 200 million in Q4 of 2017, with a global total of 5.2 billion subscriptions.

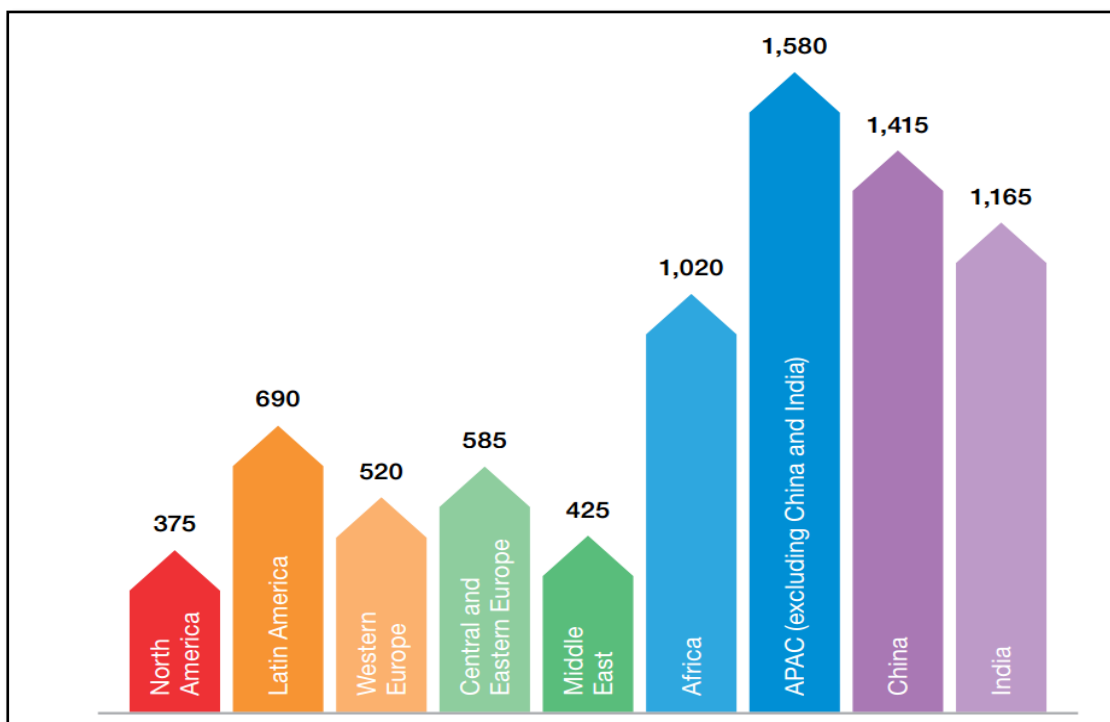


Figure 1: Mobile Subscriptions Q4 2017 (in million) [13].

This indicates a global year-on-year increase of approximately 15%. The same report also highlights that Long Term Evolution (LTE) subscriptions in Q4 of 2017 surged by

approximately 180 million, reaching a global total of 2.7 billion, while 3G subscriptions increased by approximately 30 million. Consequently, there was a surge in mobile subscriptions during the same quarter, with approximately 400 million smartphones (accounting for 59 percent of all global mobile phone subscriptions) being sold. As GSM (2G) can serve as a fallback for most of these 3G/LTE subscriptions, there has been a significant decline in 2G-only mobile subscriptions by around 150 million, as reported in the mobility report [13].

This global increase in smartphone subscriptions and subsequent rise in mobile data traffic has also impacted the Zimbabwean mobile network market, where mobile smartphone penetration currently stands between 20 and 23 percent [6]. This growth is predominantly observed in urban populations, who are increasingly upgrading to 3G and LTE-capable devices offering enhanced data speeds and improved user experience, as depicted in Figure 2.

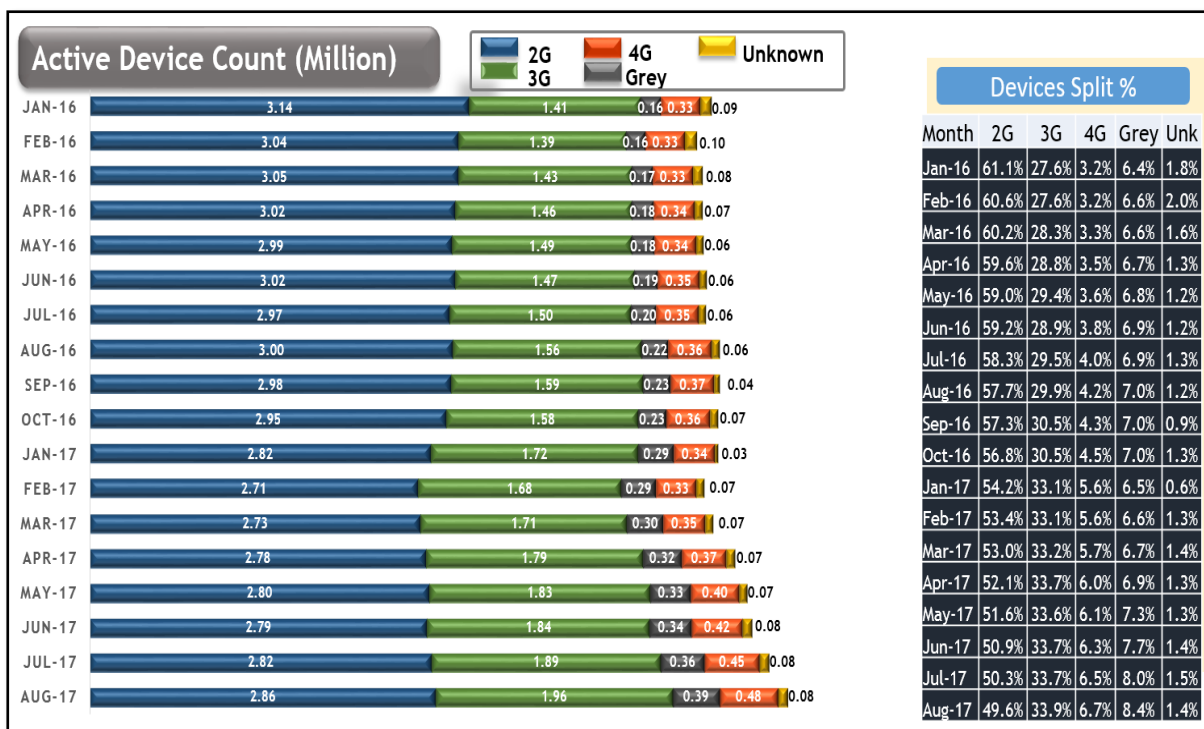


Figure 2: Handset distribution in Zimbabwe Urban Areas (2016-2017) [14]

In Zimbabwe, LTE currently operates on the 1800 MHz spectrum (FDD: 1710-1930 MHz) and the 2300 MHz spectrum (TDD: 2300-2450 MHz) [86]. The mobile operator under investigation in this Dissertation holds a licensed bandwidth of 24.8 MHz in the 1800 MHz spectrum, with an annual cost of \$297,600, translating to \$12,000 per MHz. Given the exorbitant cost of acquiring new spectrum dedicated to LTE, the mobile operator has opted to repurpose 15 MHz for LTE from its existing licensed 24.8 MHz bandwidth, which was primarily allocated for DCS. The technologies are separated with guard bands. Figure 3, visually depicts how the spectrum is divided between DCS and LTE in the mobile network operator (MNO) under investigation in this Dissertation:

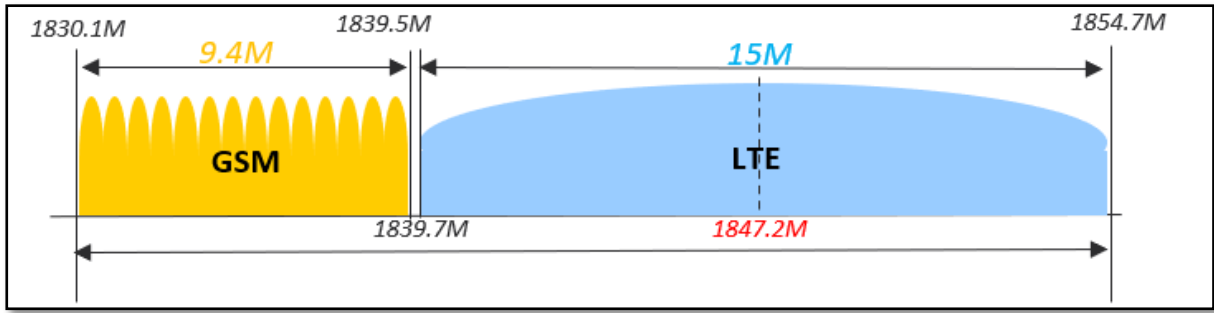


Figure 3: Spectrum split between DCS and LTE for the MNO.

The expensive wireless spectrum in Zimbabwe, coupled with the rising adoption of mobile smartphones fuelled by the demand for improved user experience, has made traditional network expansions prohibitively costly for most mobile operators. With the standardization of 5G [15], the spectrum crunch remains a significant challenge that could impede wireless application growth in Zimbabwe. These circumstances necessitate innovative spectrum management methods, such as dynamic spectrum sharing, which is anticipated to enhance spectrum efficiency while realizing gains in user and network performance with minimal or no major capital investments.

In light of the ongoing discourse and investigations into dynamic spectrum management, 3GPP Technical Specification Group Radio Access Network (TG RAN), has recently launched a new specification, referenced 37.870, within the framework of standard release 13. This report aims to identify overarching scenarios and requirements for coordinating multiple RATs and to explore potential solutions. [16]. The Technical Report emphasizes the necessity of RAT coordination grounded in actual network observations. Such observations unveil notable disparities in traffic load distribution across network cells for each RAT independently. Legacy systems may occasionally fall short in fully utilizing allocated spectrum, whereas more advanced RATs have the potential to leverage additional capacity. Therefore, the specification argues that traditional spectrum refarming might not adequately address the decrease in spectrum demands of legacy RATs. Additionally, it implies that the magnitude of traffic load fluctuations is contingent upon the cell's location. This implication suggests that such variations can be harnessed to optimize spectrum usage, thereby benefiting both network operators and subscribers.

The 3GPP work item delves into two techniques, namely dynamic spectrum sharing and traffic steering, aimed at leveraging traffic load variations to enhance quality of experience for end-users, optimize resource utilization and bolster network capacity. These techniques are applicable to both cellular networks and Wireless Local Area Networks (WLANs) [17]. However, these approaches require validation to substantiate the anticipated benefits. The main goal of this Dissertation is to validate DSS as one of the proposed techniques, exploring its effectiveness across both spatial and temporal dimensions. It acknowledges the time-dependent nature of spectrum sharing

opportunities, which can vary between cells dynamically. The Dissertation research is focused on DCS and LTE radio technologies, utilizing cellular network data provided by a Zimbabwean network operator. The operator aims to comprehend the potential advantages that coordination between these technologies could offer for network operators. While traffic steering is an important area of study, it falls outside the scope of this Dissertation.

1.2 Problem Statement

The increasing demand for mobile data and spectrum scarcity present significant challenges for network operators. One potential solution is inter-RAT DSS between DCS and LTE, which could optimize spectrum utilization and improve overall network performance. However, the effectiveness of DSS in real-world deployments remains unclear, particularly in terms of its impact on both network efficiency and user experience. Outlined below are the objectives of this Dissertation.

1.3 Objectives

The primary objective of this Dissertation is to evaluate the effectiveness of DSS between DCS and LTE in improving spectrum utilization and enhancing network performance. The specific objectives are as follows:

1. **Validate 3GPP Assumptions on DSS:** Investigate the 3GPP assumption that spectrum sharing can increase network throughput without negatively impacting the performance of traditional systems like DCS.
2. **Quantify User Throughput Improvements:** Measure and quantify the enhancement in user throughput resulting from the implementation of DSS in real-world network environments.
3. **Assess Environmental Impact on DSS Performance:** Examine how different network environments (urban vs. suburban) influence the benefits and challenges of DSS implementation.
4. **Develop and Test a DSS Algorithm:** Design and evaluate a DSS algorithm tailored for intra-operator scenarios, focusing on dynamic spectrum allocation between DCS and LTE under varying traffic conditions and sharing period durations.
5. **Evaluate Key Performance Indicators (KPIs):** Analyse the impact of DSS on critical network metrics, including LTE throughput, Physical Resource Block (PRB) utilization, and Evolved Radio Access Bearer (ERAB) establishment, as well as DCS performance metrics such as voice call drops, total carried traffic, and receiver (Rx) signal quality.

To validate the feasibility and effectiveness of DSS, computer-based simulations will be conducted using live network propagation models, traffic data, and KPIs provided by the MNO. The findings will offer insights into the technological advancements required in the RAN to facilitate efficient DSS implementation. Notably, this study will focus solely on RAN-level enhancements, excluding any modifications to the Core Network.

1.4 Justification

The justification for this Dissertation stems from the growing need to address spectrum scarcity and improving spectrum utilization efficiency in wireless networks. Traditional fixed spectrum allocation methods are no longer sufficient to meet the increasing demand for wireless services, especially with the coexistence of legacy systems like DCS and modern technologies like LTE. DSS offers a promising solution by enabling flexible and efficient use of spectrum resources. However, its practical implementation and performance in real-world scenarios, particularly in intra-operator environments, require thorough investigation.

This research is significant for several reasons:

1. **Practical Relevance:** By leveraging live network data and realistic propagation models provided by an MNO, this study provides actionable insights into the feasibility and benefits of DSS in actual network deployments.
2. **Performance Validation:** The research validates the theoretical assumptions made by 3GPP regarding DSS, ensuring that the proposed solutions are grounded in empirical evidence.
3. **Network Optimization:** The findings of this study will help MNOs optimize their spectrum resources, improve user experience, and extend the lifespan of legacy systems like DCS while transitioning to advanced technologies like LTE.
4. **Environmental Considerations:** By examining the impact of urban and suburban environments on DSS performance, this research provides tailored recommendations for different deployment scenarios, enhancing the applicability of DSS across diverse settings.
5. **Technological Advancements:** The study highlights the necessary advancements in the RAN to support DSS, contributing to the broader goal of achieving more efficient and flexible wireless networks.

1.5 Dissertation Outline

The subsequent sections of this Dissertation are structured as follows:

Chapter 2 offers an overview of cellular networks, with a focus on GSM, GPRS, EDGE, and LTE technologies, accompanied by a brief discussion on Radiowave propagation modeling.

Chapter 3 presents a comprehensive review of related literature, covering the evolution of spectrum management, spectrum sharing techniques, the 3GPP work item on dynamic spectrum allocation, relevant research publications, and a discussion on the Dissertation's contribution to the overall advancements in DSS wireless systems.

Moving forward, Chapter 4 conducts an assessment of DSS in a realistic network environment by developing system-level simulators.

Chapter 5 analyses the results obtained from the proposed DSS model, with a focus on its performance regarding achievable LTE throughputs in different environments and subsequent service impacts on 2G network.

Finally, Chapter 6 summarizes the research findings, draws conclusions, and offers recommendations for future studies. To enhance the readability of this Dissertation, Table 1 is included, containing the definitions of acronyms used throughout the text.

2. OVERVIEW OF MOBILE NETWORKS

The primary objective of this chapter is to provide a comprehensive overview of mobile telecommunication networks and the modeling of Radiowave propagation. Over the course of progression of mobile networks, numerous generations of wireless technology have been introduced. This section will focus on discussing GSM and LTE technologies, both of which are utilized by the Zimbabwean MNO under study. A fundamental understanding of the operation of these technologies is essential before delving into the problem statement of the Dissertation.

2.1 GSM Overview

This subsection provides a brief introduction to GSM background, its architecture, channel structure, principles of communication and fundamental functionalities like frequency hopping.

2.1.1 GSM Network Background

GSM networks, introduced as second-generation (2G) mobile communications systems, were globally deployed to supplant the first-generation analog (1G) systems. Preceding technologies like Advanced Mobile Phone Service (AMPS) in the U.S. and Total Access Communication System (TACS) in the U.K. were analog based. Nevertheless, these technologies encountered difficulties in accommodating the expanding user base, emphasizing the requirement for a more efficient cellular technology capable of international usage.

In response to this demand, the European Conference of Postal and Telecommunications Administrations (CEPT) established a working group in 1983 with the mandate of developing a European standard for digital telecommunications, as outlined by Halonen et al. [18]. CEPT established various criteria for the new system, including provisions for international roaming, affordability, support for new services, high speech quality, compatibility with handheld devices and Integrated Services Digital Network (ISDN) capability.

According to Ngundu et al. [19], initial implementation of GSM-based mobile services occurred in Finland in 1991. During this period, the GSM standard frequency band underwent an expansion from 900 MHz to 1,800 MHz, leading to the introduction of GSM900 and GSM1800 (previously referred to as Digital Communications System (DCS)). This resulted in an increase in GSM global market share of 80% by 2010.

Currently, the ongoing advancement of GSM based solutions is supervised by the 3rd Generation Partnership Project (3GPP), a collaborative initiative among various standardization organizations globally aimed at defining a universal third generation UMTS network. The fundamental elements of this system comprise the UMTS Terrestrial

Radio Access Network (UTRAN) and the GSM/EDGE Radio Access Network (GERAN), employing GSM and Enhanced Data Rates for Global Evolution (EDGE) technology [18].

Despite experiencing a decline in its global market share, GSM has remained the most prevalent mobile subscriber technology [2]. In the subsequent subsections, an overview of the evolutionary stages of GSM specifications is provided, drawing on insights from Halonen et al. [18], Ngundu et al. [19], Saily et al. [20] and Mouly [21].

2.1.2 Network Architecture for GSM

Ngundu et al. [19] delineated the GSM network into four distinct components that collaborate to operate seamlessly: Base Station Subsystem (BSS), Network Switching Subsystem (NSS), mobile device/station (MS) and Operation and Support Subsystem (OSS). The MS establishes a connection with the network through hardware, while the Subscriber Identity Module (SIM) card furnishes the network with user identification information. Figure 4 below depicts the GSM network architecture as elucidated by Ngundu et al. [19]:

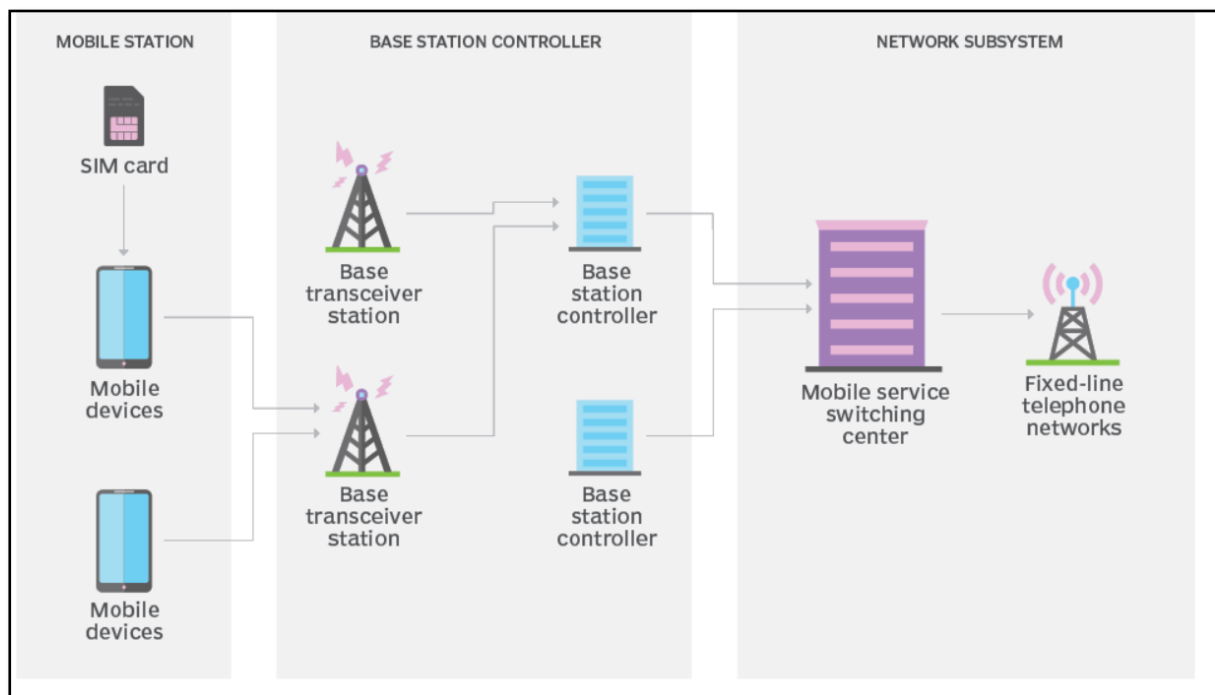


Figure 4: GSM Architecture [19]

The BSS oversees traffic between the MS and the NSS. The Base Transceiver Station (BTS) and the Base Station Controller (BSC) are the main components of BSS. The BTS accommodates equipment responsible for mobile phone communication, including radio transmitter/receivers and antennas, while the BSC acts as the central intelligence. The BSC holds the overall control of a cluster of BTSs.

On the other hand, the NSS segment often referred to as the core network, is responsible for tracking the location of callers to facilitate the provision of cellular services. Mobile carriers own and operate the NSS, which encompasses various components, such as

the Mobile Switching Centre (MSC) and the Home Location Register (HLR). They fulfil diverse functions, including call routing, Short Message Service (SMS) transmission, and authentication, as well as the storage of caller account information via SIM cards.

2.1.3 Basic Channel Structure

Mouly et al. [21] described GSM standard based on a multi-carrier, frequency division duplex, time-division multiple access and MC/FDD/TDMA. The frequency bands as defined by GSM are shown in Table 2 below:

Table 2: GSM standardised frequency bands [21].

GSM Frequency band (MHz)	Available frequencies	Where available
400	450.4–457.6 MHz paired with 460.4–467.6 MHz or 478.8–486 MHz paired with 488.8–496 MHz	Europe
800	824–849 MHz paired with 869–894 MHz	America
900	880–915 MHz paired with 925–960 MHz	Europe, Asia Pacific, Africa
1800	1710–1785 MHz paired with 1805–1880 MHz	Europe, Asia Pacific, Africa
1900	1850–1910 MHz paired with 1930–1990 MHz	America

The 900 and 1800 MHz bands support 174 and 374 radio frequency channels, respectively, with a carrier spacing of 200 kHz. At the end of each sub band, a guard band of 100kHz is incorporated. Each channel is divided into TDMA frames lasting 4.615 milliseconds (ms). These frames are then subdivided into eight full slots, with each slot lasting 577 μ s. Each slot can be allocated to a full-rate (FR) traffic channel (TCH), two half-rate (HR) TCHs, or one of the control channels. One timeslot (TSL) on one frequency channel is termed a slot [18]. The time and frequency structure is illustrated in Figure 5 below:

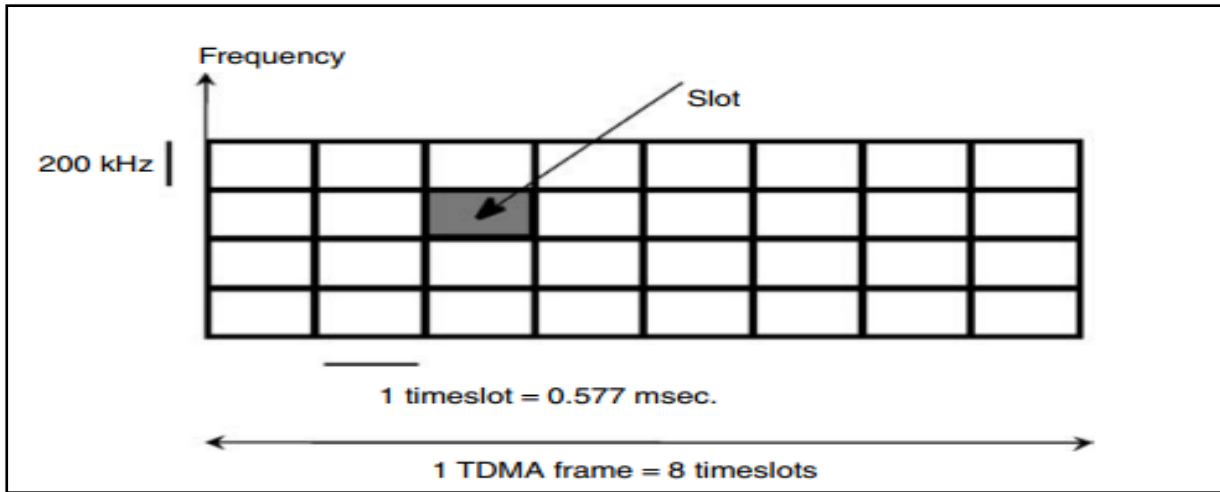


Figure 5: GSM Frame structure [18].

In GSM, the data sent within one slot is referred to as a burst. The ETSI GSM Technical Specification, GSM 05.02 [43], classifies bursts into five types: normal burst, frequency correction burst, synchronization burst, access burst and dummy burst. Format and content of each burst type depend on the channel to which it belongs.

GSM classifies channels as physical and logical channel, where a physical channel represents a single timeslot on a carrier, while a logical channel denotes the specific information transmitted via the physical channel. Different logical channels carry various types of information, which are then multiplexed onto physical channels. Logical channels are divided into two main categories: control channels and traffic channels [18]. Traffic channels are specifically used for transmitting user data, such as speech or data.

In GSM, a logical traffic channel designated for circuit-switched data and speech is known as a Traffic Channel (TCH), available in two variants: full rate (TCH/F) and half rate (TCH/H). The full-rate TCH (TCH/F) supports a data channel or coded speech with raw data rates of 2.4, 4.8, or 9.6 Kbps, while the half rate (TCH/H) supports rates of 2.4, 4.8, and 7 Kbps [22]. Both TCH channels enable bidirectional transmission for speech and data communication.

Meanwhile, a logical channel for transmitting user data on one physical channel is termed a Packet Data Traffic Channel (PDTCH). The PDTCH/F, utilizing Gaussian Minimum Shift Keying (GMSK) modulation, carries information at an instantaneous bit rate ranging from 0 to 22.8 Kbps. Conversely, the PDTCH/H using 8-PSK modulation carries information at an instantaneous bit rate ranging from 0 to 69.6 Kbps. The bit rate is mapped to a specific user payload based on the applied channel coding scheme. Additionally, a PDTCH/H corresponds to the resource allocated to a single mobile station on half a physical channel for user data transmission, with a maximum instantaneous bit rate half that of a PDTCH/F [22].

2.1.4 TCH Link Performance with Frequency Hopping

This section focuses on the core link-level performance of TCH logical channels, excluding the PDTCH utilized for packet-switched traffic, which will not be explored here.

Mogensen et al. [23] furnished comprehensive specifications detailing the necessary performance criteria for mobile stations concerning sensitivity and interference tolerance under specific test conditions. The specified performance in the presence of interference is outlined in Table 3 for both frequency hopping (FH) and non-hopping (NH) scenarios. These specifications are detailed for the typical urban (TU) channel profile with two distinct speeds: 3 and 50 km/h. The combinations of speed and channel profile are denoted as TU_x, where x represents the speed, while parameter α varies from 1 to 1.6, depending on the prevailing channel conditions.

Table 3: Interference performance (9 dB C/I) [24]

	TU3 NH	TU3 FH	TU50 NH	TU50 FH
Max. FER (Frame erasure rate)	21α%	3α%	6α%	3α%

The GSM specifications accommodate a slow FH mode, where the frequency of transmission changes on a burst-by-burst basis. In this mode, both the uplink (UL) and downlink (DL) frequencies are duplex frequencies. GSM delineates two types of frequency hopping: sequential and random hopping.

The Hopping Sequence Number (HSN) and the Mobile Allocation Index Offset (MAIO) serve as two parameters to characterize the hopping channel utilized in each frame. The MAIO can adopt as many values as there are channels in the hopping list, denoting the offset within the hopping list used to identify the employed frequency. The Mobile Allocation (MA) list establishes the hopping list. Conversely, the HSN can assume 64 different values, defining the hopping sequence employed. When the HSN is set to zero, the hopping mode operates sequentially, while frequencies vary pseudo-randomly when it deviates from zero [18].

The frequency hopping algorithm described in ETSI GSM Technical Specification, GSM 05.02 [22], provides a method for obtaining the index to an Absolute Radio Frequency Channel Number (ARFCN) within the mobile allocation for a given set of parameters. This algorithm utilizes the frame number (FN) and the total number of frequencies (N) and follows the procedure outlined below:

```

if HSN = 0 (cyclic hopping) then:
    MAI, integer (0.. N-1): MAI = (FN + MAIO) modulo N
else:
    MAI, integer (0.. N-1): MAI = (S + MAIO) modulo N
  
```

where S is calculated from the HSN, time parameters, the number of frequencies and a predefined table, which can be found in [22].

Sequences with the same HSN but different MAIOs will never overlap, ensuring the orthogonality of their hopping sequences. Likewise, channels with different HSN values but the same frequency lists and timeslots will only interfere with each other in a fraction of bursts, specifically $1/m$, where m represents the number of frequencies in the hopping sequence. This capability allows the network to effectively average out interference [25].

Certain control channels, such as the Broadcast Control Channel (BCCH), which occupies one timeslot on the BCCH transceiver (TRX), are restricted from utilizing frequency hopping. This limitation is necessary because the BCCH frequency must remain fixed to facilitate mobile device discovery. The activation of frequency hopping in GSM enhances link performance primarily through two mechanisms: frequency diversity and interference diversity.

2.2 GPRS and EGPRS Performance

This subsection explores the performance analysis of General Packet Radio Service (GPRS) and Enhanced GPRS (EGPRS) as outlined in the Rel'97 and Rel'99 specifications, respectively. The analysis encompasses diverse potential deployment scenarios and tackles numerous practical issues related to packet-switched data dimensioning.

2.2.1 GPRS

As described by Pratima et al. [26], General Packet Radio Service (GPRS) is a packet switching technology utilized for data transfer across cellular networks, facilitating mobile internet, Multimedia Messaging Service (MMS), and other data communications. It represents a non-voice value-added service that enables the exchange of information within a mobile telephone network. GPRS offers a maximum speed of 17.2 Kbps when utilizing all eight timeslots concurrently. This speed is roughly three times faster than transmission rates over fixed telecommunication networks and ten times faster than circuit-switched data services on GSM networks.

To enable GPRS, the GSM system allocates between one to eight timeslots within a frame. These allocations are dynamic, varying depending on demand, network load and operator preferences [20]. As a result, the allocated timeslots can fluctuate throughout data transmission. In some cases, higher demand for GSM voice services may lead to a greater allocation of timeslots to voice services. Users have the flexibility to share all timeslots independently for uplink and downlink transmissions. Similar to GSM, GPRS employs Gaussian Minimum Shift Keying (GMSK) modulation. The achievable user bitrates depend on factors such as timeslot allocations by the operator, channel coding schemes determined by link quality, and the capabilities of the mobile station.

Within GPRS, four distinct coding schemes, namely CS-1 to 4, can be utilized to introduce redundancy to user information, based on the channel quality [27]. Table 4 details the attributes of the various coding schemes and the peak throughput offered [18].

Table 4: GPRS peak throughputs [18].

Coding Scheme	Bit rate (bps/slot)	Modulation
CS-1	8,000	GMSK
CS-2	12,000	
CS-3	14,400	
CS-4	20,000	

2.2.2 EGPRS

EGPRS, also known as Enhanced Data rates for GSM Evolution (EDGE), distinguishes itself from GPRS by incorporating several enhancements [18]. It offers nearly three times faster speeds compared to GPRS, with a maximum speed of 473 Kbps for eight timeslots, albeit typically limited to 135 Kbps to conserve spectrum resources [26]. EGPRS employs 8-PSK modulation to enable higher data rates and implements incremental redundancy to enhance link adaptation and improve link performance. Additionally, EDGE introduces various error coding schemes that adapt based on channel quality, enabling higher bitrates. The modulation and coding schemes and achievable throughputs are detailed in Table 5.

Table 5: EDGE peak throughputs [26].

Coding Scheme	Bit rate (bps/slot)	Modulation
MCS-1	8,800	8-PSK
MCS-2	11,200	
MCS-3	14,800	
MCS-4	17,600	
MCS-5	22,400	
MCS-6	29,600	
MCS-7	44,800	
MCS-8	54,400	
MCS-9	59,200	

However, it's important to note that 8-PSK modulation exhibits greater sensitivity to phase noise compared to GMSK, primarily due to the reduced inter-symbol distance. This sensitivity is particularly pronounced for lower-protected MCSs, as they lack the capability to correct errors induced by phase noise. Therefore, achieving peak data rates mandates the establishment of a robust radio link.

2.3 LTE

This subsection encompasses the performance analysis of LTE, also known as fourth-generation technologies, as referenced by M. Sauter [28].

Despite continuous evolution, UMTS, akin to GPRS and GSM a decade ago, harbours inherent design limitations. Acknowledging this, the 3GPP opted to revamp both the radio network and the core network, culminating in what is commonly referred to as LTE.

During its initial design phase, UMTS adopted a daring approach by defining an air interface with a carrier bandwidth of 5 MHz. While Wideband Code Division Multiple Access (WCDMA), the selected access interface, operated effectively within this limit, it encountered scalability challenges. Expanding the carrier bandwidth to achieve higher transmission speeds shortened the interval between two transmission steps. However, this reduced transmission interval intensified the effects of multipath fading on the received signal.

Multipath fading arises when radio waves reflect off objects along the path from transmitter to receiver, causing the receiver to detect multiple instances of the signal arriving at varying times. Consequently, segments of the signal from a prior transmission step, which reflected off objects and experienced delayed arrival at the receiver, coincide with the signal from the current transmission step, received through a more direct route. As transmission steps decrease in duration, this overlap intensifies, posing a greater challenge for the receiver to accurately decipher the received signal.

To mitigate the effects of multipath fading, LTE utilizes Orthogonal Frequency Division Multiplexing (OFDM) as its air interface. Unlike UMTS, which distributes a single signal across the entire 5MHz carrier bandwidth, OFDM divides the data into numerous narrower 180KHz bandwidth carriers. Instead of a single rapid transmission, LTE splits the data stream into multiple slower data streams transmitted concurrently. As a result, LTE achieves comparable data rates to UMTS within the same bandwidth, albeit with significantly reduced multipath effects due to longer transmission intervals.

In the downlink, LTE employs OFDMA to allocate resources to users across both frequency and time domains. This method utilizes narrowband carriers which are spaced at 15 kHz intervals. Each resource block (RB) comprises 12 subcarriers and occupies precisely one slot, lasting 0.5 milliseconds. A slot consists of 7 symbols, and two slots together form a subframe with a duration of 1 millisecond, as depicted in Figure 6. A subframe serves as the LTE scheduling time, meaning that at each millisecond (referred to as Transmission Time Interval or TTI), the eNode-B makes decisions regarding which users are scheduled and which RBs are assigned to each user.

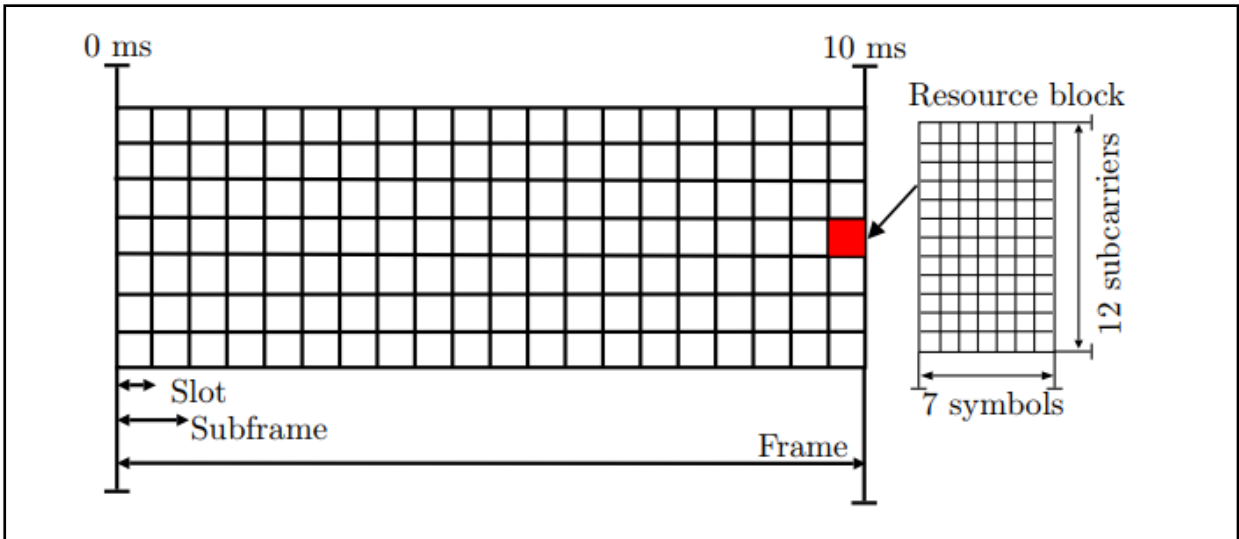


Figure 6: Frame structure of LTE [28].

The quantity of concurrent RBs within every subframe varies according to the system's bandwidth. For instance, with a 10 MHz carrier, there are 600 subcarriers accessible (as shown in Table 6). Considering each RB comprises 12 subcarriers, up to 50 resource blocks can be allocated to one or multiple users in each subframe.

Table 6: Defined bandwidths for LTE.

Bandwidth (MHz)	Number of Subcarriers
1.4	90
3	200
5	300
10	600
15	900
20	1200

When transmitting uplink data, OFDMA is not preferred due to its high Peak to Average Power Ratio (PAPR) resulting from merging signals from multiple subcarriers [35]. In practical terms, the amplifier in a radio transmitter circuit must accommodate the maximum power output required for data transmission, thereby determining the power consumption of the PA device regardless of the current transmission power level needed. Therefore, the 3GPP opted for Single-Carrier Frequency Division Multiple

Access (SC-FDMA) as an alternative transmission scheme for the uplink. This decision was influenced by SC-FDMA's ability to maintain a low signal PAPR, crucial for preserving the battery power of UEs. Achieving this low ratio involves effectively distributing information across subcarriers, thereby minimizing power variations between them.

M. Sauter [28] suggests that to enhance overall data throughput, widening the transmission channel by increasing the number of narrowband carriers without altering their parameters is beneficial. LTE can flexibly adjust to bandwidths less than 5MHz by reducing the number of narrowband carriers. Various bandwidths have been designated for LTE, ranging from 1.4 MHz to 20 MHz, including 1.4/3/5/10/15/20 MHz. This bandwidth allocation notably impacts the system capacity. However, other parameters can also influence system capacity, such as:

- Modulation Coding Scheme (MCS).
- Radio conditions for the User Equipment (UE).
- Antenna MIMO Configurations.

Each LTE device must be equipped to support all bandwidths, with the particular bandwidth utilized in practice being contingent upon factors such as the spectrum band and the spectrum allocated to a network operator. Under ideal radio conditions and with a 20 MHz carrier, data rates surpassing 100 Mbps are easily achievable.

Moreover, all LTE devices are equipped with MIMO transmissions, in addition to their flexible bandwidth support. MIMO technology allows the base station to simultaneously transmit multiple streams of data over the same carrier. In ideal radio conditions, the data rates achievable through MIMO transmission can be twice those achievable with single-stream transmission.

The air interface in LTE accommodates both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes of operation. In FDD, distinct frequency bands are assigned for downlink and uplink transmissions, whereas in TDD, the same frequency band is shared for both uplink and downlink, albeit with temporal separation. Although FDD is more commonly adopted in commercial deployments worldwide, TDD, introduced later, hasn't attained widespread popularity. Nonetheless, some LTE devices now support both FDD and TDD, catering to regions where both standards are in use. Table 7 offers an overview of LTE frequency bands categorized by region.

Table 7: LTE frequency bands categorized by region [29].

Region	Band	Downlink (DL)(MHz)	Uplink (DL)(MHz)	UL/DL separation (duplex gap in MHz)	Duplex mode	Carrier bandwidth (MHz) typically used
Europe	3	1805–1880	1710–1785	20	FDD	20
	7	2620–2690	2500–2570	50	FDD	20
	20	791–821	832–862	10	FDD	10
Japan	1	2110–2170	1920–1980	130	FDD	20
Americas	4	2110–2155	1710–1755	355	FDD	10
	13	746–756	777–787	21	FDD	10
	17	734–746	704–716	20	FDD	10
China	38	2570–2620	2570–2620	-	TDD	20
	39	1880–1920	1880–1920	-	TDD	20
	40	2300–2400	2300–2400	-	TDD	20

LTE networks are deployed across various frequency bands, selected according to geographical factors. Table 7 offers a summary of the frequency bands specified in LTE standards and currently in use. It's worth noting that the list of utilized bands is not exhaustive, and additional bands are frequently introduced. The band numbers cited in the table are defined in the 3GPP TS 36.101 Specification [30].

Moreover, following 3GPP Release 8 [31], five distinct classes of user equipment (UE) have been specified, as depicted in Table 8. In contrast to UMTS, where UEs support a wide range of modulation and coding schemes, LTE UEs primarily support fast 64-QAM (Quadrature Amplitude Modulation) in both downlink and uplink, alongside antenna diversity. While additional device categories have been defined for LTE-Advanced (LTE-A), they are not considered in our evaluation efforts.

Table 8: LTE UE Categories [31].

Category	1	2	3	4	5
Maximum downlink data rate (Mbps~20 MHz carrier)	10	50	100	150	300
Maximum uplink data rate (Mbps)	5	25	50	50	75
Number of receive antennas	2	2	2	2	4
Number of MIMO downlink streams	1	2	2	2	4
Support of 64 QAM in the uplink direction	No	No	No	No	Yes

For the uplink direction, LTE utilizes the more reliable 16 QAM modulation scheme for UE classes 1 up to 4, while class 5 terminals, as an exception, support 64 QAM. Additionally, all LTE mobile terminals can handle MIMO transmission in the downlink, except for terminals in category 1, which were never introduced to the commercial market.

MIMO transmission involves simultaneously sending multiple data streams over the same carrier frequency using multiple antennas from the base station to UEs or vice versa. This advanced transmission scheme allows the receiver to distinguish between different transmissions arriving via different paths, such as reflections at different angles from objects, thanks to the spatial separation of the transmitter and receiver antennas. The number of transmit and receive antennas determines the number of data streams that can be sent simultaneously. Typically, LTE base stations and UEs utilize 2×2 MIMO, indicating two transmit and two receive antennas.

In recent developments, LTE networks have started supporting 4×4 MIMO, which is enabled by category 5 UEs. However, incorporating four antennas into a small UE poses a challenge for most mobile device vendors. Moreover, LTE operates across numerous frequency bands, complicating antenna design for mobile devices, especially when considering that terminals must support legacy radio technologies such as GSM and UMTS which operate at different frequency bands.

In typical commercial deployments, the majority of UEs fall into classes 3-4, with observed peak data rates ranging between 100 and 150 Mbps under optimal conditions for a 20 MHz carrier bandwidth. However, average throughputs tend to be lower due to factors like load in the cell, neighboring cells interference and suboptimal radio conditions. For further information on user terminals, readers are directed to Sauter [32].

2.3.1 LTE Network Architecture

For this Dissertation, we will focus solely on the radio section of the LTE network architecture, which shares similarities with GSM and UMTS. This architecture is divided into two main components i.e. radio network and core network, illustrated in Figure 7.

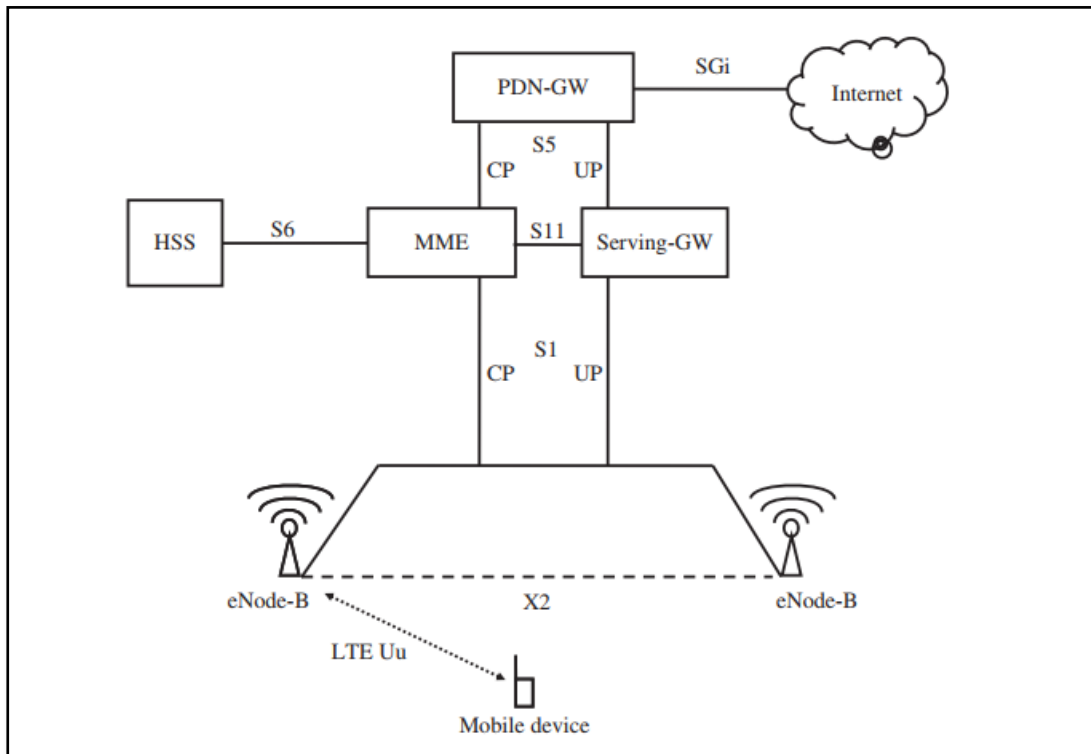


Figure 7: LTE Network Overview [28].

Figure 7 provides an overview LTE architecture. Further details about the various nodes and their interactions are elaborated upon in the subsequent sections.

The LTE base station is referred to as the eNode-B, a name derived from the UMTS base station (Node-B), with the 'e' signifying 'evolved'. The eNode-B comprises three key elements:

- Antennas, utilized for transmitting and receiving signals.
- Radio modules, responsible for modulating and demodulating all signals received and transmitted over the air interface.
- Baseband modules, responsible for processing all signals transmitted and received over the air interface. They serve as an interface to the core network.

Many vendors' designs incorporate an optical connection between the radio module and the baseband module. This setup, known as Remote Radio Head (RRH), allows the radio module to be placed near the antennas, reducing the length of expensive coaxial copper cables needed for antenna connectivity. This approach offers significant cost savings,

especially in situations where the antennas and the base station cabinet cannot be installed near each other.

LTE eNode-Bs operate autonomously, communicating via the X2 interface to manage handover requests and interference coordination. With much of the functionality previously handled by the radio network controller (RNC) now integrated into the eNode-B, it's responsible for several tasks beyond managing the air interface:

- Scheduling air interface resources and overall user management.
- Ensuring Quality of Service (QoS) by maintaining latency and minimum bandwidth requirements for real-time bearers, and maximum throughput for background applications based on user profiles.
- Load balancing among different simultaneous radio bearers for various users.
- Managing mobility and interference.

The air interface in LTE is denoted as the LTE Uu interface. The maximum data rates theoretically attainable over the air are contingent upon the spectrum allocated to the cell. However, actual speeds achievable are influenced by various factors, including the distance between mobile devices and base stations, the transmission power of the base station, and interference from neighboring base stations. As a result, practical speeds are typically lower.

The S1 interface serves as the link between the eNode-B and the core network, typically facilitated through optical fibre or high-speed microwave links, often Ethernet-based. Given that most eNode-Bs encompass multiple sectors, requiring transmission speeds of several hundred Mbps or even Gbps, the transmission capacity needs of backhaul links may surpass those of a single sector. The S1 interface comprises two logical components: the S1 User Plane (S1-UP) for user data transport and the S1 Control Plane (S1-CP) for eNode-B interaction with the core network, including status updates and user signaling messages, as outlined in 3GPP TS 36.413 [33].

For further insights into LTE technology, readers are encouraged to consult Sauter [28]. The subsequent subsection delves into the propagation models utilized in these wireless systems.

2.4 Radiowave Propagation Modeling

In this subsection, we delve into radio wave propagation modeling in outdoor environments for mobile network planning, drawing insights from Chariyev et al. [34], Barclay [35], and Goldsmith [36]. Comprehending signal propagation and path losses is essential in crafting wireless networks to guarantee efficient spatial coverage of signals.

The wireless channel is subject to both additive effects, like co-channel interference, and multiplicative effects, such as propagation losses. When a wireless signal reaches a

receiver, it experiences free-space loss as it spreads outward spherically. Moreover, it may encounter different physical phenomena during propagation through a medium, including scattering, reflection, diffraction and absorption. This phenomenon is commonly classified as free space loss, slow or fast fading. Their effects on a specific channel depend on the relative positions of the receiver and transmitter.

Wireless communications usually occur within shorter wavelengths ranges, typically ranging from 1 to 10 meters. As a result, propagation modeling relies on high-frequency approximations. Although modeling radio wave propagation with high resolution is feasible, it comes with substantial computational expenses. As a result, there's often a need to strike a balance between the size of the area, modeling complexity, and accuracy.

Goldsmith [36] defines signal attenuation between a transmitter and a receiver as path loss, a factor of paramount importance in mobile communication system design. Path loss models are pivotal in determining cell locations and overall network performance optimization. Numerous propagation models have been proposed to forecast path loss from base station to mobile station, and considerable effort has been invested in developing mathematical models for path loss prediction across various environments.

Predicting path loss can be achieved using deterministic models, empirical models, or a combination of both, as outlined by Chariyev et al. [34]. Empirical models shed light on the mechanisms underlying complex propagation loss by conducting extensive observations of path loss. These models then fit appropriate functions to the data, using specific parameters tailored to a particular environment.

2.4.1 Empirical Model

In this model, extensive field-based measurements are conducted across various wireless propagation environments such as urban, rural, and suburban areas to determine an average path loss value for each propagation environment. The model's output can be presented in formulas or graphical representations that best capture the obtained average path loss measurements. Vinko Erceg et al. [37] highlighted examples of empirical path loss models, including the Hata models (Okumura and COST 231) and the Stanford University Interim (SUI).

The Okumura-Hata model [37] is widely recognized as one of the most used empirical models in radio access networks. Originating from Japan, it was developed based on a series of path loss measurements conducted in Tokyo, with subsequent enhancements incorporating computational approximations of measured data to account for variations in antenna heights and terrain irregularities. The model proposed the following equation to estimate path loss in urban environments:

$$PL(d)=A+B\cdot\log_{10}(d)+C$$

Where:

- $PL(d)$: Path loss in dB at distance d (km).
- A, B, C : Model-specific parameters based on frequency and environment.

According to Barclay [35] and Goldsmith [36], the Okumura-Hata model spans distances of up to 20 km and covers a frequency range of 150 MHz–1500 MHz. An extension of this model is the COST 231-Hata model (Extended Hata model), which was developed in Europe specifically for designing 3G mobile networks. It covers a frequency range of 1500 MHz–2000 MHz and distances of 10 km and below. For the COST-231 extension, below is the equation formulated to estimate path loss:

$$PL(d) = 46.3 + 33.9 \cdot \log_{10}(f) - 13.82 \cdot \log_{10}(hb) - a(hm) + (44.9 - 6.55 \cdot \log_{10}(hb)) \cdot \log_{10}(d) + C_m$$

Where:

- f : Frequency in MHz.
- hb : Base station antenna height in meters.
- $a(hm)$: Mobile station antenna height correction factor.
- C_m : Environment-specific constant (0 dB for urban, 3 dB for suburban).

2.4.2 Deterministic Model

The deterministic models, such as Longley-Rice, Ikegami, and free space, consider the multipath effects of the propagation environment when determining signal strength. These models are particularly effective for microcells where complex terrain topology is not a significant factor. They are generally considered to be more accurate than empirical models. However, a major drawback of deterministic models is the high computational cost associated with detailed path loss calculations, as well as the requirement for costly information about objects like trees, buildings, walls, and roofs.

Ray tracing is an alternative deterministic method for modeling radio wave propagation. This approach models radio waves as rays traversing from transmitter to the receiver, with the potential to bounce off different surfaces during their journey. By identifying all possible paths through which energy can transmit through the free space and calculating potential attenuations, Ray tracing offers a comprehensive understanding of all multipath mechanisms. However, the model relies heavily on detailed area information, limiting its applicability to specific sites and making it less suitable for other locations.

To develop a comprehensive propagation model for radio planning in a specific area, a combination of these different models may be necessary. While deterministic models

excel at shorter distances in urban environments, empirical models are often employed for evaluating path loss over longer distances.

3. LITERATURE REVIEW

This chapter offers an examination of spectrum sharing, tracing its historical evolution from the nascent stages of radio communications to contemporary practices. Subsequent subsections delve into spectrum sharing concepts, role of AI in DSS and dynamic spectrum access, offering a detailed examination of these topics.

Numerous survey papers in the literature cover various aspects of dynamic spectrum sharing, including spectrum occupancy modeling and measurements [39, 40], interweave DSS [41, 42, 43], underlay DSS [44–46], overlay DSS [47], MAC protocols for DSS [48], spectrum decision [49], spectrum assignment [50], security for DSS [51], learning for DSS [52, 53], DSS under practical imperfections [54], licensed spectrum sharing techniques [55], coexistence of LTE and Wi-Fi [56], AI in DSS [57-66] and transition to Dynamic Spectrum Sharing [67].

Additionally, a comprehensive review conducted by [63] offers insights into radio resource allocation techniques for efficient spectrum sharing. This review discusses different design approaches such as transmission power-based versus SINR-based methods, as well as centralized versus distributed methods. Additionally, it delineates several prerequisites for efficient resource allocation methodologies, presenting diverse strategies and situations alongside noteworthy research contributions.

Ultimately, the chapter wraps up by underscoring the distinct contributions of this Dissertation to the current knowledge base in spectrum management and sharing.

3.1 Spectrum Evolution

The spectrum management process plays a crucial role in determining the allocation of radio services, specifying where, when, and under what conditions they are permitted to operate. Initially, the rapid adoption of radio communications brought about a surge in its usage, leading to significant interference issues. Early radio systems, such as those utilizing spark-gap transmitters [17], occupied extensive portions of the spectrum, exacerbating interference concerns.

The advent of modulation techniques like amplitude modulation (AM) in 1906, pioneered by Reginald Fessenden, allowed for multiple transmitters to send signals simultaneously. However, as the number of radios proliferated worldwide, interference remained a persistent challenge. Later advancements brought about additional modulation methods like phase modulation (PM) and frequency modulation (FM). However, these techniques fell short in effectively mitigating interference concerns.

To mitigate interference, various multiple access techniques were established across different domains. These include Time Division Multiple Access (TDMA), Frequency

Division Multiple Access (FDMA), Space Division Multiple Access (SDMA), Code Division Multiple Access (CDMA), and Polarization Division Multiple Access (PDMA), as well as random access methods like Carrier Sensing Multiple Access/Collision Avoidance (CSMA/CA).

Today, these techniques are commonly utilized alongside spectrum management practices, which entail dividing the spectrum into bands and allocating them to stakeholders or owners. This allows them to apply suitable modulation and multiplexing techniques tailored to their specific communication needs, thereby optimizing spectrum utilization, and minimizing interference.

According to Chris Doyle et al. [68], a spectrum manager is an individual or entity responsible for allocating specific frequencies to users within defined areas, usually through licensing agreements. Traditionally, this role has been fulfilled by state-regulated agencies overseeing communication regulations. These administrative regulations tightly control radio usage within allocated frequency bands.

Early broadcasting licenses, as documented by J. Wood in the History of International Broadcasting Journal [69], were issued without a structured framework, leading to interference issues despite an abundance of spectrum. The establishment of the Radio Act in the USA in 1927 [70] marked a pivotal moment in spectrum management, introducing stricter limitations on licenses in terms of geographical boundaries, transmission power, and usage time.

With the advancement of wireless technologies, such as the Internet of Things (IoT), the demand for spectrum resources has surged. Spectrum, vital for services like cellular and broadcasting, is also essential for government functions like public safety and aviation. As demand for spectrum grew, regulators imposed stricter regulations, partitioning the spectrum into narrower bands, enforcing restrictions on spectral leakage, and implementing criteria for spectral efficiency.

Commercial spectrum auctions have become commonplace to address spectrum scarcity while accommodating the increase in demand. These auctions serve dual purposes: generating revenue for regulators and ensuring efficient spectrum usage. Frequencies within the "sweet spot" region, spanning from 0.3 to 3 GHz, are particularly coveted by mobile network operators due to their favourable propagation characteristics. Consequently, license prices for these frequencies can be substantial, as highlighted by European spectrum auction experiences discussed in Chapter 1 under the Research Motivation section.

The high cost of spectrum licenses motivates operators to maximize the efficiency of their allocated spectrum. This can be achieved by selecting the most appropriate technology for each frequency band. Technological advancements have significantly

improved spectral efficiency. For instance, LTE-Advanced, utilizing 8x8 MIMO, achieves a maximum of 30 bits per second per Hertz [71], a remarkable improvement compared to the modest 0.01 bits per second per Hertz achieved by AMPS [72].

Before the adoption of spectrum auctions, alternative approaches to spectrum distribution were explored. For instance, the lottery approach was attempted in the USA [73]. However, this method faced challenges, with an overwhelming number of entrants vying for participation. Many entities without genuine telecommunications interests sought to exploit the system by speculating on the obtained spectrum. Another approach, known as the "beauty contest" [74], selected winners based on criteria such as consumer cost guarantees and infrastructure investment commitments. Nevertheless, this method was deemed flawed, as quantifying the long-term benefits and utility of such guarantees proved challenging.

The historical overview provided above highlighted the spectrum management approach known as Fixed Spectrum Allocation (FSA), which was widely accepted until around 2002. However, the efficiency of FSA was called into question when the FCC published a tech-report [75] revealing its shortcomings. The report indicated that FSA resulted in inefficient spectrum usage, leading to a "spectrum drought" where channels were often idle despite licensed users not actively transmitting. Subsequent investigations [76, 77] corroborated these findings.

Surprisingly, the FCC advocated for a shift towards more dynamic spectrum management to address these inefficiencies and alleviate spectrum shortages. This revelation sparked a surge in research activities and projects focused on dynamic spectrum access, a branch of spectrum management aimed at sharing spectrum among multiple users or operators to improve efficiency and enhance the end-user experience.

For a comprehensive exploration of spectrum allocation policy history, readers are encouraged to refer to Hazlett [70]. In the following subsections, dynamic spectrum access will be presented.

3.2 Spectrum Management

The continuously increasing data volume in mobile broadband networks necessitates higher capacity in wireless networks. To address this demand, providing more spectrum and wider bandwidths is crucial. The revelation of underutilization of the radio spectrum through extensive measurements of actual spectrum usage [8] has spurred exciting activities in engineering, economics, and regulation communities, leading to the exploration of better spectrum management policies.

Spectrum sharing encompasses various techniques, including administrative, technical, and market-based approaches. It can occur across different dimensions such as time, space, and geography. Spectrum sharing can be achieved through both

technical means and licensing arrangements. Embracing spectrum sharing opens numerous possibilities for addressing the challenge of the data tsunami in the coming years, while also presenting new challenges.

To provide a comprehensive understanding of spectrum access, the following subsections will present the taxonomy of spectrum access based on selected detailed dynamic spectrum access survey papers. The spectrum management taxonomy is depicted in Figure 8 [78].

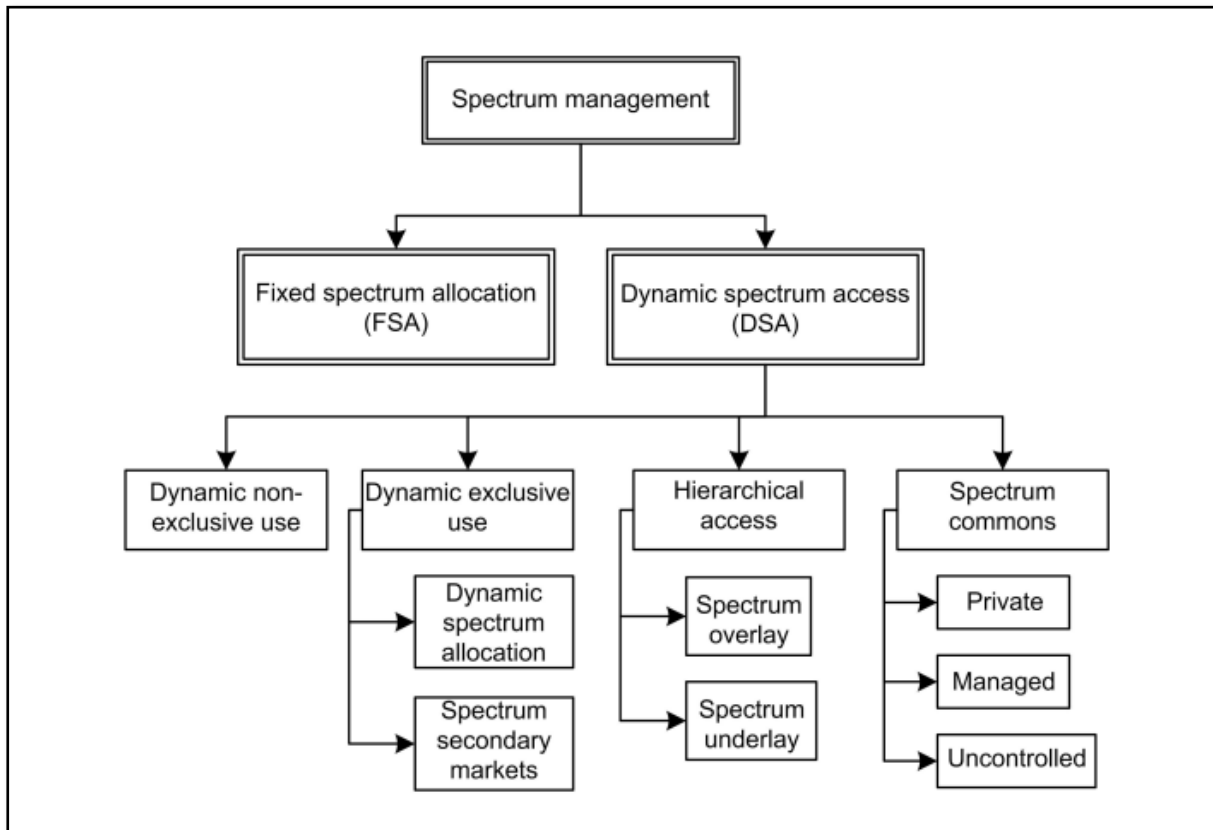


Figure 8: Spectrum management taxonomy [78].

The research conducted in [79, 84, 85] explored the distinct features of various spectrum access methods, which can be categorized into spectrum coordination, access rights, and orthogonality.

Spectrum coordination involves centralized management of spectrum usage across multiple systems, known as Centralized coordination. Alternatively, spectrum access can be facilitated through a terminal-centric approach, where terminals autonomously evaluate environmental settings and select a spectrum band for operation, termed Distributed coordination.

Regarding access rights, systems may have equal entitlements to access a specific spectrum band, known as horizontal rights. Alternatively, one or more systems may be granted primacy over others in accessing the spectrum, termed vertical rights.

Finally, in terms of orthogonality, spectrum can be exclusively allocated to a single operator, whereas in non-orthogonality, multiple operators can simultaneously access similar frequency bands within the same geographic zone. The subsequent subsections will provide further elaboration on how these characteristics correlate with the taxonomy of spectrum access methods.

3.2.1 Fixed Spectrum Allocation (FSA)

The conventional spectrum assignment approach, often referred to as the command-and-control method, has been the prevailing mode of spectrum allocation overseen by regulatory authorities. In Zimbabwe, for example, the Postal and Telecommunications Regulatory Authority of Zimbabwe (POTRAZ) continues to employ this method to allocate spectrum to operators [86]. Under this approach, technology and services are assigned to specific spectrum bands over a predetermined license lifetime. Operators typically acquire these licenses through auctions or bids, while military and government entities, such as meteorological departments, may receive dedicated licenses for specific uses without going through auction processes.

Despite its convenience and ease of management for regulatory bodies, as discussed by Pereirasamy et al. [87], this method presents two main problems, as summarized in Table 9:

Table 9: Major drawbacks of Fixed Spectrum Allocation.

Scalability	Each region requires thorough frequency planning to prevent interference among various services, thereby preserving quality of service. The time needed to introduce new services and technologies is substantially impacted, as dedicated spectrum blocks are necessary for each new offering, significantly impeding the growth of wireless applications.
Scarcity	The available and usable spectrum is highly limited, making it challenging, if not impossible, to provision dedicated spectrum blocks for each service and technology.

Fixed spectrum allocation presents challenges in efficiently utilizing allocated spectrum, particularly due to dynamic changes in network load. This results in unused radio resources, known as spectrum holes [88], across time, space, and frequency domains. While Cognitive Radio (CR) shows promise in addressing this issue [80-81], it primarily targets future systems and may not be practical for existing GSM and LTE systems according to Peha [80-81]. The papers by Peha [80-81] are more focused on the principles and challenges of CR rather than its practical implementation in current networks, mainly representing the early stages of the CR research. However, a study by

Luís et al [82], provides a practical and application-oriented, specifically addressing the deployment of CR in existing GSM systems, forming a more advanced stage of CR research. It provides a detailed framework for identifying and exploiting RF-spectrum opportunities in GSM channels. The authors use real-world measurements and analytical models to demonstrate the feasibility of CR in GSM networks, making a strong case for its practical deployment. While the paper focuses on GSM, its methodologies could potentially be extended to LTE systems. The paper also provides quantitative results and performance metrics, showing that CR can be deployed in GSM systems without significant disruption to existing operations.

The limitations of fixed spectrum allocation become evident when considering future developments in the wireless space. Operators are constrained to wait for traffic to naturally decrease on existing technologies and services to free up spectrum for newer services and technologies. This hinders the cultivation of high-end mobile services and inhibits the exploration of new revenue streams, thereby stunting business growth. To address these challenges and improve spectral efficiency while supporting newer technologies and services, dynamic spectrum allocation is essential. In the following subsection, an attempt is made to unify the terminology and document recent developments through the taxonomy of dynamic spectrum access, along with an overview of the technical challenges and advances in this emerging research area.

3.2.2 Dynamic Spectrum Access

It refers to the dynamic selection of a radio network's operating spectrum from the available spectrum resources. Often, the term "Cognitive radio" is used interchangeably with dynamic spectrum access, encompassing various approaches to spectrum utilization. This concept, relatively novel in spectrum management, seeks to introduce increased flexibility in frequency usage. The breadth of ideas discussed at the first IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) [89] underscores the scope of this concept. Dynamic spectrum access aims to achieve several key objectives, including neutrality to service and technology, reducing spatial and time-based limitations to allow for more spectrum refarming independently in any area, and enabling secondary usage. Advancements in computational power have facilitated the realization of many of these ideas. Given the diverse goals to be achieved across different network setups, experts in the field have proposed various models and approaches to dynamic spectrum access.

M. Parvini et al. [67] paper gave an in-depth analysis of spectrum sharing schemes, tracing their evolution from 4G to 5G and beyond. It covers protocol flows, regulatory frameworks, ecosystem dynamics, and economic considerations. The paper highlights the transition from static spectrum allocation to dynamic and flexible sharing mechanisms, emphasizing the role of cognitive radio and AI in enabling efficient

spectrum utilization. Qing Zhao and Ananthram Swami [90] categorized dynamic spectrum access strategies into three models, as depicted in Figure 9.

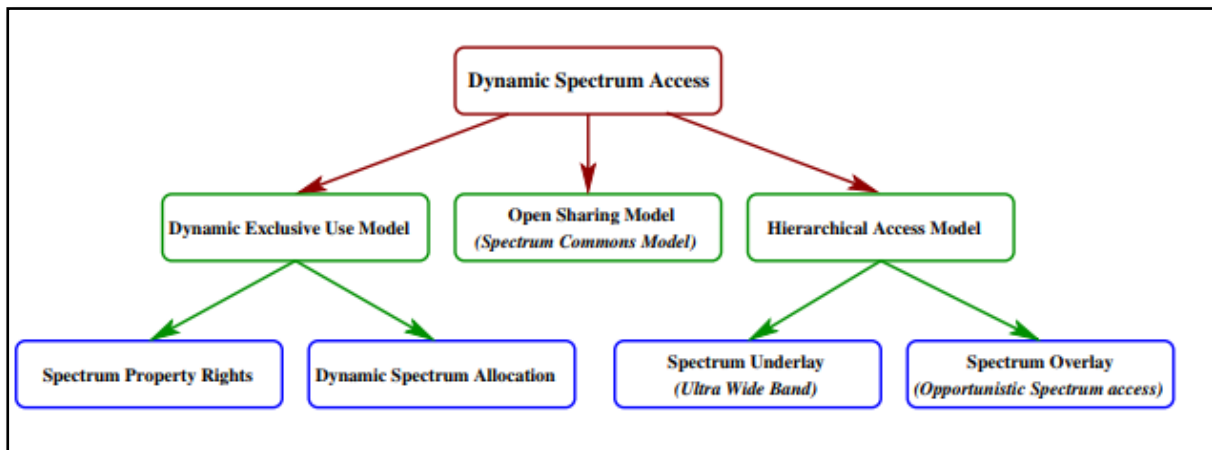


Figure 9: Dynamic spectrum access taxonomy [90].

1. Dynamic Exclusive Use Model

In the dynamic exclusive use model, specific spectrum rights are exclusively held by one entity, although ownership and services may change over time. This model maintains the fundamental structure of current spectrum regulation policies, where spectrum bands are licensed to services for exclusive use. Dynamic exclusive use marks a moderate advancement in dynamic spectrum allocation, where the operator centrally coordinates spectrum sharing in this model, maintaining orthogonality. In essence, this model resembles traditional spectrum allocation, where spectrum bands are allocated to service providers for their exclusive use, but with added flexibility to enhance spectrum efficiency.

Two approaches have been proposed within this model: spectrum property rights and dynamic spectrum allocation. The spectrum property rights approach, as proposed by [91, 92], allows licensees to buy, sell, and trade spectrum, as well as freely choose their technology. This approach introduces market dynamics, enabling licensees to optimize spectrum usage for profitability. However, it's important to note that while licensees have the right to lease or share spectrum for profit, such sharing is not mandated by regulation policies.

The European DRiVE (Dynamic Radio for IP Services in Vehicular Environments) project [93] pioneered the dynamic spectrum allocation model, aiming to enhance spectrum efficiency by dynamically assigning spectrum based on spatial and temporal traffic statistics of various services. Unlike static spectrum allocation policies, this approach assigns a portion of the spectrum to a radio access network for exclusive use at specific times and locations. However, the allocation adapts much more rapidly than current policies, enabling more dynamic spectrum utilization.

These two approaches will be discussed in detail in the following subsections.

a) Spectrum Property Rights

Ronald Coase's seminal paper from 1959 [91] introduced the concept of spectrum property rights, sparking numerous subsequent studies and reform initiatives. Further examination of the challenges and existing research in defining spectrum property rights is available in [92]. Arthur De Vany [94] and Lawrence White [95] proposed a framework for spectrum property rights, defining them based on three parameters: time, geographic area, and spectrum band. Essentially, these rights confer the privilege to transmit over a specified spectrum band within defined geographic boundaries and during specific time periods, with the caveat that signal strength constraints are not breached.

However, enforcing such spectrum property rights faces significant challenges due to the unpredictable nature of radio wave propagation in both frequency and space. Spectral and spatial spill-over, which are inevitable and unpredictable, depend on the characteristics of both transmitters (potential trespassers) and receivers (property right owners). As highlighted by D. Hatfield and P. Weiser [92], spectrum rights cannot be as "clearly defined and readily enforced as their real property counterparts." This inherent unpredictability presents a major obstacle in the implementation of this approach to spectrum reform.

b) Dynamic Spectrum Allocation (DSA)

DSA utilizes spatial and temporal traffic statistics from various radio technologies to enhance spectrum efficiency by enabling time and space-dependent spectrum sharing among coexisting radio services. Spectrum re-farming is currently implemented to redistribute portions of spectrum from technologies that are declining [96, 97]. However, dynamic allocation targets more precise temporal granularity, measured up to minute-level increments, as well as reduced spatial scales, down to individual cell levels. Like FSA, DSA guarantees that a spectrum block is exclusively assigned to a specific technology and owner at any given time and location.

Intra-operator dynamic spectrum allocation to various Radio Access Technologies is one of the primary applications of DSA [98], which constitutes the central focus of this Dissertation study. Extensive literature on dynamic spectrum allocation is discussed in [93, 99, 100, 101]. The European DRiVE project [93] focused on dynamic spectrum allocation in heterogeneous networks, envisioning a logical common coordination channel. Its objective was to merge mobile and broadcast technologies to facilitate spectrum-efficient high-quality wireless IP, particularly for delivering in-vehicle multimedia services.

A simulation study exploring the impact of load prediction through load history and simple regression schemes is outlined in [101]. Meanwhile, [99] delves into regulatory aspects and challenges related to dynamic spectrum allocation across multiple

networks. [99] analysed the actions of regulators concerning the possibilities of Dynamic Spectrum Access (DSA) and the convergence of reconfigurable systems, along with associated challenges. They further explored methods for coordinating spectrum sharing between collaborative and competitive systems.

Additionally, [100] describes two centralized dynamic spectrum allocation protocols relying on a super base-station and evaluates their performance through simulations. These studies contribute valuable insights into the implementation and effectiveness of dynamic spectrum allocation protocols.

2. Hierarchical Access Model

In the hierarchical access model, systems function within a spectrum access framework with unequal rights to spectrum utilization. In this setup, unlicensed secondary users can dynamically access licensed spectrum. This ensures that any interference to licensed primary users remains within acceptable limits. Secondary users achieve this by opportunistically utilizing idle spectrum without causing disruption to primary user transmissions. The fundamental concept is to grant secondary users access to licensed spectrum while mitigating interference to primary users, who hold the licenses.

Cognitive radio (CR), leveraging a Software Defined Radio (SDR) platform, serves as a pivotal technology facilitating this strategy. The DARPA NeXt Generation (xG) program, extensively discussed by Akyildiz et al. [102], extensively delved into this technology, striving to develop policy-based intelligent radios for future dynamic access networks. Other studies, including those referenced in [7, 103], have also thoroughly explored this concept. CR embodies a context-aware intelligent radio capable of autonomous reconfiguration, learning, and adaptation to the communication environment. While dynamic spectrum access remains a prominent application of cognitive radio, CR encompasses a broader paradigm where various facets of communication systems can leverage cognitive capabilities.

This model closely aligns with the concept of dynamic spectrum access, where terminals autonomously make decisions based on prevailing conditions to optimize spectrum utilization, without the need for centralized coordination. For further insights into CR and SDR, readers are referred to J. Mitola [7, 103].

There are two approaches to hierarchical access between primary and secondary users, as defined by Danda B. Rawat and Gongjun Yan [83]:

a. Spectrum overlay

It's also known as opportunistic spectrum access, aiming to capitalize on spatial and temporal "white-spaces" that secondary users could exploit without causing interference. In this model, secondary users operate within a unified network and follow three primary stages: spectrum sensing, where radios scan for the existence of white

spaces; coordination with peers, involving several nodes contending and coordinating transmissions; and spectrum relinquishment, where the spectrum is returned upon detection of primary user transmission. This model is presented in Figure 10(a).

b. Spectrum underlay

Spectrum underlay leverage Ultra-Wide Band technology for transmitting information at high data rates over short ranges and with low power. Spectrum sharing in this approach occurs in the power domain, allowing secondary users to operate in a non-intrusive manner by maintaining transmission power very low, often lower than primary users noise floor. In this scenario, transmission opportunities are termed as "grey-spaces." However, the variety of network configurations is usually restricted, limited by communication distances because of the low-power characteristics of wireless access. Moreover, spread spectrum access methods such as CDMA can be applied for spectrum underlay, ensuring the protection of primary users from explicit interference and enforcing Quality of Service (QoS) constraints for secondary users. This model is illustrated in Figure 10(b).

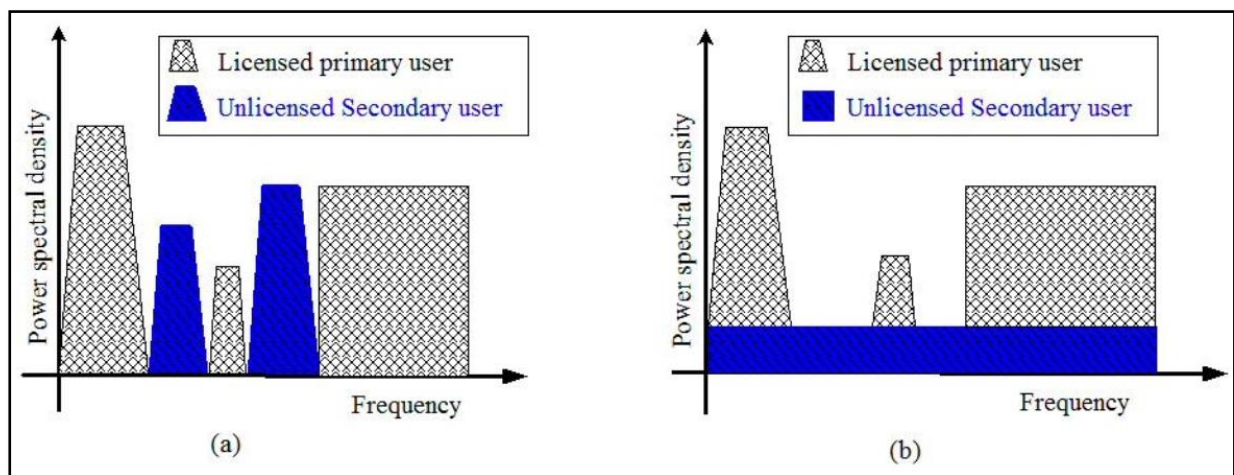


Figure 10: Spectrum overlay and underlay approaches [83].

Both the spectrum overlay and underlay approaches have their own sets of advantages and drawbacks. In the spectrum overlay approach, secondary cognitive radio (CR) users have the flexibility to transmit with high transmission power, which can potentially increase their data rates within available spectrum opportunities. However, they must first identify idle frequency bands not utilized by primary users, which adds complexity to the process. On the other hand, the spectrum underlay approach allows secondary users to transmit concurrently with primary users without needing to identify specific spectrum opportunities. However, they are restricted from transmitting with high transmission power, even if the entire radio frequency band is idle, limiting their potential transmission capabilities.

3. Open Sharing (Spectrum Commons) Model

This model, also known as spectrum commons, facilitates shared spectrum usage by secondary users without the need for licensing. Here, wireless services operate within unlicensed industry, scientific, and medical (ISM) radio bands, such as in wireless LAN or WiFi, where all users have equal opportunities to access the spectrum. Compared to the other two models, many technical issues under this model closely resemble conventional medium access control problems. Centralized spectrum sharing protocols with a central coordinator (referred to as a spectrum server) have been proposed in [104, 105, 106]. Distributed spectrum sharing and power control have been studied in [107–109, 110]. Interestingly, game theory, known for handling selfish and non-cooperative users, has found application in this context, as discussed in [105–107, 110]. Spectrum commons model is mainly composed of three variants i.e. Private, Managed and Uncontrolled. The private commons permit the utilization of frequency-agile radios, equipped with spectrum sensing resources or capable of listening to coordination channels, to access licensed spectrum blocks under the decision of the licensee. The spectrum's ultimate ownership remains centralized with the licensee, who sets the access rules. In managed commons, a consortium of entities collectively own and administer the spectrum, imposing regulations on who can use it, how, and when, to maintain order and prevent chaos. This configuration allows for the shared utilization of the spectrum across different technologies without the need for licenses. The uncontrolled commons approach, also known as "open spectrum access," is the simplest form of commons. In this scenario, the spectrum is open to anyone to use with unlimited devices. However, there are restrictions, such as limits on transmit power and the requirement to confine transmissions within a designated band. An instance of unregulated open sharing is the Industrial, Scientific, and Medical (ISM) spectrum bands, commonly utilized by technologies like Wi-Fi. Due to the absence of controls, particularly interference control, there has been widespread adoption of devices reliant on ISM band technology, such as Bluetooth, Wi-Fi, and ZigBee. This approach lacks any form of coordination, whether centralized or distributed.

3.3 Artificial Intelligence (AI) in DSS

Artificial Intelligence (AI) has emerged as a transformative technology in various domains, including wireless communications and spectrum management. Its ability to process large volumes of data, learn from patterns, and make real-time decisions makes it particularly well-suited for addressing the complexities of DSS. This section explores the potential applications of AI in DSS, focusing on its role in optimizing spectrum utilization, enhancing decision-making, and enabling intelligent spectrum access in cognitive radio networks (CRNs).

3.3.1 AI for Spectrum Sensing and Prediction

One of the key challenges in DSS is the accurate detection of spectrum opportunities, often referred to as "spectrum holes." Traditional spectrum sensing techniques, such as energy detection and matched filtering, are limited by their inability to adapt to dynamic

environments. AI, particularly machine learning (ML) and deep learning (DL), offers advanced solutions for spectrum sensing and prediction:

- **Reinforcement Learning (RL):** RL algorithms enable CRNs to learn optimal spectrum access strategies by interacting with the environment. For example, RL-based agents can dynamically select the best available spectrum bands while minimizing interference to primary users (PUs) [57].
- **Deep Neural Networks (DNNs):** DNNs can be trained to detect spectrum occupancy patterns and predict future spectrum availability. For instance, convolutional neural networks (CNNs) have been used to classify spectrum usage in real-time, improving the accuracy of spectrum sensing [58].
- **Time-Series Forecasting:** AI models such as Long Short-Term Memory (LSTM) networks can analyze historical spectrum usage data to predict future spectrum availability, enabling proactive spectrum allocation [59].

3.3.2 AI for Dynamic Spectrum Allocation

AI can play a pivotal role in optimizing spectrum allocation in multi-RAT environments, where multiple radio access technologies (e.g., GSM, LTE, 5G) coexist. AI-driven approaches can dynamically allocate spectrum based on real-time traffic demands, network conditions, and user requirements:

- **Game Theory and AI:** Game-theoretic models combined with AI can model the strategic interactions among multiple users competing for spectrum resources. These models ensure fair and efficient spectrum allocation while maximizing network performance [60].
- **Centralized AI Controllers:** AI-based centralized controllers can manage spectrum allocation across multiple cells or regions. For example, AI algorithms can optimize the allocation of spectrum blocks to different RATs based on traffic load, interference levels, and quality of service (QoS) requirements [61].
- **Federated Learning:** Federated learning enables distributed AI models to collaboratively learn from data across multiple nodes without sharing raw data. This approach is particularly useful for DSS in large-scale networks, where privacy and scalability are critical [62].

3.3.3 AI for Interference Management

Interference is a major challenge in DSS, especially in dense networks with overlapping spectrum usage. AI can enhance interference management by predicting and mitigating interference in real-time:

- **Self-Organizing Networks (SONs):** AI-powered SONs can autonomously adjust transmission parameters, such as power levels and beamforming directions, to minimize interference and optimize network performance [63].
- **Generative Adversarial Networks (GANs):** GANs can be used to model and predict interference patterns, enabling proactive interference mitigation strategies [64].

3.3.4 AI for Security and Trust in DSS

The dynamic nature of DSS makes it vulnerable to security threats, such as spectrum sensing data falsification (SSDF) attacks. AI can enhance the security and trustworthiness of DSS systems:

- **Anomaly Detection:** AI algorithms can detect anomalies in spectrum usage patterns, identifying potential malicious activities or unauthorized access [65].
- **Blockchain and AI:** Integrating blockchain with AI can provide a secure and transparent framework for spectrum sharing. Smart contracts can automate spectrum allocation, while AI ensures optimal decision-making [66].

3.3.5 Challenges and Future Directions

While AI holds great promise for DSS, several challenges must be addressed to realize its full potential:

- **Data Availability:** AI models require large amounts of high-quality data for training, which may not always be available in real-world scenarios.
- **Computational Complexity:** AI algorithms, particularly deep learning models, can be computationally intensive, posing challenges for real-time implementation in resource-constrained devices.
- **Standardization:** The lack of standardized frameworks for AI-driven DSS hinders its widespread adoption. Collaborative efforts among industry stakeholders are needed to develop standardized protocols and interfaces.

Future research should focus on developing lightweight AI models for real-time DSS, exploring the integration of AI with emerging technologies such as 6G and quantum communications, and addressing ethical and regulatory considerations in AI-driven spectrum management.

In the subsequent discussion, we will delve into the Dynamic Spectrum Allocation approach, which is categorized under the dynamic exclusive spectrum use structure. This serves as the central theme of our Dissertation.

3.4 Dynamic Spectrum Allocation (DSA)

The exploration of multi-RAT joint coordination is an initiative led by the 3GPP Technical Specification Group Radio Access Network (TSG RAN) as part of standard release 13. The Specification #37.870, which was a key reference for the Dissertation, highlights the operational coordination challenges faced by network operators when dealing with the coexistence of multiple RATs. Recognizing the significance of this challenge, multi-RAT coordination is considered vital for improving user QoE, optimizing resource utilization, and maximizing network capacity. The main goals of this project are as follows:

1. Identifying potential scenarios and use cases where multi-RAT coordination could yield benefits, encompassing GUL and WLAN. This includes evaluating advantages, functionalities, and traffic steering while considering Quality of Experience (QoE) and operational constraints.

2. Developing and assessing effective strategies for multi-RAT joint radio resource coordination entails crafting and evaluating methodologies to optimize resource allocation across various Radio Access Technologies (RATs). The emphasis lies in enhancing load balancing within the network and aiding operators in tasks like spectrum re-farming. There's a particular focus on facilitating the transition from GSM to LTE, ensuring a seamless migration while maintaining crucial GSM coverage for services like voice communication. Similar spectrum and migration sharing scenarios may also be applicable to UMTS, LTE, and 5G networks.

The Dissertation will primarily explore multi-RAT joint radio resource coordination, particularly focusing on centralized dynamic spectrum allocation within an intra-operator inter-RAT framework (DCS/LTE). This aspect serves as the central theme of the study. However, the term Dynamic Spectrum Sharing (DSS) will be used throughout the Dissertation. In this context, DSS refers to the allocation of spectrum from one RAT to another, either temporarily or spatially [111]. This aspect can be framed as "bringing resources to the traffic." However, traffic steering across various RATs, essentially "routing traffic to the resources," falls outside the scope of this inquiry.

Spectrum reallocation can be classified into spatial and temporal types based on the TSG RAN classification. Spatial reallocation involves reallocating spectrum within a specific geographical area, while temporal reallocation can be further divided into various subtypes. These include dynamic reallocation, occurring on a timescale of minutes or seconds; semi-static reallocation, occurring over hours or days; and static reallocation, occurring over months or years, also known as spectrum re-farming.

As older generations of radio technology decline, portions of the spectrum they once occupied become available for other uses. Static reallocation, also known as spectrum re-farming, is a common practice, as seen in the recent re-farming of 5MHz in the GSM1800 band to LTE across the entire network by the MNO under study. However, the potential benefits of dynamic and semi-static allocation approaches have not been extensively explored. Therefore, this Dissertation aims to provide further insight into the potential benefits for end-users through dynamic/semi-static allocation approaches within an operator's network.

3.4.1 Related Work

The DRiVE project [112], part of the European Information Society Technologies (IST) initiative, delved into the coexistence of UMTS and DVB-T dynamic Radio Access Networks (RANs), presuming uncorrelated time-varying traffic patterns. It explored two methodologies: temporal and spatial dynamic spectrum access (DSA), with a specific focus on vehicular environments. The temporal DSA methodology is crafted to adapt spectrum allocations to accommodate varying loads over time. Conversely, the spatial DSA approach adjusts to load fluctuations across diverse geographical regions. In this

project, a contiguous DSA scheme was employed, allocating blocks of spectrum to networks with a guard band separating them. The size of these blocks could vary, and their priority was predetermined based on the observed load. The operation relied on load differences experienced by individual RANs at a given time. When there was competition for extra spectrum, algorithms were investigated to blend factors like allocated and requested carriers to ascertain which RAN obtained supplementary spectrum. The sharing scheme involved three primary roles: time-series prediction, load history, and load measurements. When investigating temporal DSA, various factors such as spectrum reallocation time gap analysis, methods for traffic prediction, and strategies for spectrum allocation were examined. The research suggested that the most effective prediction method entailed integrating load history with short-term forecasting. Additionally, it was found that for DSA systems with imperfect load prediction, intervals shorter than one hour were considered optimal.

Conversely, Spatial DSA focused on addressing regional load disparities for each RAN. Computational algorithms managed spectrum allocations of adjacent regions to prevent overlap, primarily aiming to improve GoS in each RAN. Findings from time-based and cell-level DSA suggested a potential enhancement in spectrum efficiency of around 30%, depending on traffic patterns.

The OverDRiVE project [113], an extension of the IST initiative, expanded on the DRiVE project's findings by introducing fragmented DSA allocation. Here, frequency band is viewed as a unified shared chunk, and RANs can obtain a segment of spectrum from any location within this chunk. While this approach offers advantages for multiple RANs sharing spectrum, it poses challenges in terms of interference management. Additionally, OverDRiVE explored the coexistence of various cell-layer networks within a unified spectrum at a regional level. The goal was to develop algorithms for delineating DSA zones and cellular planning, with regional traffic demands acting as constraining factors. Unfortunately, the specific outcomes of the study remain unclear.

Kovacs et al.'s study [114] revisits DSA, this time within the spatio-temporal domain, building upon concepts introduced by the DRiVE and OverDRiVE strategies. In this framework, spectrum allocation is supervised by a Regional Spectrum Broker (RSB), responsible for overseeing spectrum access across various regions. The introduction of a Spectrum Broker (SB) becomes imperative in scenarios involving spectrum contention among various entities, like providers. To mitigate interference problems stemming from multiple regions and providers, a versatile framework incorporating access technology and geographical coupling constraints is employed. These parameters elucidate how radios functioning at identical frequencies in distinct areas could potentially interfere with one another. The optimal allocation of spectrum is determined through the solution of an Integer Linear Programming (ILP) problem. Results from this model indicate

superior performance during peak hours compared to the OverDRiVE proposal, achieving a 26.15% improvement compared to 17.65%.

The SEMAFOUR (Self-Management for Unified Heterogeneous Radio Access) venture delved into exploring the functionality of DSA, as documented in one of their work items [115]. At the outset, the project scrutinized a DSA scenario within an intra-LTE context, encompassing macro and micro cells with multiple frequency tiers. Their algorithm, utilizing cell traffic as input and employing a predetermined fixed cell traffic threshold, demonstrated marginal DSA gains of 1% in network capacity amidst varying traffic conditions. Following this, the project delved into exploring a practical inter-RAT configuration, where the DSA algorithm was deployed to enable the coexistence of GSM and LTE technologies. The test setup comprised spectrum overlapping between LTE and GSM. The DSA algorithm governed the activation and deactivation of overlapping LTE band and GSM carriers in a designated cell every hour, contingent on the load, aiming to enhance LTE capacity while minimizing interference to GSM. Moreover, the algorithm adjusted the position of the overlapping band within the entire band range to optimize setup and minimize interference. The results from this investigation demonstrated a significant potential to enhance LTE cell capacity by over 100%.

In [116], the research explores dynamic spectrum access in 5G millimetre-wave (mmWave) networks, emphasizing the importance of sharing to fully exploit the wide bandwidth and numerous antenna degrees of freedom available in millimetre-wave spectrum. Moreover, it emphasizes the necessity of sharing to enable statistical multiplexing, thereby accommodating the highly variable characteristics of traffic in such networks.

In [5], ZTE introduced its DSA solution named "Magic Radio," which offers a range of functionalities including spectrum refarming, adaptation to traffic changes, and flexible scheduling of GSM/UMTS/LTE spectrum. This solution, enables versatile spectrum sharing and scheduling between GSM and LTE networks, incorporating features such as LTE/GSM dynamic bandwidth extension, GSM dynamic frequency allocation, LTE/GSM band-in spectrum overlay and collaborative spectrum scheduling for LTE/GSM. Field tests have demonstrated the effectiveness of Magic Radio, showing good network performance and enhanced user experience. For instance, China Mobile has implemented dynamic frequency allocation in traffic-tide areas, resulting in a spectrum gain of up to 35%.

In [117], Sidra Tul Muntaha et al. provided a comprehensive review of DSA, examining current methodologies and the associated challenges they pose. Following this, it delves into network slicing, discussing its key components, architecture, parameters, existing techniques, and associated challenges. The article subsequently explores a comprehensive analysis of blockchain technology, covering its operational principles,

factors influencing implementation, and a comparative assessment of open source blockchain platforms enabling smart contracts. Lastly, it synthesizes the discussion by presenting the current state of blockchain-enabled DSA and network slicing, discussing challenges, trade-offs, and opportunities for future research.

Irina Cotanis from Infovista [118] further outlined Dynamic Spectrum Sharing (DSS) as a revolutionary technology enabling LTE and 5G to operate concurrently in the same frequency band. This allows operators lacking dedicated 5G frequency bands to swiftly deploy 5G NR within existing LTE bands as part of Non-Standalone (NSA) networks. DSS emerges as a pivotal short-term solution for expeditious 5G network rollout, offering notable advantages over the laborious process of spectrum re-farming.

The research conducted by G. Salami et al. [119] offers valuable insights into spectrum management algorithms, which are broadly classified into two main categories: centralized "dynamic spectrum allocation" and distributed "dynamic spectrum selection." The former, which forms the basis for the proposal in this Dissertation, involves scenarios where spectrum sharing occurs among various Radio Access Technologies (RATs). In this approach, a centralized management entity governs both licensed and unlicensed spectrum. In contrast, the latter category encompasses all forms of Opportunistic Spectrum Access (OSA) within Cognitive Radio Networks (CRNs), employing distributed techniques, particularly focusing on sensing methods. Throughout their study, Salami et al. delve into the technical challenges inherent in these approaches, such as traffic prediction, signaling overhead, and complexity. By addressing these challenges, the authors provide a comprehensive comparison between the centralized and distributed methodologies, outlining their respective strengths and weaknesses.

In [120], Y. Xu et al. explored the challenges associated with OSA schemes. These challenges include the requirement for interactions among multiple users to identify dynamic spectrum opportunities, the balance between sequential sensing information, cost considerations, convergence speed and the equilibrium between exploitation and exploration in the absence of prior statistical information. To tackle these challenges, the authors conducted a comprehensive review and comparison of various decision-theoretic solutions. These solutions include game models, Markovian decision processes, optimal stopping strategies, multi-armed bandit algorithms, and others. Through this analysis, the authors shed light on the strengths and limitations of each approach, offering valuable insights into the design landscape of OSA schemes.

In [87], the authors employ Monte Carlo simulations to assess the prospective benefits of spectrum sharing in a multi-operator network for downlink UMTS-FDD, with a focus on speech-type traffic. Their results underscore the significant influence of the relative displacement of multi-operator Base Stations (BSs) on capacity enhancement.

Specifically, they note that BSs situated in proximity outperform those in scenarios where BSs are displaced. This enhancement is credited to the avoidance of the near-far effect and the reduction of adjacent channel interference (ACI), facilitated by the similarity in Received Signal Strength (RSS) among co-located BSs.

In [9], S.K. Sharma et al. provide valuable insights into DSS within radio access systems, with a particular focus on 5G networks where Full-Duplex (FD) communication presents numerous benefits and opportunities. These include concurrent sensing and transmission (CST), simultaneous transmission and reception, enhanced sensing efficiency and secondary throughput, and resolution of the hidden terminal problem. The paper commences with a detailed overview of FD-enabled DSS, followed by an extensive survey of recent advancements in this domain. Subsequently, the authors outline various potential techniques for implementing FD operation in DSS wireless systems. Additionally, they propose a novel communication framework aimed at facilitating CST in DSS systems through the utilization of a power control-based Self-Interference mitigation algorithm. Finally, the authors discuss open research challenges and future directions to encourage further exploration in the burgeoning field of FD-enabled DSS radio access systems.

Ying-Chang Liang [122], dissertation laid the groundwork for cognitive radio networks (CRNs) by introducing DSA algorithms that enable secondary users to opportunistically access underutilized spectrum bands without interfering with primary users. It developed spectrum sensing techniques to detect idle spectrum and proposes spectrum sharing protocols to coordinate access among multiple users. The work included a performance analysis of these algorithms under various channel conditions, such as fading and interference, providing theoretical bounds on achievable throughput and latency. A key innovation is the use of machine learning for adaptive spectrum sensing, which improves the reliability of DSA in dynamic environments. This dissertation is foundational for CRNs and has influenced subsequent research on spectrum efficiency and coexistence in wireless networks.

The research carried out by Allen Brantley MacKenzie [123] in his dissertation applied game theory to model spectrum sharing in wireless networks, treating spectrum allocation as a strategic interaction among users. It introduced distributed algorithms for spectrum access that ensure fairness and efficiency, even in the absence of centralized control. The work explored Nash equilibria in spectrum sharing games, providing insights into how users can reach stable and optimal resource allocation outcomes. It also addressed collaborative and competitive scenarios, such as cooperative sensing and non-cooperative spectrum access, and evaluates their impact on network performance. The dissertation is significant for its interdisciplinary approach, combining wireless communications with economic theory to solve spectrum management challenges.

The dissertation by Ahmed Alshamrani [124], explored the application of machine learning (ML) techniques to improve DSA in cognitive radio networks. It introduced reinforcement learning (RL) algorithms that enable secondary users to learn optimal spectrum access strategies in real-time, adapting to dynamic environmental conditions. The work also proposed deep learning models for spectrum sensing, which improve the accuracy of detecting idle spectrum bands compared to traditional methods. A key contribution is the integration of predictive analytics to forecast spectrum availability, reducing the latency and overhead associated with spectrum sensing. The dissertation demonstrated significant improvements in spectrum utilization and network throughput through simulations and experimental validation. This work is highly relevant for next-generation wireless networks, where ML-driven approaches are increasingly used to optimize resource allocation.

In [125], Walid Saad's dissertation investigates DSA for IoT networks, where a massive number of low-power devices compete for limited spectrum resources. It proposes distributed spectrum access algorithms that optimize energy efficiency and spectrum utilization for IoT devices. The work introduces game-theoretic models to analyse the strategic interactions among IoT devices, ensuring fair and efficient spectrum allocation. It also explores blockchain-based spectrum sharing mechanisms, which provide secure and transparent coordination among IoT devices. The dissertation includes experimental evaluations using IoT testbeds, demonstrating the scalability and robustness of the proposed solutions. Its contributions are particularly relevant for enabling large-scale IoT deployments in smart cities and industrial applications.

Yong Zeng [126] dissertation focused on spectrum management in unmanned aerial vehicle (UAV)-enabled wireless networks, where UAVs act as aerial base stations or relays. It proposed dynamic spectrum allocation strategies that account for the mobility and line-of-sight characteristics of UAVs. The work introduced interference mitigation techniques for UAV networks, leveraging spatial diversity and beamforming to reduce cross-link interference. It also explored cooperative spectrum sharing between UAVs and ground-based networks, optimizing spectrum utilization in heterogeneous environments. The dissertation includes extensive simulations and field experiments, validating the proposed solutions in realistic UAV network scenarios. Its contributions are significant for enabling UAV-assisted communication in emergency response, rural connectivity, and beyond.

3.5 Contribution of this Dissertation

From this comprehensive literature review, it becomes evident that dynamic spectrum access encompasses various dimensions, each holding the promise of significant performance improvements and benefits for wireless networks. The growing interest in academia underscores the potential of these approaches. However, amidst the advancements in cognitive radio technology and signal processing, a critical debate

arises regarding the practical applicability of these dynamic spectrum access methods within real-world wireless networks.

DSS stands out among the various approaches as a particularly viable solution to the urgent problem of spectrum scarcity. It offers a promising avenue for mitigating the existing constraints on spectrum availability.

The primary aim of this Dissertation is to conduct an in-depth exploration of the intra-operator inter-RAT DSS approach, focusing specifically on the coexistence of DCS and LTE technologies within the MNO's infrastructure in Zimbabwe. This case study holds significant relevance, as underscored by 3GPP TSG RAN specification #37.870 [111]. Previous research efforts predominantly concentrated on spectrum sharing investigations, often lacking a direct application within typical mobile network environments. Moreover, the reported results often stemmed from non-realistic network setups.

Thus, the central focus of this Dissertation is to leverage real-time traffic data from the targeted mobile network. This includes traffic distribution, network layout, signal propagation models and interference matrices, which serve as input for DSS simulations. By employing system-level simulations, the aim is to model realistic performance outcomes, enabling a comparison with the currently implemented fixed spectrum allocation (FSA). This comparative analysis will illuminate the achievable gains and performance trade-offs associated with dynamic spectrum sharing in practical mobile network scenarios.

4. METHODOLOGY.

This Dissertation aims to evaluate how dynamic spectrum sharing affects mobile network performance. It intends to achieve this by creating an algorithm and conducting simulations to compare the efficacy of fixed spectrum allocation versus dynamic spectrum allocation for downlink communications in different network environments. This approach is deemed necessary due to the dynamic nature of factors affecting mobile network operation, rendering an analytical study impractical. Given the continuously changing RAT capacity in dynamic spectrum sharing, dependent on time-varying observed traffic load, the proposed approach is deemed suitable.

The main goal of these simulations is to ensure their realism while adhering to the time constraints of the project. This was largely achieved through the utilization of credible data provided by the MNO under study. Unlike most publications that rely on simulations built from generalized network architectures, traffic loads, propagation environments, and interference matrices, this Dissertation project leverages data extracted from actual mobile network traffic and conditions. In essence, the simulations aim to replicate real-world mobile network performance with both fixed spectrum allocation and dynamic spectrum sharing enabled. The following sections outline the decisions made in developing the algorithm and the data collection methods used.

4.1 Data Collection and Modelling.

To provide clarity before delving into the details of the simulator's construction, let's introduce the approach to DSS adopted in this Dissertation.

While prior studies on DSS have utilized various methodologies, this study endeavours to investigate a straightforward and potentially the most practical approach. In the DSS model employed here, a designated spectrum block is exclusively assigned to a single RAT at any given time and location. However, from the viewpoint of a radio networks, the quantity, bandwidth, and positioning of spectrum blocks allocated to it may vary over time. These fluctuations in spectrum assignments are contingent upon the detected traffic load on a specific RAT and the available spectrum accessible to an operator.

In a typical real-world scenario, a network operator holds licenses for one or multiple spectrum blocks distributed throughout the frequency spectrum. Depending on factors such as its size, operator preferences and regulatory requirements, each spectrum block can be allocated to one or multiple radio technologies. The DSS model examined in this dissertation seeks to leverage the varying traffic loads of individual RATs over time and space, along with the flexibility in frequency domain division supported by each RAT. Specifically, this dissertation concentrates on implementing DSS for DCS and LTE

access networks, with minimum channel bandwidth of 200 kHz and 1.4 MHz, respectively, enabling the exploration of potential spectrum reallocation opportunities.

Once potential spectrum reallocation possibilities are identified, another crucial element enabling DSS is the traffic load prediction algorithm. This algorithm aims to estimate or predict the anticipated load that will occur during the upcoming spectrum allocation period. Precision in prediction is crucial, as inaccuracies could result in under-allocation of spectrum to a specific RAT, leading to a diminished quality of service (QoS) for its users in terms of call blocking, dropping, and throughput. The forthcoming subsections will provide a detailed description of the traffic load prediction algorithm utilized in this Dissertation.

The prediction algorithm and spectrum allocation period in DSS simulations are adjustable parameters. The duration of the allocation period can vary, from as brief as one hour to several hours. Shorter durations indicate a more dynamic algorithm, as described in the 3GPP specification #37.870. The prediction algorithm can be fine-tuned using various time series forecasting techniques. Moreover, the algorithm's "aggressiveness" is adjusted by setting the load threshold that triggers spectrum sharing decisions. It's essential to highlight that in the proposed simulations, once a spectrum sharing decision is made for a specific time, it remains static until the period concludes. This approach ensures consistency and stability in the simulation environment.

In this Dissertation, the DSS setup involves utilizing DCS technology as the spectrum donor, reallocating a portion of its spectrum to LTE for a predetermined period based on predicted DCS traffic load, without considering future or current traffic load base of LTE. The aim of this reallocation decision is to potentially enhance LTE capacity for a certain period, contingent upon the traffic load. In terms of spatial organization, the DSS model operates at a cell-level granularity, with spectrum allocation decisions made for DCS-LTE sector-pairs within the same cell. Additional details regarding the specific spectrum blocks utilized, the traffic load prediction algorithm, allocation periods, and other parameters will be provided in subsequent sections.

4.2 Simulation Model

According to Jerry Banks [127], simulation entails replicating the behaviour of an actual network over a specified period. In the context of this dissertation, the simulation must faithfully replicate the operations of the MNO under study. Romero et al. [18] outlined the essential components of a system-level simulation, which include:

- Generating mobile stations (MS) in random locations within the network.
- Adjusting transmission power parameters.
- Managing radio resources.
- Collecting performance statistics.
- Selecting the serving base station (BS).

These processes are iterated continuously until a desired level of statistical confidence level of 99% is achieved with acceptable margin of error for example +/- 1Mbps for throughput. Each step may involve further iterations to refine the simulation accuracy. Simulations can be categorized as time-driven or event-driven. Time-driven simulations use fixed time steps, while event-driven simulations are triggered by specific events such as MS movement or call arrivals. For this dissertation, the simulations will be time driven.

A fundamental requirement for a simulator is its capability to generate reproducible results when provided with the same input. Cellular system-level simulations are built upon several foundational elements that profoundly impact network performance. These include:

- Traffic services such as voice calls and data sessions.
- Characteristics of services (e.g., distributions of session size).
- Models for radio wave propagation, which simulate how signals propagate through the wireless medium, considering factors like path loss, shadowing, and multipath effects.
- Parameters specific to each RAT.
- Models for the geographical placement of MS, which determine the spatial distribution of users within the network, influencing signal strength, interference, and handover decisions.
- Layout of the network.

To accurately model radio wave propagation, the simulation must account for path loss, shadowing, and fading effects. The following equations define these parameters:

1. Path Loss Model

The **Hata model** (for urban environments) estimates the path loss as:

$$PL(d) = A + B \log_{10}(d) + C$$

where:

- $PL(d)$ is the path loss in dB at a distance d (km).
- A , B , and C are model-specific parameters determined based on frequency and environment.
- This model is extended by COST-231 for frequencies above 1.5 GHz.

2. Shadowing Model

Log-normal shadowing accounts for large-scale signal variations due to obstacles:

$$PL_{\text{shadow}}(d) = PL(d) + X_{\sigma}$$

where:

- $X\sigma$ is a Gaussian-distributed random variable with mean 0 and standard deviation σ , representing shadow fading.

3. Multipath Fading Model (Rayleigh Distribution)

Rayleigh fading is common in urban environments with no dominant line-of-sight (LOS) component:

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \quad r \geq 0$$

where:

- $p(r)$ is the probability density function of the signal amplitude r .
- σ^2 is the variance of the underlying Gaussian process.

4. Signal-to-Interference-plus-Noise Ratio (SINR)

The **SINR** at a given user equipment (UE) is expressed as:

$$\text{SINR} = \frac{P_s G_s}{I + N}$$

where:

- P_s is the received signal power.
- G_s is the signal gain.
- I is the interference power from neighboring cells.
- N is the noise power.

The data rate is then determined using the Shannon Capacity formula:

$$C = B \log_2(1 + \text{SINR})$$

where B is the channel bandwidth.

These mathematical models will be used to simulate different network scenarios, allowing us to assess the impact of inter-RAT DSS on network performance. Further details on the implementation of these models will be provided in subsequent sections.

4.2.1 Network Architecture

To construct a system-level simulation, data from two distinct cellular network areas in Zimbabwe was gathered, selected to represent urban and suburban environments. These areas, located in Harare City Centre and Norton respectively, are depicted in Figure 11 and 12 below, which are extracted from a site location plot from Google Earth:



Figure 11: Urban area- Harare City Centre.

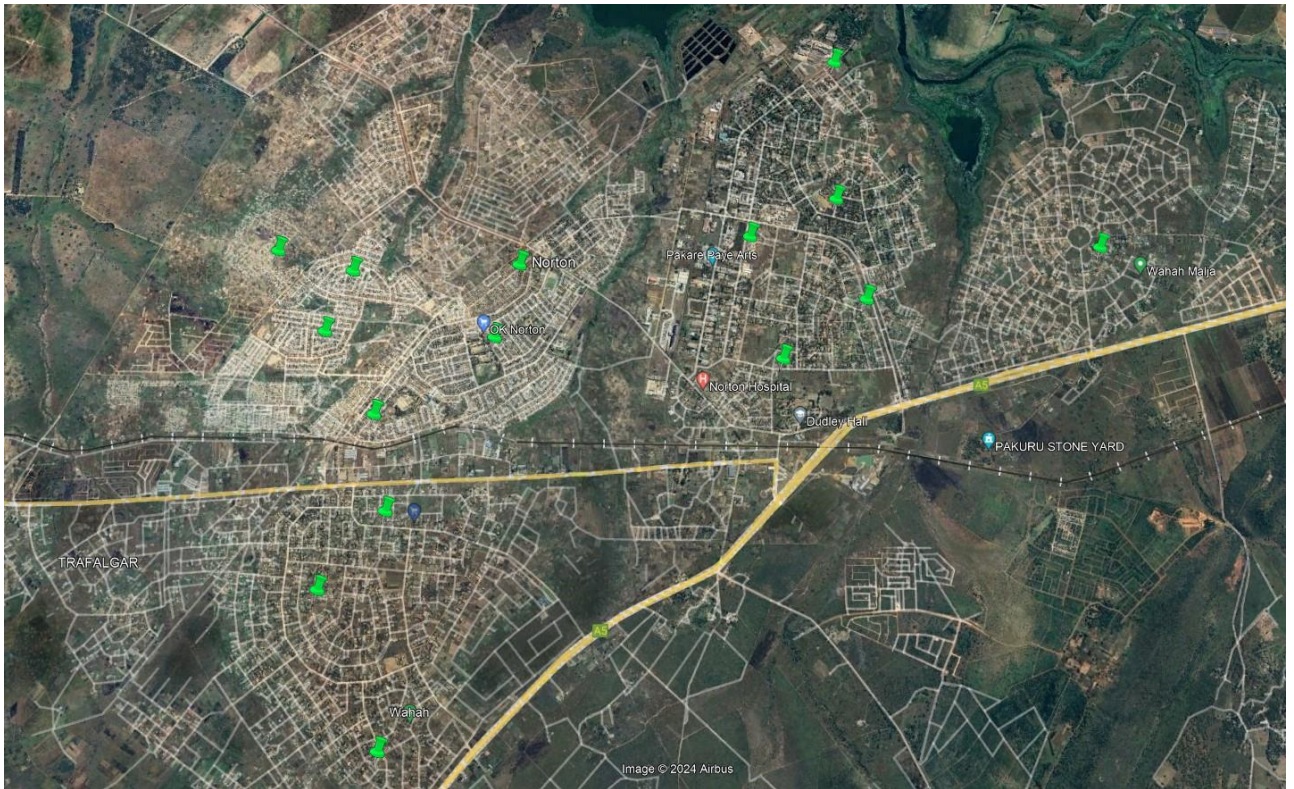


Figure 12: Suburban area- Norton.

Using the gathered network data, our objective is to reproduce the operational performance of these clusters with and without DSS enabled. The comprehensive composition of the networks is outlined in Table 10.

Table 10: Simulated Network Clusters

Area [sq. km]	Environment	Number of Base Stations	Number of Cells		
			DCS	LTE	Total
Harare City Centre [12]	Urban	260	780	780	1560
Norton [34]	Suburban	15	45	45	90

We determined the number of cells to cover a substantial area while still maintaining computational efficiency. Figures 13 and 14, snapshots from Atoll, illustrate the clutter weight conditions and penetration losses for 1800MHz spectrum of the two selected environments, which were utilized to create traffic maps based on density. Subsequently, simulations were generated based on these maps.

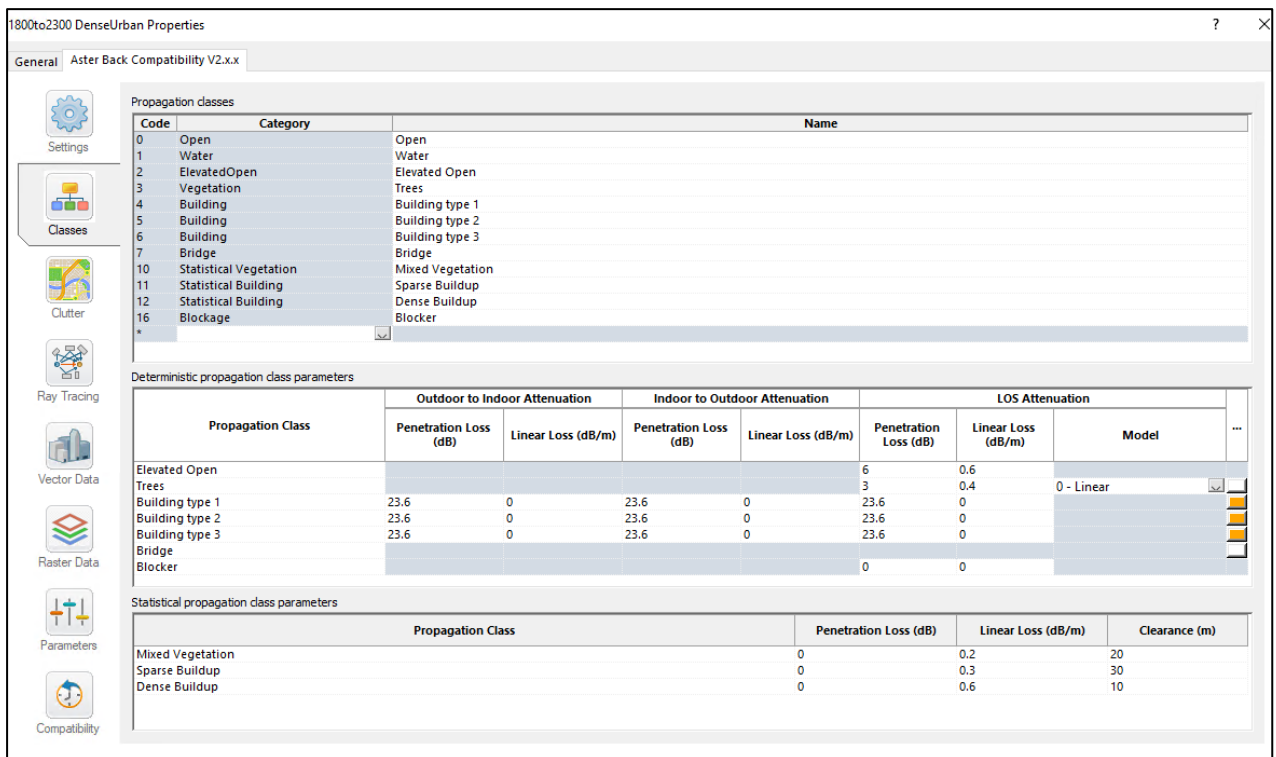


Figure 13: Urban area.

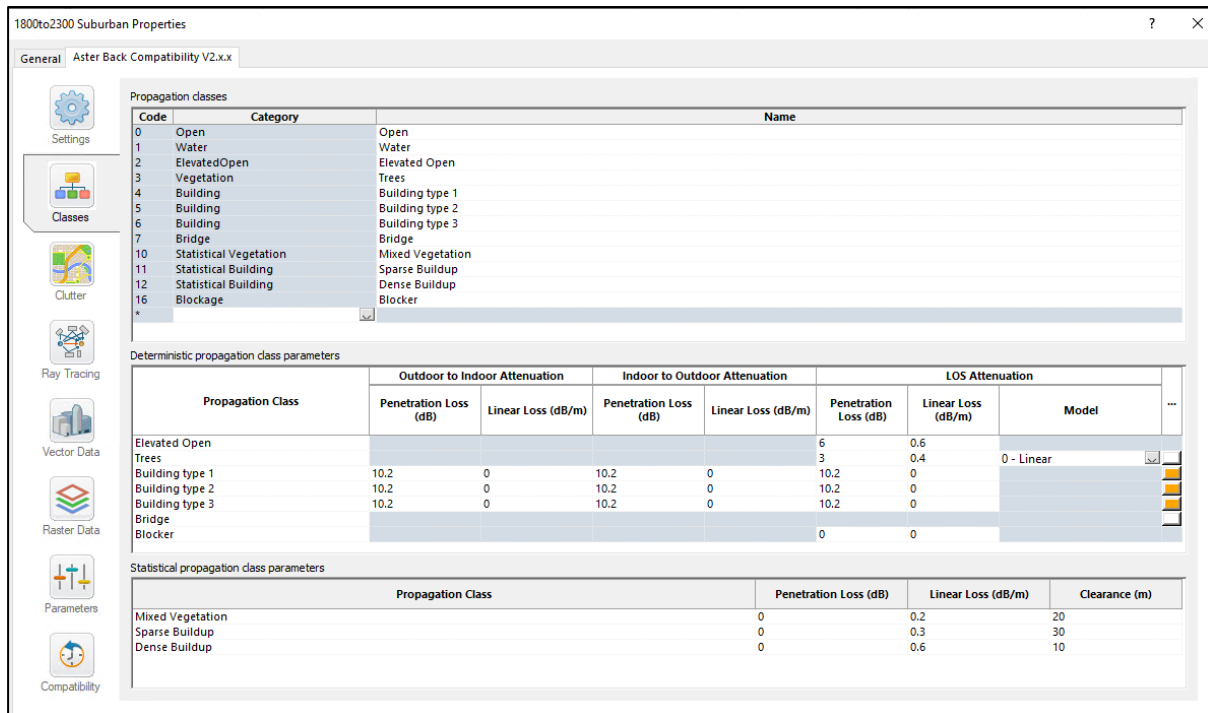


Figure 14: Suburban area.

4.2.2 Propagation Model

Accurate modeling of radio wave propagation is a crucial aspect of simulation, as briefly discussed in Section 2.4. Realistic propagation modeling is essential in mobile network simulations due to its substantial influence on the SINR and, consequently, on the performance of the communication link, which directly impacts the user's perceived signal bit rate.

In our simulations, path-loss calculations were unnecessary, as we relied on propagation maps supplied and validated by the MNO for each frequency band. These maps incorporate a combination of empirical and deterministic models, meticulously refined using empirical data collected from real-world environments where the mobile network operates. Professional modeling tools were employed to fine-tune these models, resulting in realistic propagation models. The tuning process encompassed urban, suburban, and rural environments across different frequency bands such as 900MHz, 1800MHz and 2100MHz.

The propagation models utilized in this Dissertation offer impressive geographical resolutions of 5m, 10m and 20m, making them well-suited for our simulations to faithfully replicate real network performance. With finer resolutions, these maps provide a detailed representation of the propagation environment, allowing our simulations to closely mirror the intricacies of real-world scenarios. Visualizations from Atoll depicting achievable RSRP values in a hypothetical maximum signal attenuation case for the LTE1800 band are showcased in Figures 15 and 16 for the selected areas.

In the simulations conducted for this Dissertation, it is assumed that all traffic originates from all areas, including indoor and outdoor settings. Therefore, in addition to outdoor propagation losses, Building Penetration Losses (BPL) are also factored in effective SINR determination using the below equation:

$$\text{SINR}_{\text{eff}} = \frac{P_s \cdot G_s}{I + N + \text{BPL}}$$

Where:

- BPL is derived from empirical data provided by the MNO.
- P_s : Received signal power from the serving cell.
- G_s : Signal gain (including antenna gain and path loss).
- I : Interference power from neighboring cells.
- N : Noise power.

Average BPL values for the selected areas are derived from the MNO Radiowave propagation models, as detailed in Figures 13 and 14, snapshots from Atoll. Each radio signal received by a mobile station (MS), whether it's the intended signal or an interfering one, is subjected to the corresponding Building Penetration Loss (BPL) value when estimating SINR. This approach maintains the specific load of each cell in the simulated area at any given point in time.

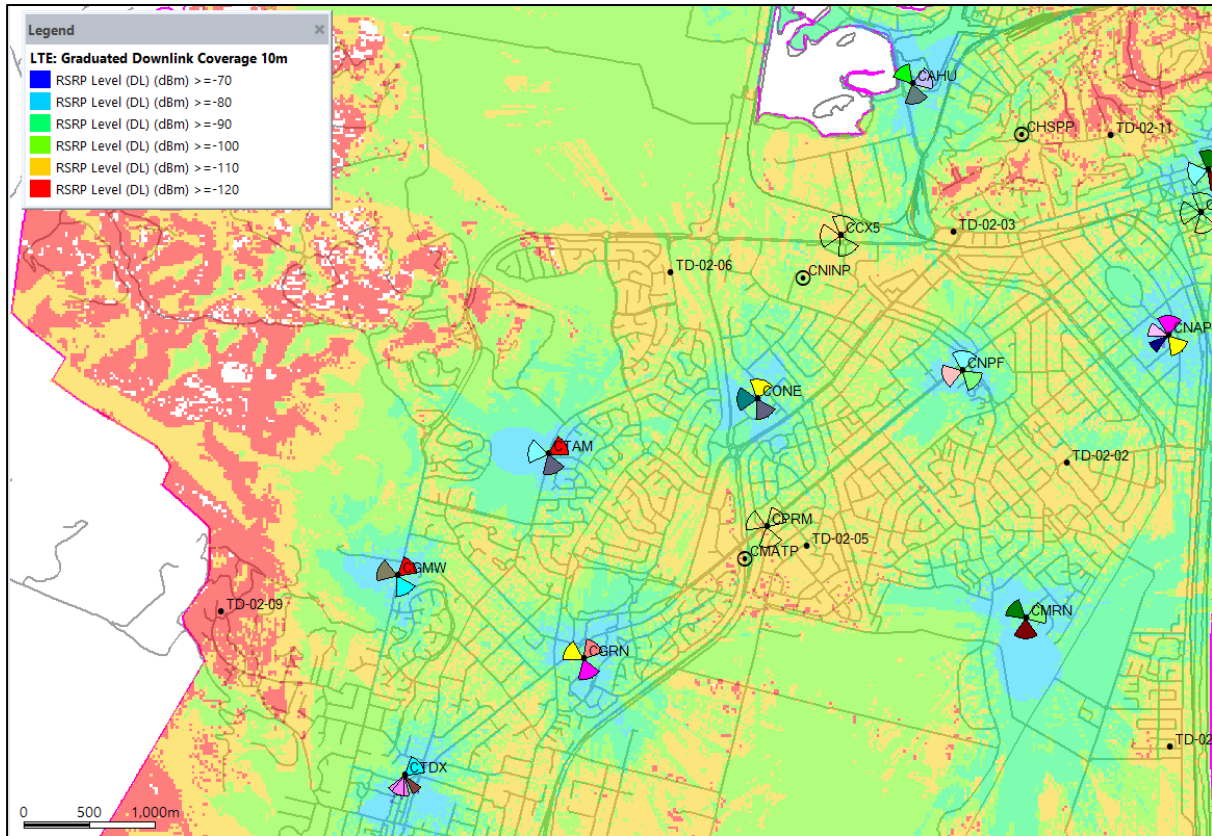


Figure 16: Norton Area RSRP Map.

4.2.3 Carrier Allocation

Carrier frequency allocations dictate the amount of available bandwidth at specific frequencies for a given network operator and how it's distributed among different Radio Access Technologies (RATs). Tables 11 and 12 provides a summary of the current fixed spectrum strategy by the MNO in the selected network areas.

Table 11: DCS Frequency Allocation.

Frequency Band	Bandwidth (MHz)	Downlink (ARFCN)	
		Start	End
DCS	9.4	637	683

Table 12: LTE Frequency Allocation.

Band	Name	Bandwidth (MHz)	Mode	Earfcn DL	Downlink (MHz)	Earfcn UL	Uplink (MHz)
3	1800	15	FDD	1622	1847.2	19622	1752.2

In this dissertation model scenario, we have opted to simulate the GSM1800 and LTE1800 bands. Access to carrier frequency allocations empowers us to authentically simulate potential radio spectrum reallocation scenarios and distribute bandwidth to MS, thereby determining attainable data rates.

As previously outlined, the objective of this dissertation is to model the transition of spectrum allocation from legacy RATs to more contemporary ones, particularly from 2G to 4G radio interfaces, as depicted in Figure 17 below.:

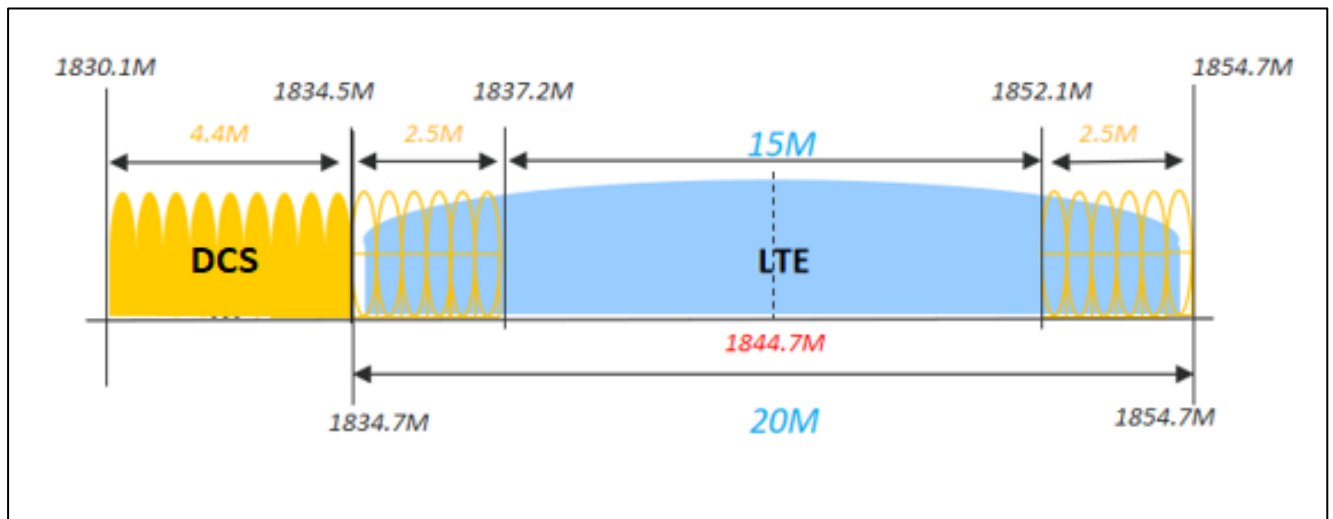


Figure 17: Proposed DSS Spectrum Strategy.

The minimum bandwidth available for reallocation is determined by either the receiving RAT or a donor RAT. For example, in reallocating spectrum from GSM to LTE, LTE requires a minimum operational spectrum block of 1.4 MHz.

Moreover, the MNO possesses GSM frequency spectrum in the 900MHz band, prompting the implementation of Co-BCCH (also referred to as GSM900&DCS1800, multi-band cell) channel allocation. In this configuration, the 900MHz band serves as the underlay (UL), managing BCCH, SDCCH, PDCH, and TCH channels, whereas the 1800MHz band serves as the overlay (OL) layer, exclusively handling TCH channels. The UL primarily focuses on coverage, whereas the OL is dedicated to capacity.

Given that DCS has 9.4MHz of spectrum allocated to TCH channels and BCCH-carrying frequency channels are situated on GSM900, it is apparent that a spectrum block of 1.4MHz represents the minimum and a 5MHz block represents the maximum spectrum block that can be reallocated from DCS to LTE in this scenario.

Under typical operational circumstances, the DCS network allocates 47 dedicated TCH carriers, resulting in a total bandwidth of 9.4MHz (calculated as 47 channels multiplied by 200 kHz per channel). Synthesized frequency hopping, specifically, is exclusively

implemented across the TCH carrier spectrum, with the Mobile Allocation Index Offset (MAIO) function enabled on each site.

Moreover, the MNO adopts a frequency reuse factor of 4x3 for TCH carriers. Here, "4" indicates 4 sites, while "3" denotes 3 cells within each site, as illustrated in Figure 18 below.:

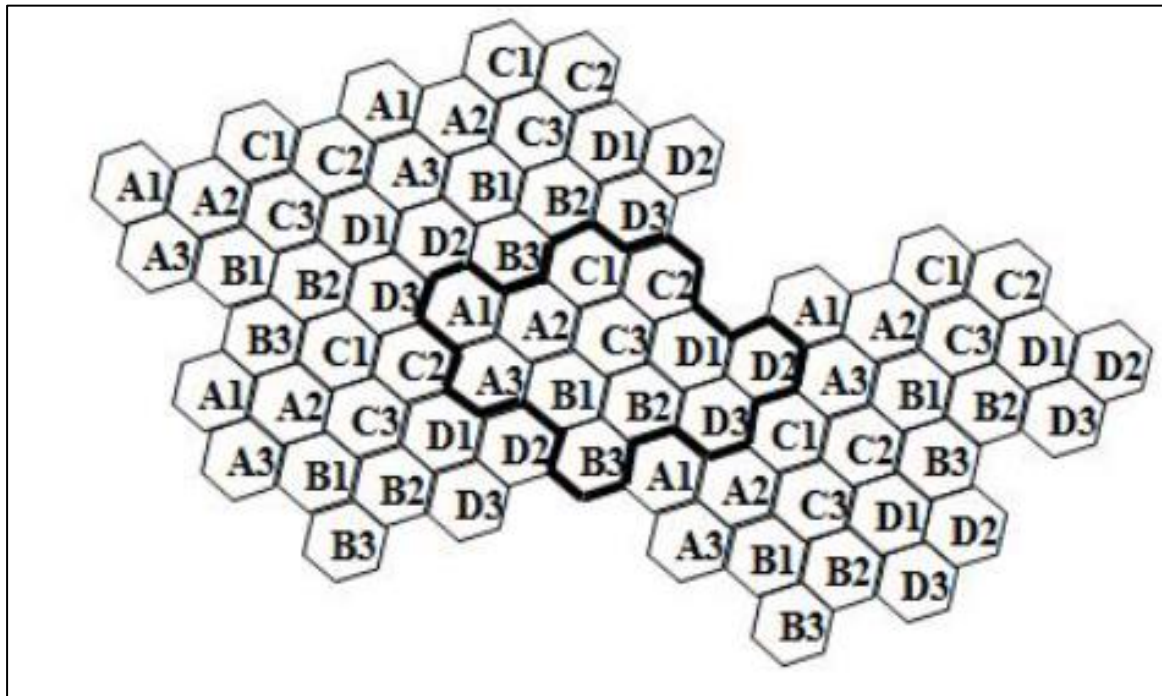


Figure 18: 4x3 Frequency reuse factor used by the MNO.

In the overall configuration, 12 cells form the fundamental frequency reuse cluster. Within this cluster, different cells utilize different frequencies to minimize interference. The MAIO function plays a crucial role in preventing interference between sectors within the same site by strategically scheduling timeslots. This ensures that co-channel interference within the site is effectively eliminated.

As a result, each sector within the cluster has the capacity to simultaneously utilize up to four TCH carriers. However, frequency hopping is deployed across all 12 carriers, ensuring that each transceiver cycles through every frequency in a hopping list. The strategy is pivotal for averting timeslot overlaps within any individual site, particularly given that each site comprises three sectors, thus leading to four carriers per sector. A simplified representation of this scenario is illustrated in Figure 19.

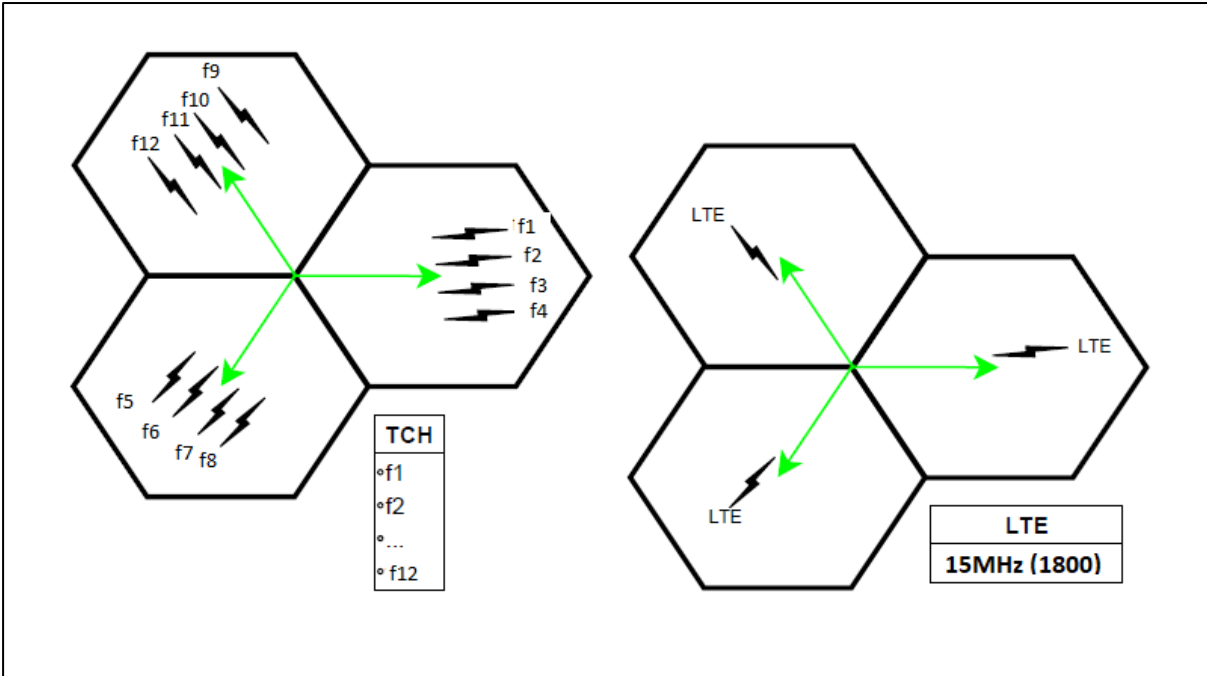


Figure 19: Current fixed spectrum allocation setup for the MNO.

In the visualization provided above, the DCS and LTE spectrum conditions are uniformly depicted across all sectors within a site. However, our model allows for the possibility of different spectrum conditions for each sector.

In the scenario where a portion of the spectrum (5MHz in this instance) is reassigned to LTE, DCS is left with only six Traffic Channel (TCH) frequency carriers. Consequently, to uphold compatibility and prevent timeslot overlap, only two TCH carriers are permitted per sector. This ensures that even if all three sectors within a single site undergo spectrum reallocation, no timeslot overlap would occur, as illustrated in Figure 20. This principle remains consistent regardless of the specific spectrum reallocation scenarios among sectors within a site.

Put simply, if spectrum is shifted within a sector, the DCS TRx in that sector can only utilize two TCH carriers. These carriers then cycle through six frequencies as part of frequency hopping.

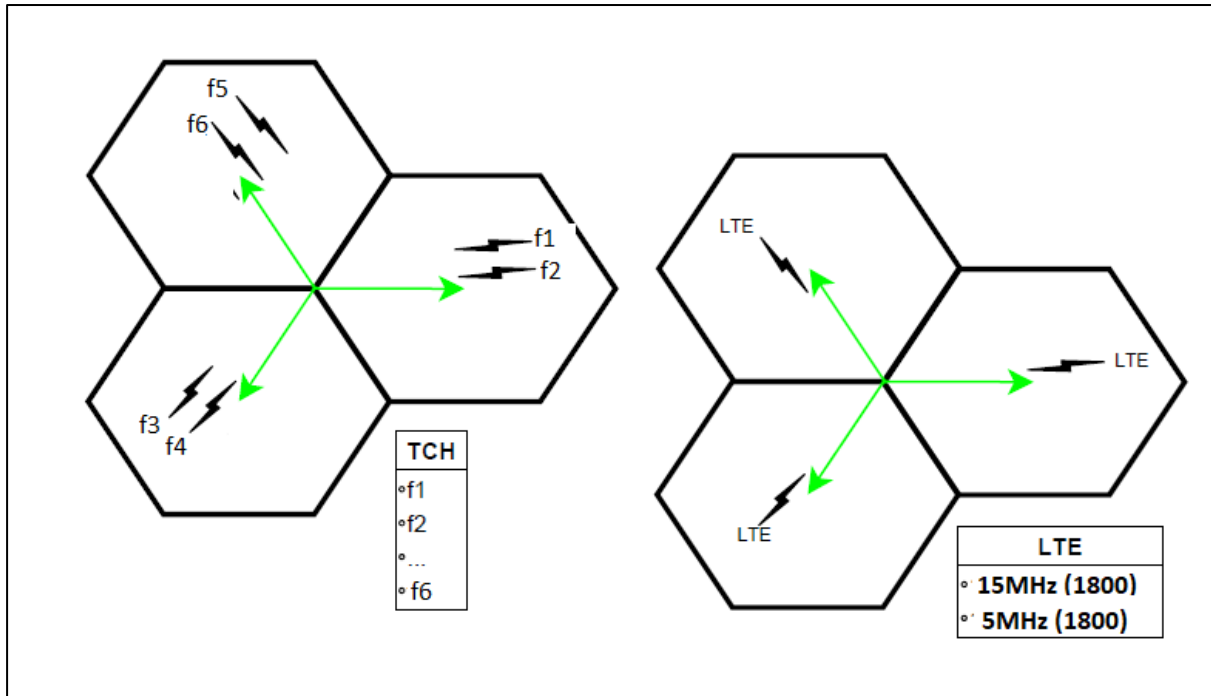


Figure 20: DSS conditions.

4.2.4 Traffic Map Modeling

For the DSS algorithm to function optimally, a precise traffic load prediction algorithm is indispensable. While Leaves and Huschke [128] proposed a combination of historical traffic data with linear and exponential regression methods for predicting traffic load in dynamic spectrum periods, this Dissertation takes a different approach. Here, historical traffic data provided by the MNO through raster traffic maps, along with time series prediction, is utilized to forecast the DSS bitmap. The use of moving average prediction, as discussed by XU Shuona and ZENG Biqing [129], where the next period's traffic load is assumed to be the same as the previous one, was not adopted in this study. This decision was made to avoid potential under-dimensioning of DCS spectrum in real-world networks, as such assumptions may not accurately reflect dynamic traffic patterns.

The simulations conducted in this dissertation to evaluate the potential capacity advantages of DSS employed the Monte Carlo simulation methodology. The Monte Carlo simulation output for user distribution and traffic load is expressed as:

$$\text{User Distribution} = \sum_{i=1}^N \text{Traffic Density}_i \cdot \text{Area}_i$$

Where:

- Traffic Density i : Traffic density in the i -th region.
- Area i : Area of the i -th region.

This equation models the spatial distribution of users in the network, which is critical for generating realistic traffic maps and conducting Monte Carlo simulations. The methodology leverages traffic data obtained from raster traffic maps, subscriber lists, and user penetration data, all of which were supplied by the Mobile Network Operator (MNO). By incorporating these data sources, the simulations accurately reflect real-world traffic patterns and user behaviour, enabling a robust evaluation of DSS performance.

Figure 21 illustrates various types of traffic maps utilized in Monte Carlo simulations, including raster traffic maps, vector traffic maps, live traffic maps, and traffic density maps.

- **Raster Traffic Maps:** These maps are ideal for utilizing traffic data sourced from the Operation and Maintenance Centre (OMC). The OMC collects data from all cells in the network, such as the number of users or throughput in each cell, and categorizes content based on various services. Traffic is distributed within the optimal server area of each transmitter and across all provided areas based on parameters like throughput, downlink, or the number of users per activity status.
- **Vector Traffic Maps:** In this type of map, vectors (which can be polygons, lines, or points) represent customer density, along with user profiles and mobility types. These maps illustrate traffic patterns based on user profile environments, with each pixel assigned to an environmental class.
- **Live Traffic Maps:** These maps come into play when traffic data is sourced from marketing channels. They offer real-time insights into traffic patterns derived from marketing data, providing valuable information for analysis and decision-making.
- **Traffic Density Maps:** This mapping approach leverages traffic data linked to population regions, where each pixel on the map represents the actual density of users in a given area. These maps offer a comprehensive view of user distribution across different geographical regions, aiding in network planning and optimization.

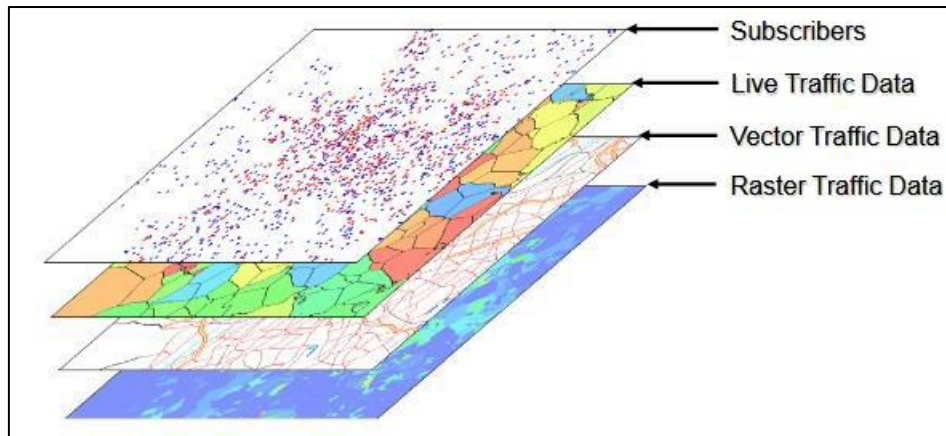


Figure 21: Types of Traffic Data [130].

Service characteristics for both voice and data sessions, including voice call duration and session size, were modelled using distributions derived from raster traffic maps for each of the two selected areas individually over multiple days. To account for the anticipated differences in service usage behaviour between Harare City Centre and Norton, distinct service models were developed for each area. This meticulous approach ensures that the models accurately represent real-world usage scenarios in each specific location, enabling more precise simulations and analyses.

The performance perceived by end-users is greatly influenced by how mobile stations (MS) are distributed geographically and their movement patterns within the network area. Regions with dense user populations, such as office buildings, public venues, and large residential complexes, typically share similar signal attenuation traits, resulting in a uniform communication experience for users under the same carrier. Furthermore, network operators frequently optimize their networks to enhance signal coverage in these high-traffic areas.

As outlined previously in this chapter, the simulator utilized for this study integrates raster traffic maps, allowing it to generate traffic maps with near real-time accuracy. Through the utilization of network probes, this module captures essential information regarding the distribution of mobile stations and their mobility patterns. The data collected offers comprehensive insights into traffic intensities, mobility behaviours and measured interference levels on the radio interfaces at the granularity of individual cells within the network.

This dissertation focuses exclusively on predicting traffic load for 2G networks, aligning with the objective of the proposed dynamic spectrum sharing model. The aim is to enhance LTE throughputs and overall user experience by utilizing existing spectrum resources more efficiently. As a result, spectrum will be temporarily shifted from DCS to LTE during voice off-peak times. The proposed algorithm will concentrate on analysing voice call traffic, while treating packet data traffic as a best effort service.

To forecast traffic load, the algorithm will utilize voice call traffic generated during the previous period and historical average voice call duration as inputs to the Erlang B formula. The Erlang B formula can be expressed as:

$$P_b = \frac{\frac{A^C}{C!}}{\sum_{k=0}^C \frac{A^k}{k!}}$$

Where:

- P_b : Blocking probability (target: 0.005 in this study).
- A : Total traffic load in Erlangs (calculated from historical data).
- C : Number of available channels.

This formula will determine the full-rate channels required to accommodate the forecasted traffic for the upcoming period. The channel assessment algorithm is based on the research conducted by Qiao and Qiao [121]. These calculations will adhere to a maximum permissible blocking probability of 0.005, which is determined based on the MNO network configuration.

4.3 DSS Design

The principle of DSS involves optimizing spectrum utilization by dynamically reallocating bandwidth between DCS and LTE networks based on their respective traffic loads. When the DCS system experiences high traffic load, it occupies its entire bandwidth i.e. 9.4MHz while the LTE system utilizes its dedicated bandwidth i.e. 15MHz. Conversely, during periods of low 2G traffic load, the excess DCS frequency spectrum is released for LTE use. As a result, the LTE system dynamically extends its spectrum from 15MHz to 20MHz), as depicted Figure 22 below. Subsequently, when 2G traffic load peaks again, the LTE system dynamically reduces its bandwidth (e.g., scaling down from 20MHz to 15MHz) to free up frequency spectrum for the DCS system. This dynamic spectrum sharing mechanism optimizes spectrum efficiency by allowing both networks to utilize available bandwidth more effectively based on their current traffic demands.

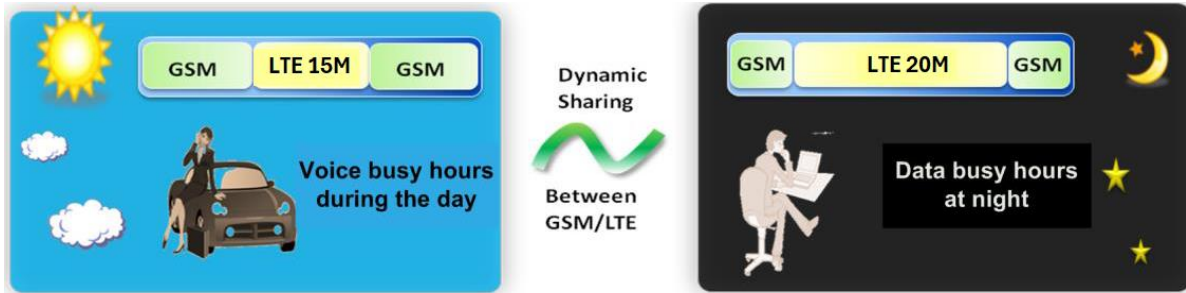


Figure 22: DSS working principle.

4.3.1 DSS Architecture

The DSS system operates based on the changing traffic demands of both GSM and LTE systems. Therefore, it's essential to analyse the traffic patterns of both systems and coordinate spectrum usage accordingly. This will be achieved by introducing an additional node in the network called the Centralized Self-Organizing Node (CSON). Figure 23 illustrates how the CSON will be integrated into the DCS and LTE systems.

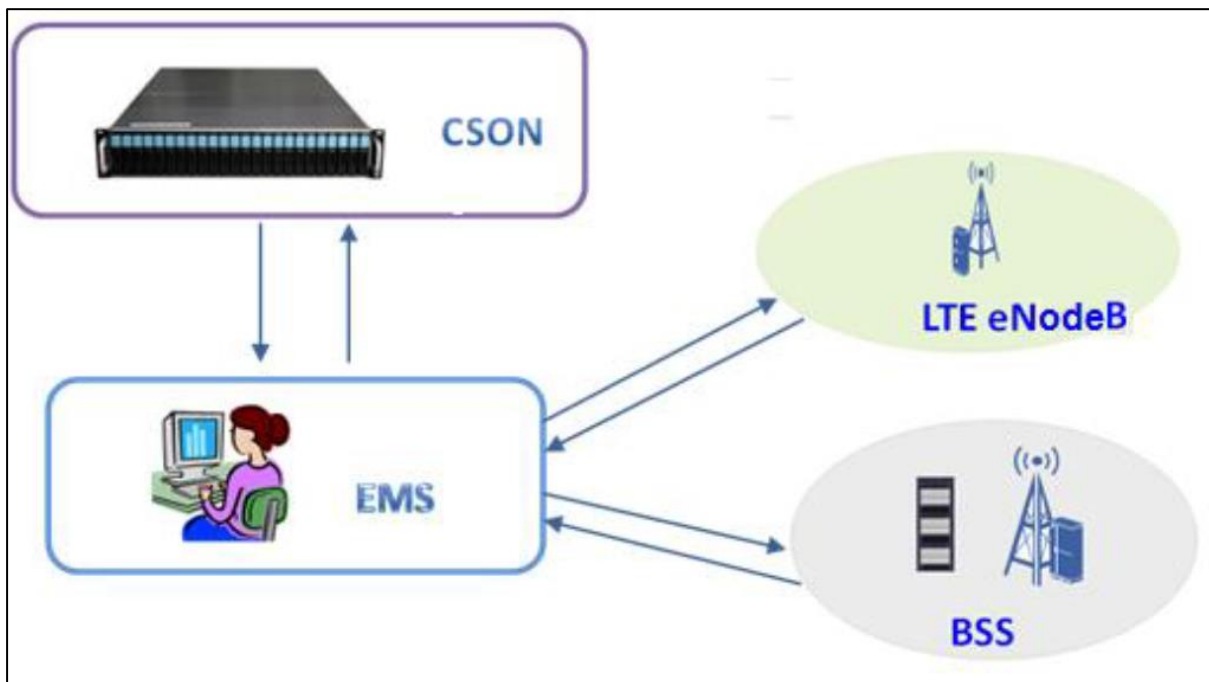


Figure 23: CSON.

DSS is engineered to optimize spectrum utilization by leveraging DCS spectrum resources for LTE during periods of low DCS traffic volume and relinquishing spectrum resources when DCS traffic volume is high. This efficiency enhancement is achieved through a distributed system involving GSM BSCs, LTE eNodeBs, EMSs, and CSON. These network elements collaborate to implement DSS.

With the inclusion of CSON, the Element Management System (EMS) of DCS and LTE systems relay performance data to the CSON. Subsequently, the CSON analyses this data to determine the duration for sharing spectrum resources between GSM and LTE. This sharing duration is represented within a 24-hour period, where periods of allowed sharing are designated as 1, and disallowed periods are marked as 0, thus forming the

sharing time bitmap. The bandwidth allocation between GSM and LTE is dynamically adjusted according to the real-time traffic loads experienced by both networks during the sharing-enabled periods.

Below is a summary of the functions of the network elements constituting the DSS system:

- The BSC calculates the cell load in the sharing area to ascertain the number of cells meeting spectrum sharing or retracting demands. It determines whether to share or retrieve spectrum resources and communicates results to EMS and CSON.
- The CSON orchestrates bandwidth coordination between the GSM and LTE systems, configures sharing areas, and computes sharing time.
- EMS provides performance and configuration data, facilitating transparent message transmission between the GSM BSC and CSON, as well as between LTE eNodeBs and the CSON.
- eNodeBs dynamically extend or restore bandwidths when GSM spectrum resources are released or retracted.

4.3.2 Sharing Area Configuration

DSS-related data is configured on the CSON, which employs a template comprising three parameter modules: ShareArea, GSMCell, and LTECell.

- **ShareArea** defines parameters of the sharing area, including its ID, time bitmap, and the judgment condition for release/retract of spectrum resources.
- **GSMCell** defines the GSM cells within the sharing area and specifies the load threshold for spectrum resource release/retract.
- **LTECell** defines the LTE cells within the sharing area.

The CSON generates the frequency pool in terms of LTE cells (indicating GSM frequencies released when LTE extends bandwidth) and transmits it to EMS along with ShareArea and GSMCell data. EMS then forwards this information to the BSC. Further details on frequency pool generation will be discussed in the subsequent subsections.

4.3.3 Time Bitmap Calculation for DCS/LTE Spectrum Sharing

In the DCS network, peak load hours fluctuate based on real-time traffic conditions, which vary throughout the day. As a result, the period for spectrum sharing is not fixed; instead, it dynamically adjusts according to DCS cell loads. To predict the traffic load for the next period, a time series forecasting model (e.g., exponential smoothing) can be applied, which is then used to update the time bitmap for DSS:

$$\hat{A}_{t+1} = \alpha A_t + (1 - \alpha) \hat{A}_t$$

Where:

- A^{t+1} : Predicted traffic load for the next period.
- A_t : Observed traffic load at time t .
- α : Smoothing factor ($0 < \alpha < 1$).

Spectrum resources from DCS can be allocated to LTE without impacting DCS services, necessitating real-time monitoring of DCS Key Performance Indicators (KPIs). Spectrum sharing between DCS and LTE occurs only when DCS cell loads fall below a specific threshold, with the sharing time period updated in the time bitmap accordingly. For instance, a time bitmap like "1;1;1;1;1;1;1;1;1;0;0;1;1;1;1;1;1;1;1;1" indicates that spectrum sharing is disallowed during the 11:00-12:59 period while allowed during other time slots.

To accommodate spectrum sharing across multiple days, a one-week time bitmap is stored in the CSON. Initially, this bitmap is configured manually. Subsequently, the time bitmap for the previous day is automatically updated early each morning, with the updated bitmap becoming effective at the same time in the subsequent week. Figure 24 below shows the proposed time bitmap update process for DSS:

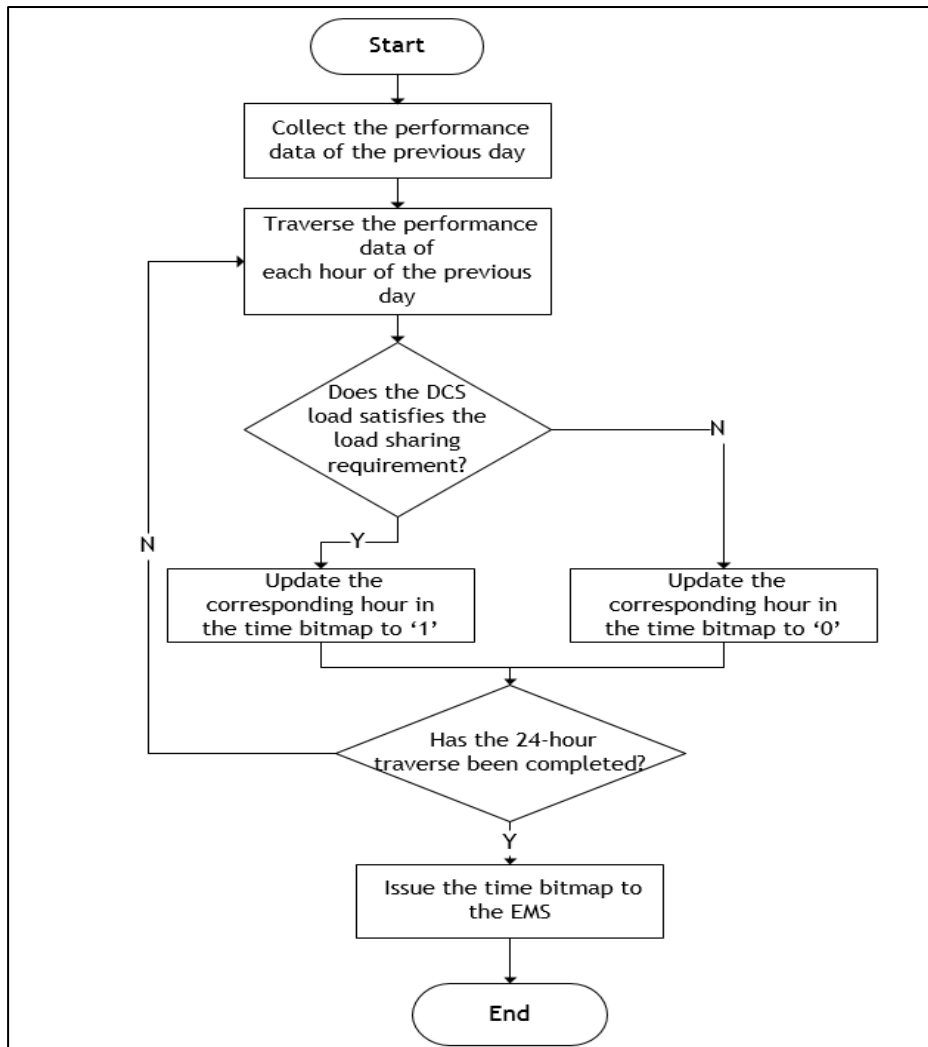


Figure 24: Bitmap update flowchart for DSS.

The flowchart operational steps are further explained bellow:

1. When it is time for calculating the time bitmap, collect the performance data of the previous day.
2. Traverse the performance data of each hour of the previous day.
3. Calculate the DCS load of the current hour based on the performance data, and judge whether spectrum sharing is allowed within the hour.
4. If spectrum resources can be shared, update the corresponding hour in the time bitmap to 1; otherwise, update the corresponding hour to 0.
5. If the 24 hours are not traversed completely, go to step 2.
6. If the 24 hours are traversed completely, issue the time bitmap of the previous day to the EMS. The time bitmap will be valid on the same time of next week.

By applying the proposed Bitmap flowchart to real network performance data provided by the MNO for a specific day, valuable insights can be gained to inform the design of the proposed DSS utilizing CSON.

simulation platform equipped with all the necessary functions to conduct simulations relevant to the study. The physical attributes of cells, including azimuths, antenna heights, tilts, transmit power, antenna types, and cell configuration data, were obtained from the MNO's network data.

Monte Carlo-type system-level simulations were conducted using Atoll, utilizing raster traffic maps obtained from the EMS. These simulations had two primary objectives: firstly, to compare the simulator's performance against actual network performance data extracted from EMS, and secondly, to validate the impact of DSS on the network by comparing it against the current fixed spectrum sharing employed by the MNO.

MATLAB was not chosen due to its limitations in providing the required functionalities to accurately simulate real mobile network operations. Integrating spatial data such as real network Geodata, propagation models, call traces, drive tests, interference matrices, and population maps into MATLAB to facilitate realistic mobile network simulations was not feasible. Additionally, MATLAB lacks support for computationally intensive propagation characterization procedures, which are supported by Atoll.

Atoll, developed by Forsk, is a system-level simulator platform primarily utilized for wireless network planning, modeling, and optimization across a wide range of technologies, encompassing 2G, 3G, 4G, 5G, and Wi-Fi. It integrates mobile call traces, configuration data management, and network performance counters to facilitate live network planning. Detailed information such as layer 3 signaling, user and phone identification, mobile measurements and signaling information are encapsulated within call events in Atoll. Moreover, it employs passive probes for collecting real-world mobile network performance data, which are placed on relevant interfaces such as Abis for 2G, Iub for 3G, and X2 for LTE. With Atoll's live network planning capabilities, identifying traffic hotspots becomes more accessible, and accurate network models can be generated.

Table 13 shows the DCS and LTE simulation parameters that were applied in Atoll.

Table 13: Simulation Parameters.

Parameter	Value/Description
LTE Network	5km radius macro cell with 3 sector directional antennas
GSM Network	10km radius macro cell with 3 sector directional antennas
User type	Indoor and Outdoor
User distribution	Network based
Frequency Band	1800 MHz
Bandwidth	LTE: 15MHz GSM: 9.4MHz

Additional bandwidth (DSS)	1.4MHz, 3MHz, 5MHz
Duplexing method	LTE: FDD GSM: TDMA
Max. DL transmit power	LTE: 40W per Tx GSM: 20W per TCH
LTE MIMO	2T2R
SINR	$\geq 13\text{dB}$
RSRPmin	-110dBm
RxLevmin	-113dBm
Half rate utilization thresholds (TCH/H)	$\geq 25\%$ $15\% \leq x \leq 25\%$ $\leq 15\%$
Background Noise	-115dBm
Propagation model	Operator Proprietary (blend of empirical and deterministic models)
DTX	Yes (factor of 0.5)
MAIO	No intra-site co-channel interference
Frequency Hopping list length	12
User satisfaction criteria	Uninterrupted connectivity
Environment	Urban and Suburban
Traffic Load	Time varying, based on collected logs
Multipath fading	Averaged
Cell configurations, antennas etc	Actual network based
Cell selection	Propagation loss based

An in-depth analysis of the simulation parameters outlined in Table 13, is given below, demonstrating their relevance to the study:

Network Configuration and Propagation Model

The choice of a 5km LTE macro cell and a 10km GSM macro cell with three-sector antennas aligns with typical real-world deployment scenarios. These configurations ensure accurate modeling of inter-cell interference and traffic distribution.

The signal propagation in the simulation follows the operator's proprietary model, which is a blend of empirical and deterministic models. The path loss (PL) for both LTE and GSM can be estimated using the COST-231 Hata Model as illustrated by equations in 2.4.1.

Duplexing and Bandwidth Allocation

The LTE network operates using Frequency Division Duplexing (FDD), while the GSM network employs Time Division Multiple Access (TDMA). The allocated bandwidths are 15 MHz for LTE and 9.4 MHz for GSM, with additional bandwidth for Dynamic Spectrum Sharing (DSS) ranging from 1.4 MHz to 5 MHz.

The LTE system capacity in terms of maximum throughput (in Mbps) can be approximated using Shannon's Capacity Theorem:

$$C = B \log_2(1 + \text{SINR})$$

where:

- B is the bandwidth (15 MHz for LTE),
- SINR is the Signal-to-Interference-plus-Noise Ratio (≥ 13 dB in the simulation).

Using SINR = 13 dB, we obtain:

$$C = 15 \times \log_2(1 + 10^{(13/10)}) \approx 15 \times 4.29 = 64.35 \text{ Mbps}$$

This provides an estimate of the LTE network capacity under ideal conditions.

Transmit Power and Coverage Considerations

The LTE transmission power is set to 40W per Tx, while GSM transmission power is 20W per Traffic Channel (TCH). The Reference Signal Received Power (RSRP) minimum threshold is -110 dBm, ensuring that users can maintain adequate signal quality. The relation between received power and transmission power is:

$$P_{rx} = P_{tx} - PL$$

where:

- P_{rx} is the received power,
- P_{tx} is the transmitted power,
- PL is the path loss.

By ensuring RSRP_{min} of -110 dBm, network coverage and handover efficiency are maintained.

User Distribution and Traffic Load

The user distribution is network-based, incorporating both indoor and outdoor users, with traffic load varying over time based on collected logs. The simulation includes background noise at -115 dBm, and multipath fading is averaged to reflect real-world conditions.

The probability of a successful connection is influenced by system load and interference levels. The Erlang B formula is used to estimate blocking probability:

$$B(E, N) = \frac{\frac{E^N}{N!}}{\sum_{k=0}^N \frac{E^k}{k!}}$$

where:

- E is the total offered traffic in Erlangs,
- N is the number of channels available.

For LTE and GSM, the half-rate utilization thresholds are categorized as $\geq 25\%$, $15\% \leq x \leq 25\%$, and $\leq 15\%$, ensuring efficient spectrum utilization.

Cell Selection and Handover Mechanism

Cell selection is based on propagation loss, ensuring that users connect to the most optimal cell. The SINR threshold is set at ≥ 13 dB, which influences handover decisions. The handover success probability P_h can be estimated as:

$$P_h = 1 - e^{-\lambda t}$$

where:

- λ is the rate of successful handovers,
- t is the dwell time in a cell.

By ensuring effective handover policies, the network maintains uninterrupted connectivity as per user satisfaction criteria.

The simulation parameters in Table 13 are carefully designed to reflect real-world mobile network conditions, with Atoll enabling precise modeling. The mathematical equations presented validate the simulation setup, ensuring that the study accurately assesses the impact of DSS and network performance under different configurations.

4.4.1 SINR, RSRP and RxLev Estimation

The process of calculating downlink SINR for various RATs adheres to a standardized procedure. This involves determining the received power (RSRP for LTE and RxLev for 2G) of the target signal at the mobile station, considering the transmit power of the serving transceiver, and factoring in propagation and building penetration losses. The SINR for a user equipment (UE) is calculated using the following equation:

$$\text{SINR} = \frac{P_s \cdot G_s}{I + N}$$

Where:

- P_s : Received signal power from the serving cell.
- G_s : Signal gain (including antenna gain and path loss).
- I : Interference power from neighboring cells.
- N : Noise power.

The received signal power P_s can be derived from the RSRP (Reference Signal Received Power) for LTE or RxLev (Received Signal Level) for DCS:

$P_s = \text{RSRP}$ (for LTE)

$P_s = \text{RxLev}$ (for DCS)

With this SINR equation, the quality of the communication link can be evaluated and determine the feasibility of spectrum reallocation. The propagation loss, derived from

radio wave propagation model, encompasses all relevant effects including those associated with base station hardware parameters. In our specific scenario, SINR, RSRP, and RxLev values are directly sourced from raster traffic maps, eliminating the necessity for making assumptions or engaging in complex computations.

4.4.2 DCS and LTE Simulation Algorithm

In the context mentioned earlier, DCS radio cells are exclusively comprised of Traffic Channel (TCH) carriers dedicated solely to network traffic. These carriers are deployed with a frequency reuse factor of 12. In simulations of DCS voice service, Discontinuous Transmission (DTX) functionality is assumed, introducing a 0.5 probability (listen/talk ratio) for the occupancy of a voice call dedicated timeslot by a burst. LTE simulations, on the other hand, primarily involve data sessions and are comparatively simpler than DCS. A basic 2x2 MIMO antenna model is employed. Simulated LTE sessions can utilize the default 15MHz band as well as reallocated 3MHz and 5MHz bands to achieve an aggregate throughput. However, the specific band usage depends on the experienced SINR values. Depending on SINR, one or none of these bands may be utilized. Resource sharing is conducted independently for each band. Figure 26 below provides a clear illustration of the proposed algorithm for conducting DCS and LTE simulations for this Dissertation:

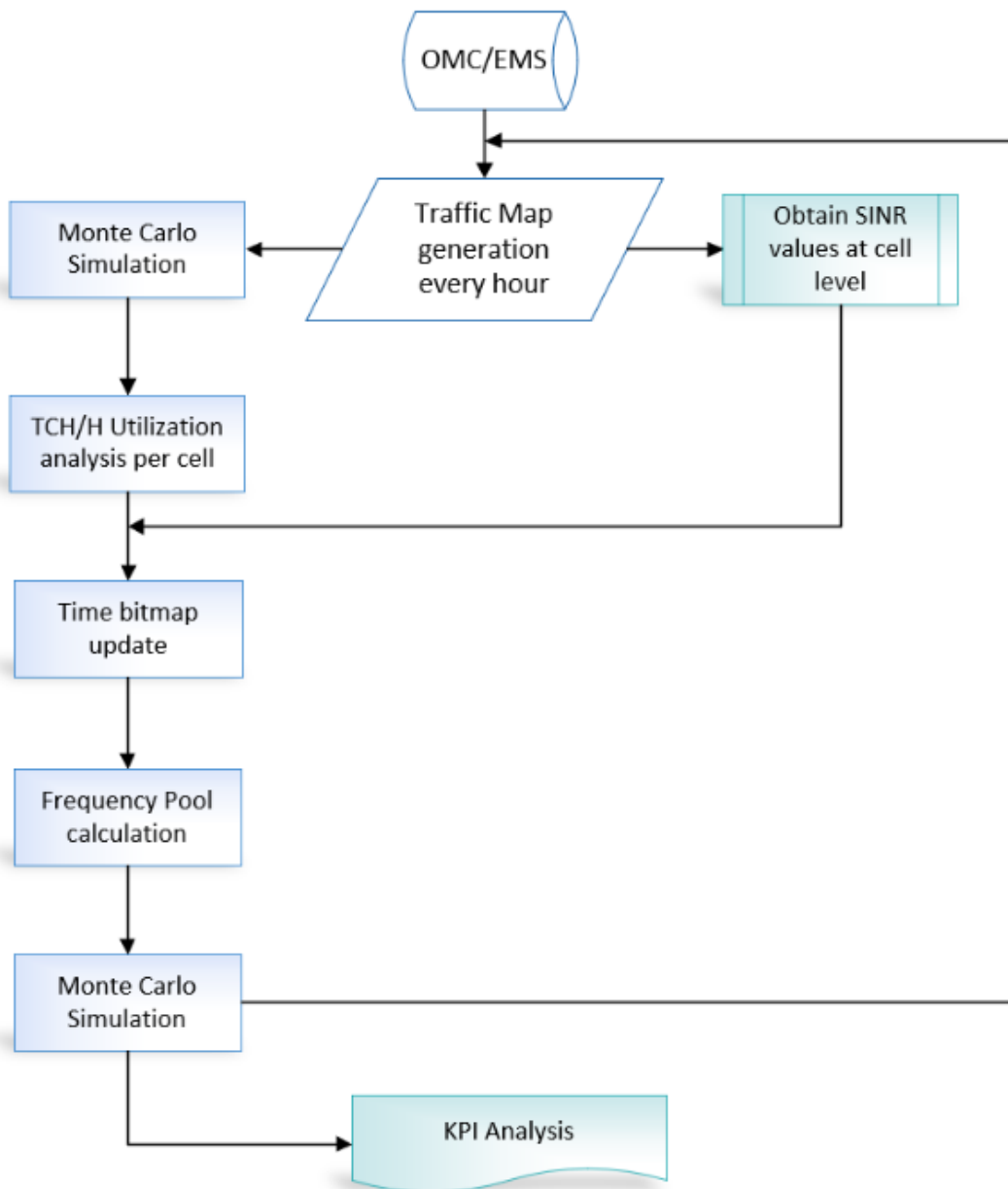


Figure 26: DCS and LTE simulation algorithm.

The algorithm's operational steps are outlined below:

1. The OMC provides performance statistics for both DCS and LTE cells from the previous performance measurement cycle in the selected areas. Subsequently, a raster traffic map is generated in the simulator.
2. Monte Carlo simulations are conducted to determine DCS cell loading, with SINR values extracted from the traffic maps.
3. Analysis of Traffic Channel Half Rate Utilization (TCH/H) is performed to assess cell loading. Predefined TCH/H utilization thresholds guide this analysis:
 - If $TCH/H \leq 15\%$, DCS traffic load is classified as low, indicating potential spectrum release to LTE.

- If TCH/H \geq 25%, DCS traffic load is deemed high, precluding spectrum release to LTE.
- For TCH/H between 15% and 25%, DCS traffic is moderately high, suggesting a possibility for spectrum sharing with LTE.

In summary, the decision to reallocate spectrum from DCS to LTE is based on the TCH/H threshold, as illustrated by the equation:

$$\text{Reallocation Decision} = \begin{cases} \text{Release 5 MHz to LTE} & \text{if TCH/H} \leq 15\% \\ \text{Release 3 MHz to LTE} & \text{if } 15\% < \text{TCH/H} \leq 25\% \\ \text{No Reallocation} & \text{if TCH/H} > 25\% \end{cases}$$

4. The time bitmap is updated to outline spectrum sharing periods within the 24-hour monitoring cycle. Spectrum sharing is authorized only when TCH/H utilization within a cell is under 25% and SINR exceeds 13dB, ensuring satisfactory quality of service on the shared spectrum. These sharing periods are marked as “1”, while “0” denotes non-sharing periods.
5. Frequency pool calculations are conducted based on the DCS load analysis results. If TCH/H \leq 15% utilization, 5MHz is allocated to LTE (Pool 1). If TCH/H \geq 25%, no spectrum release occurs. Otherwise, a maximum of 3MHz is released to LTE (Pool 2).
6. Another iteration of Monte Carlo Simulation is performed with the updated values of additional LTE bandwidth and reduced TCH channels on DCS to evaluate the impact of spectrum sharing. Subsequently, DCS/LTE KPIs are analysed for performance evaluation.
7. The entire process is repeated in subsequent monitoring cycles to ensure ongoing performance monitoring and spectrum management.

4.4.3 Key performance indicators (KPIs)

To validate the simulator's performance against actual network performance and analyse the impact of DSS on the network, selected KPIs were analysed for both DCS and LTE systems. Performance evaluation for LTE data calls encompasses crucial metrics, including average downlink throughput, total traffic volume, intra-frequency handover success rate, PRB utilization, and dropping counters. These metrics collectively assess the efficiency and reliability of data transmission, thereby ensuring an optimal user experience. These KPIs will help with network performance evaluation with and without DSS, providing insights into the impact of spectrum reallocation on user experience and network efficiency. The metrics are defined as:

- Average downlink (DL) throughput: This metric represents the average rate of successful data transmission from the LTE network to the user equipment (UE), which is calculated using the equation below:

$$\text{Average DL Throughput} = \frac{\sum_{i=1}^N R_i}{N}$$

Where R_i is the data rate for the i -th user and N is the total number of users.

- Total traffic: This metric quantifies the overall volume of data traffic transmitted over the LTE network.
- Intra-frequency handover success rate (HOSR): This metric evaluates the efficiency of handovers between different LTE cells operating on the same frequency. The equation below is used to determine HOSR:

$$\text{HOSR} = \frac{\text{Successful Handovers}}{\text{Total Handover Attempts}} \times 100\%$$

- Physical Resource Block (PRB) utilization: This metric measures the efficiency of PRB allocation within the LTE network, reflecting how effectively the available radio resources are utilized.
- Dropping counters (E-RAB DCR): These counters monitor instances where data calls are dropped, providing insights into the reliability of data connections.

Voice call performance is assessed using metrics including total voice traffic, dropped calls (both signaling and Traffic Channel (TCH) traffic), handover success rate, call setup success rate impact analysis, RX quality improvement, half-rate utilization and blocking counters. These metrics provide insights into call reliability, voice quality, handover effectiveness, and network congestion, contributing to an overall assessment of voice service performance. The metrics are defined as:

- Total voice traffic: This metric quantifies the overall volume of voice calls handled by the network.
- Dropped calls: Both signaling (SDCCH), and Traffic Channel (TCH) traffic are analysed to identify instances where voice calls are prematurely terminated.
- Handover success rate (HOSR): This metric evaluates the success rate of handovers between different cells, ensuring seamless transitions for voice calls.
- Call setup success rate (CSSR) impact analysis: This evaluation gauges the influence of call setup success rates on the overall performance of voice calls, which is best illustrated using the following equation:

$$\text{CSSR} = \frac{\text{Successful Call Setups}}{\text{Total Call Attempts}} \times 100\%$$

- RX quality (RX Qual) improvement: This metric measures improvements in received signal quality, which can enhance the overall voice call experience.
- Half-rate utilization (TCH/HR): This metric provides insights into speech quality and network congestion, particularly in situations with low Signal-to-Interference-plus-Noise Ratio (SINR).

- **Blocking counters:** These counters monitor instances where voice calls are blocked due to limited available timeslots in the DCS system, providing insights into network congestion and resource allocation efficiency.

These KPIs are used to evaluate the performance of the network with and without DSS, providing insights into the impact of spectrum reallocation on user experience and network efficiency.

4.5 Data collection strategy assessment summary

The data collection strategy employed in this dissertation is comprehensive, systematic, and well-aligned with the research objectives of evaluating the impact of DSS between DCS and LTE networks. The strategy leverages real-world network data, advanced simulation tools, and a combination of empirical and deterministic modeling techniques to ensure the accuracy and reliability of the results. Below is an assessment of the key components of the data collection strategy:

1. Use of Real Network Data

Strengths:

- The dissertation relied on actual network data from an MNO in Zimbabwe, ensuring that the simulations are grounded in real-world scenarios.
- Data from two distinct environments (urban and suburban) was collected, providing a balanced view of network performance across different geographical and traffic conditions.
- The use of raster traffic maps, subscriber lists, and user penetration data from the MNO ensures that the simulations reflect realistic traffic patterns and user behaviour.

Weaknesses:

- The reliance on data from a single MNO may limit the generalizability of the findings to other networks or regions with different operational conditions.
 - The data collection process is dependent on the MNO's data availability and quality, which may introduce biases or gaps if the data is incomplete or outdated.
-

2. Propagation Modeling

Strengths:

- The dissertation utilized validated propagation maps provided by the MNO, which incorporate a blend of empirical and deterministic models. This ensures that the simulations accurately reflect real-world radio wave propagation characteristics.
- The high geographical resolution of the propagation maps (5m, 10m, and 20m) allowed for detailed and precise modeling of signal attenuation, interference, and coverage.
- Building Penetration Loss (BPL) is factored into the simulations, enhancing the accuracy of indoor and outdoor signal propagation modeling.

Weaknesses:

- The propagation models are specific to the MNO's network and frequency bands, which may limit their applicability to other networks or frequency ranges.
 - The reliance on pre-validated propagation maps may overlook site-specific variations or anomalies that could affect network performance.
-

3. Traffic Load Prediction and Modeling

Strengths:

- The use of historical traffic data and time series prediction for traffic load forecasting ensured that the DSS algorithm is responsive to dynamic traffic patterns.
- The Erlang B formula is employed to predict voice call traffic, providing a robust mathematical foundation for spectrum allocation decisions.
- The focus on 2G traffic load prediction aligns with the study's objective of optimizing spectrum reallocation from DCS to LTE.

Weaknesses:

- The traffic load prediction algorithm does not account for LTE traffic load, which could lead to suboptimal spectrum allocation decisions if LTE traffic spikes unexpectedly.
 - The reliance on historical data may not fully capture sudden changes in user behaviour or network conditions, such as during special events or emergencies.
-

4. Simulation Methodology

Strengths:

- The use of the Atoll simulation tool, which is widely recognized for its capabilities in wireless network planning and optimization, ensured that the simulations were both accurate and reliable.
- Monte Carlo simulations were employed to account for the stochastic nature of network traffic and user behaviour, providing a robust framework for evaluating DSS performance.
- The simulation parameters, such as SINR, RSRP, and RxLev, were directly derived from raster traffic maps, eliminating the need for assumptions and enhancing the realism of the simulations.

Weaknesses:

- The simulations are computationally intensive, which may limit the scalability of the study or the ability to conduct large-scale simulations.
 - The reliance on a single simulation tool (Atoll) may introduce tool-specific biases or limitations, which could be mitigated by cross-validating results with other simulation platforms.
-

5. Key Performance Indicators (KPIs)

Strengths:

- The selection of KPIs, such as average downlink throughput, handover success rate, and call setup success rate, provides a comprehensive assessment of network performance under DSS.

- The inclusion of both LTE and DCS KPIs ensured that the impact of spectrum reallocation is evaluated from the perspective of both legacy and modern networks.
- The use of blocking counters and dropping counters provides insights into network congestion and reliability, which are critical for assessing user experience.

Weaknesses:

- The KPIs are primarily focused on technical performance metrics, with limited consideration of user-centric metrics such as Quality of Experience (QoE) or service availability.
- The analysis of KPIs is based on simulated data, which may not fully capture the complexities of real-world network operations.

6. Integration of Centralized Self-Organizing Node (CSON)

Strengths:

- The introduction of CSON as a centralized node for coordinating spectrum sharing between DCS and LTE networks is innovative and aligns with the principles of self-organizing networks (SON).
- The use of a time bitmap to dynamically adjust spectrum sharing periods based on real-time traffic conditions ensures that the DSS algorithm is responsive and adaptive.
- The frequency pool calculation mechanism provides a structured approach to spectrum reallocation, minimizing the risk of interference or service degradation.

Weaknesses:

- The implementation of CSON requires significant changes to the existing network architecture, which may pose challenges in terms of cost, complexity, and interoperability.
- The reliance on CSON for real-time decision-making may introduce latency or scalability issues, particularly in large or highly dynamic networks.

Overall Assessment

The data collection strategy used in this dissertation is robust, well-structured, and highly effective in achieving the research objectives. The combination of real network data, advanced simulation tools, and innovative modeling techniques ensures that the findings are both accurate and relevant to real-world network operations. However, the strategy could be further enhanced by incorporating user-centric metrics, cross-validating results with multiple simulation tools, and addressing potential scalability and interoperability challenges associated with the proposed DSS architecture.

4.6 Chapter Summary

The proposed DSS algorithm was clearly presented, outlining the system-level simulator to be utilized in the design and configuration of the proposed solution. The traffic load prediction and spectrum pool calculation algorithms were discussed, elucidating how these algorithms facilitate real-time dynamic spectrum sharing implementation. An assessment of the data collection strategy was discussed in depth, which provided valuable insights into the strategy employed. The next section will focus on simulation results conducted using Atoll. A benchmark validation against actual network data will precede the application of the simulator to DSS. Main KPIs for both DCS and LTE will be analysed. These results will serve as the benchmark for real-time implementation and further refinement of the simulator.

5. RESULTS

This chapter is dedicated to validating the experimental performance of the dynamic spectrum sharing algorithm by utilizing real-time network data. Multiple simulations were conducted for selected areas to address the research questions and gain insights into the proposed dynamic spectrum sharing technique. The validation process involved two main analyses: firstly, benchmarking the simulator against the actual network performance statistics and secondly, running simulations for the proposed dynamic spectrum sharing technique to evaluate its impact compared to the fixed spectrum strategy currently in place in the network. Various KPIs will be utilized as metrics for evaluating the effectiveness of dynamic spectrum sharing.

5.1 Simulator Benchmarking

To comprehensively assess the reliability of the simulator, simulations were conducted to generate network results with parameters precisely aligned with the network configuration. The selected area was Norton. These simulations spanned over 3 days (72 hours) to capture the network's performance across different times of the day. The DCS and LTE KPI results derived from these simulations are presented in Figure 27 and 28 respectively:

DCS KPIs:

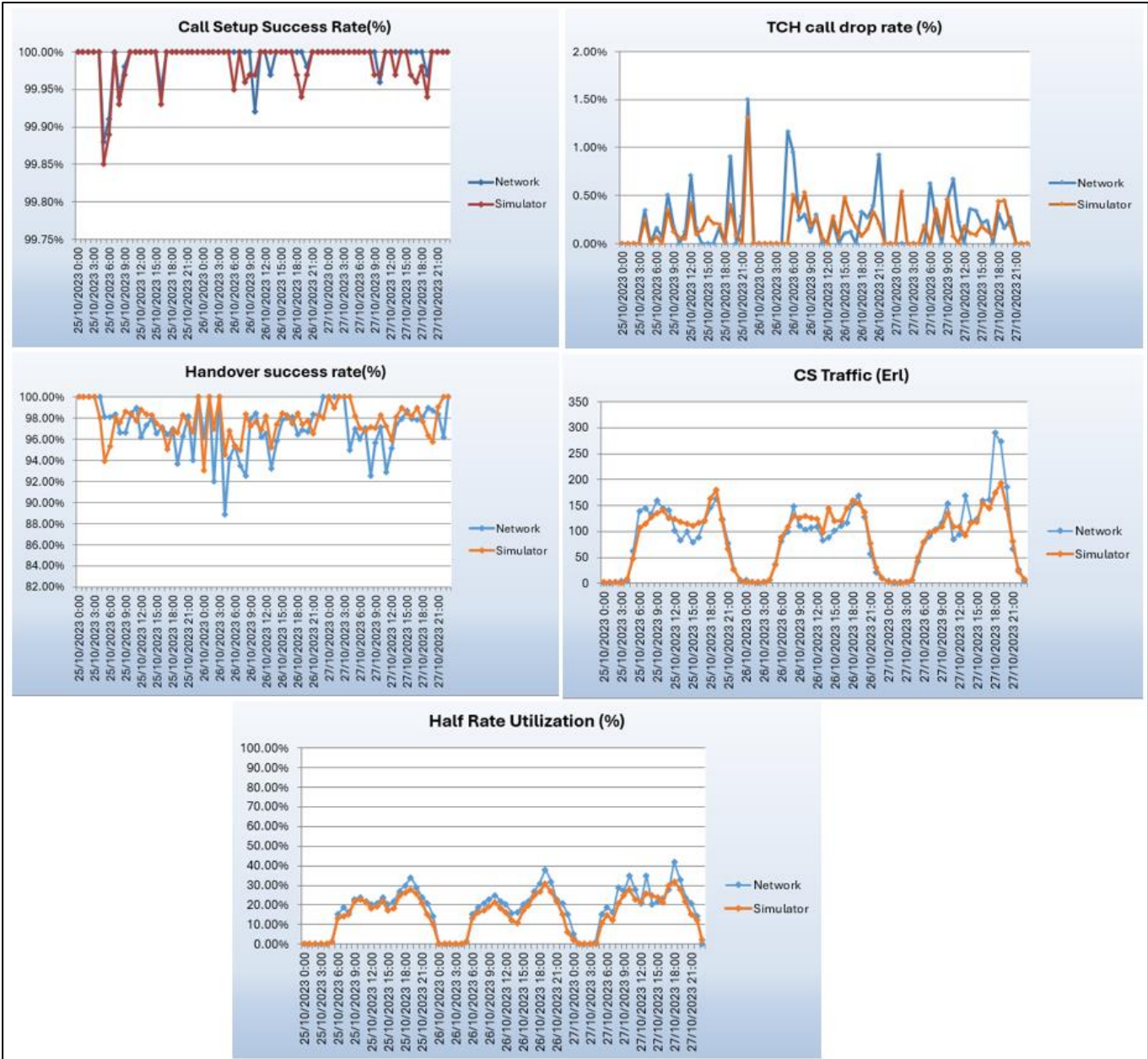


Figure 27: DCS KPIs for Network and Simulator.

The DCS benchmarking outcomes highlight a striking resemblance between the simulator and actual network results for the Norton Area, as retrieved from the MNO OMC. Notably, the simulator demonstrates a 98% alignment with the actual voice traffic volumes. Moreover, both the handover success rate and half-rate utilization exhibit consistent patterns with the actual network findings. The discrepancy in half-rate utilization, where the simulator registers slightly lower values compared to the network, might stem from the resource scheduling algorithm tailored for DCS network traffic. This algorithm is designed with the objective of prioritizing voice calls while also reserving a small portion of capacity for data sessions. During peak hours, particularly from 1600hrs to 2100hrs, there is a noticeable uptick in cell loading, reflected in TCH/HR utilization exceeding 25% for both the Simulator and Network results. These findings instil

confidence in the applicability of the simulator for the proposed DSS solution outlined in this Dissertation.

Similarly, Figures 28, which pertain to LTE simulations, reinforce these findings. In most cases, the LTE KPIs for the simulator exhibit slightly lower values compared to the network values. This discrepancy can be attributed largely to the assumed penetration losses in the simulator, which might be higher than those measured by user equipment (UE). Consequently, the simulated SINR could be lower than the actual values, resulting in slightly reduced observed throughputs and predicted traffic volumes. Nonetheless, the simulator results demonstrate a closely analogous pattern to the network values, further validating its suitability for DSS simulations.

LTE KPIs:

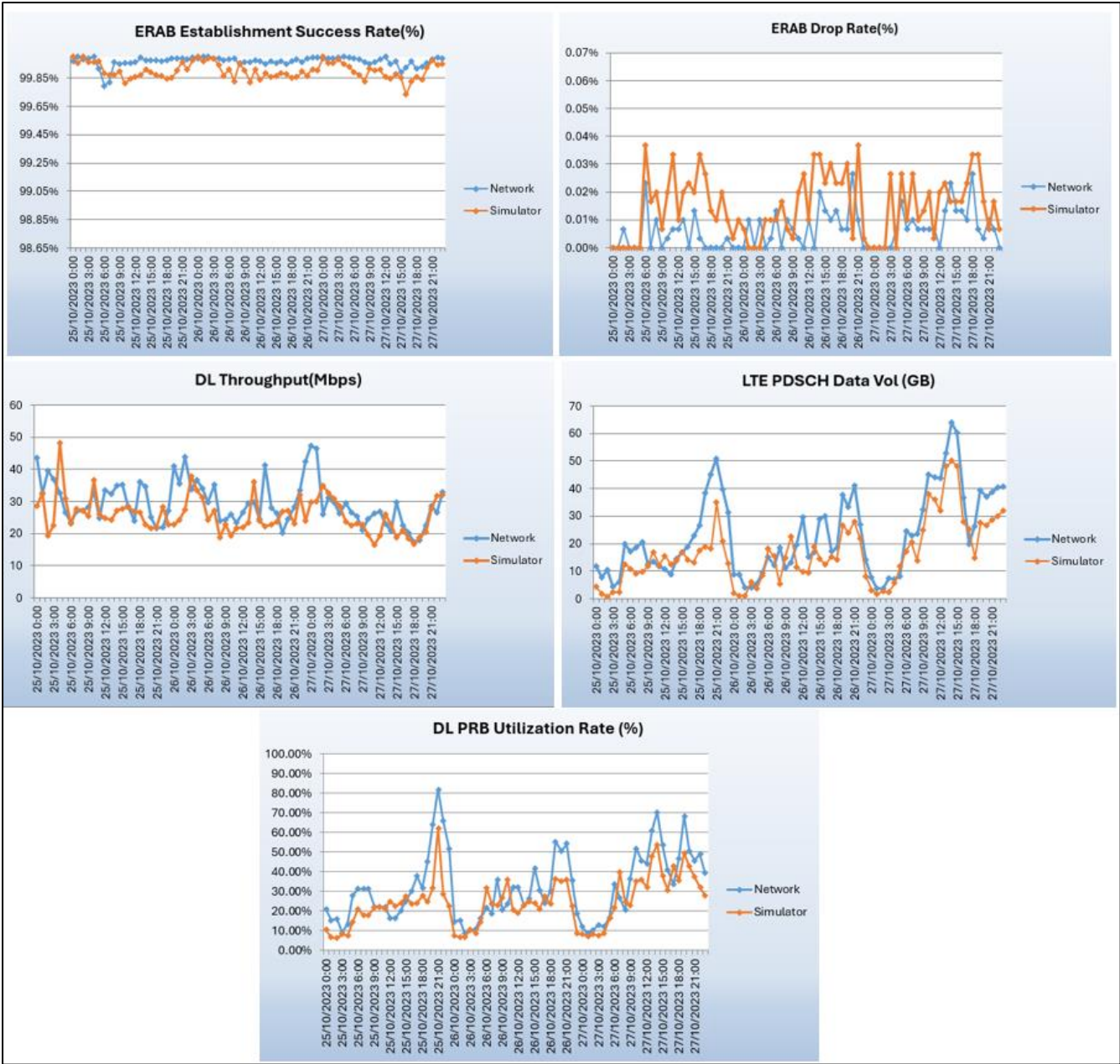


Figure 28: LTE KPIs for Network and Simulator.

5.2 DSS Simulation

After confirming the suitability and reliability of the simulator for DSS simulations, additional simulations were conducted over a period of 7 days. These simulations aimed to assess the performance of DSS and compare its impact against the fixed spectrum allocation currently utilized in the network. An analysis of the potential influence of the network environment on the advantages of DSS will be conducted, with careful consideration given to its effects on 2G network performance. Figures 29-30 and 31-34 depict the performance outcomes of DSS on both the DCS and LTE networks, respectively:

DCS KPIs:

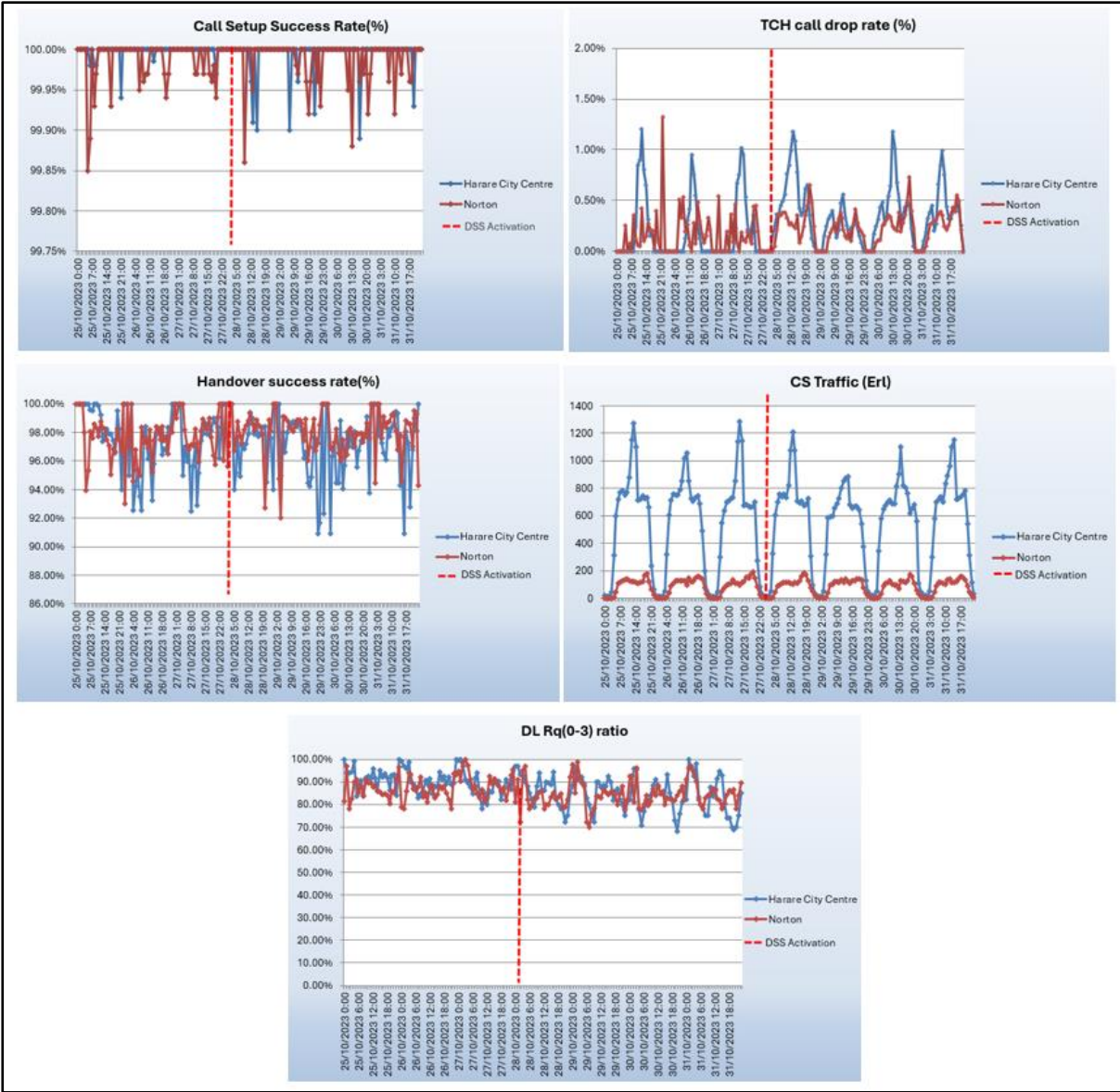


Figure 29: DCS KPIs for Norton and Harare City Centre.

Area	KPIs	25-Oct	26-Oct	27-Oct	28-Oct	29-Oct	30-Oct	31-Oct	Pre (25-27 Oct)	Post (28-31 Oct)	Gain/Loss (%)
Harare City Centre	Call Setup Success Rate(%)	100	100	100	99.99	99.99	100	100	100.0	100.0	0.00
Harare City Centre	TCH call drop rate (%)	0.22	0.14	0.21	0.47	0.21	0.38	0.34	0.19	0.35	-0.16
Harare City Centre	Handover success rate(%)	99.88	96.75	97.43	97.83	96.90	96.68	97.60	98.02	97.25	-0.77
Harare City Centre	CS Traffic (Erl)	13,827	12,916	13,865	12,890	12,061	12,745	12,850	13,536	12,637	-6.65
Harare City Centre	DL Rq(0-3) ratio	91.89	90.85	88.85	86.3	85.75	83.1	83.05	90.53	84.55	-5.98
Norton	Call Setup Success Rate(%)	99.98	99.99	99.99	99.99	99.99	99.99	99.99	99.99	99.99	0.00
Norton	TCH call drop rate (%)	0.17	0.16	0.15	0.25	0.17	0.23	0.23	0.16	0.22	-0.06
Norton	Handover success rate(%)	97.85	97.22	98.25	97.94	98.00	97.85	98.20	97.77	98.00	0.22
Norton	CS Traffic (Erl)	2,065	2,024	2,039	2,040	1,996	2,005	2,020	2,043	2,015	-1.34
Norton	DL Rq(0-3) ratio	86.95	86.29	89.36	84.56	86.52	86.04	85.93	87.53	85.76	-1.77

Figure 30: Summary of DCS DSS KPIs.

LTE KPIs:

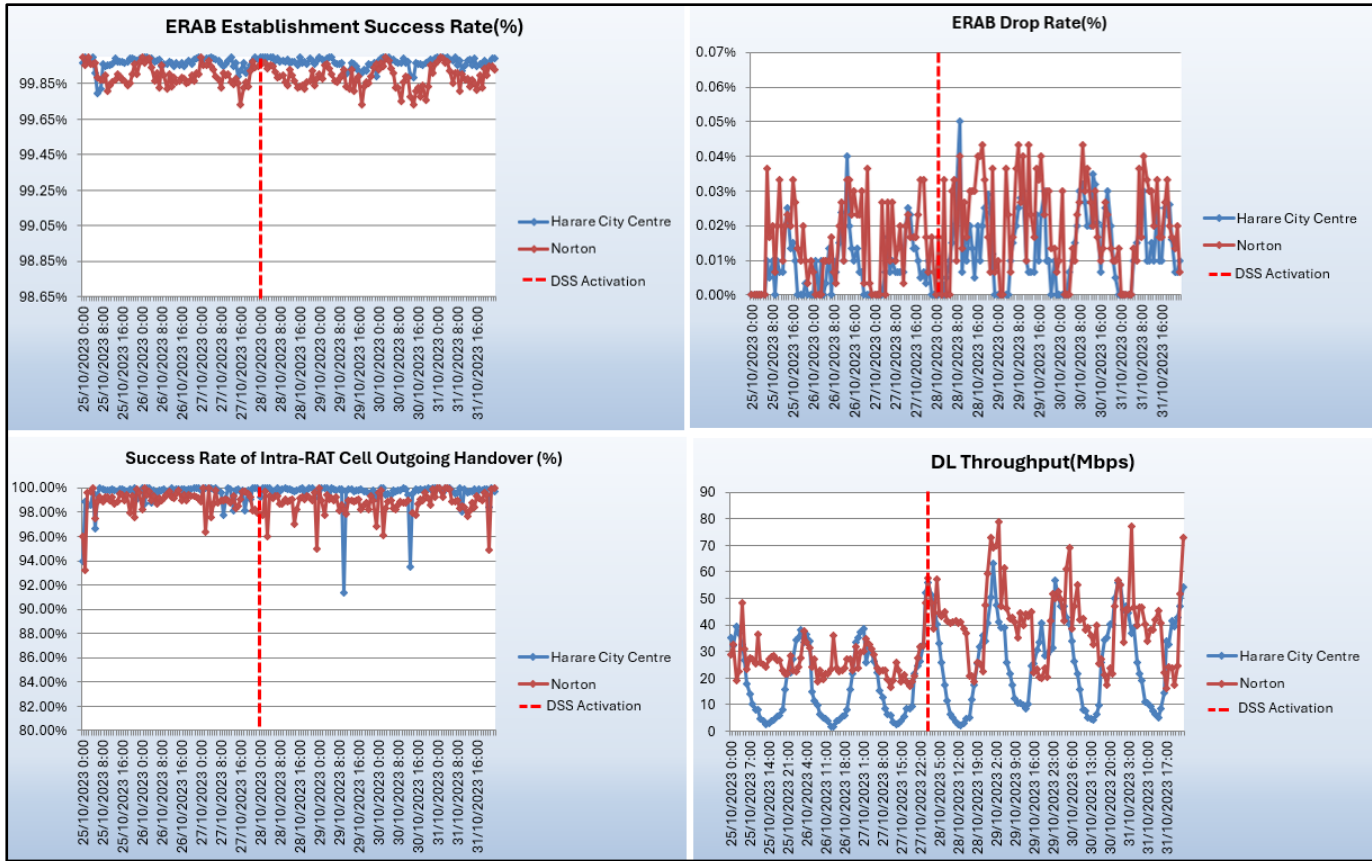


Figure 31: LTE KPIs for Norton and Harare City Centre.

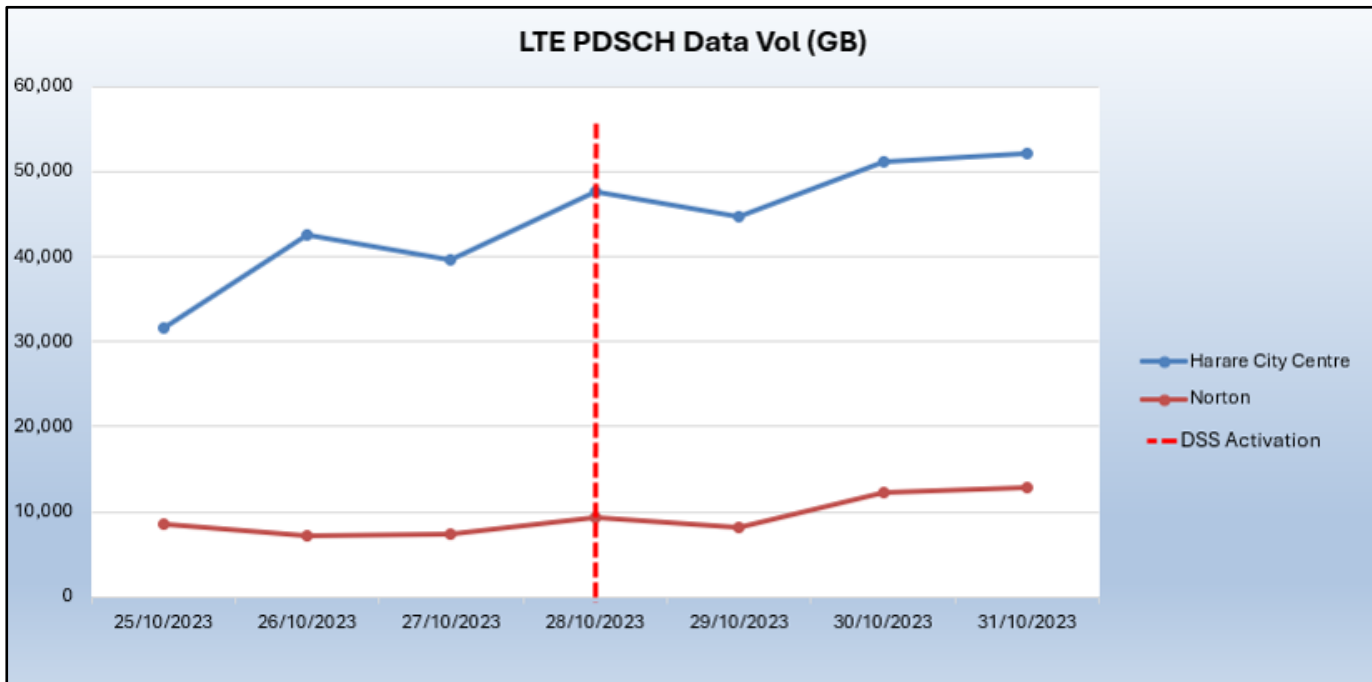


Figure 32: LTE PDSCH Data Vol (GB) for Norton and Harare City Centre.

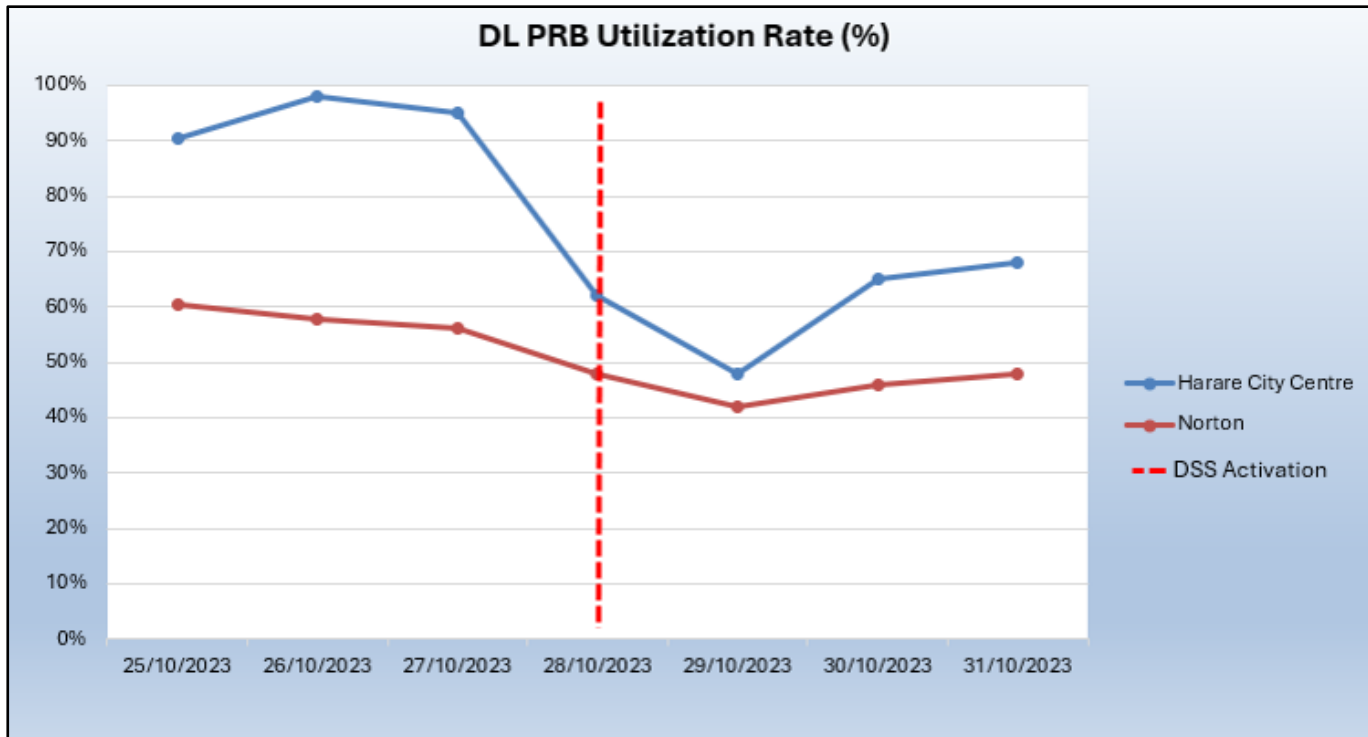


Figure 33: LTE DL PRB Utilization Rate (%) for Norton and Harare City Centre.

Area	KPIs	25-Oct	26-Oct	27-Oct	28-Oct	29-Oct	30-Oct	31-Oct	Pre (25-27 Oct)	Post (28-31 Oct)	Gain (%)
Harare City Centre	DL Throughput(Mbps)	16.19	16.9	17.08	23.6	28.3	29.6	29.2	16.7	27.7	65.5
Harare City Centre	LTE PDSCH Data Vol (GB)	31,589	42,546	39,561	47,565	44,686	51,203	52,186	37,899	48,910	29.1
Harare City Centre	DL PRB Utilization Rate (%)	90%	98%	95%	62%	48%	65%	68%	94%	61%	33.7%
Harare City Centre	ERAB Drop Rate(%)	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.00
Harare City Centre	ERAB Establishment Success Rate(%)	99.96	99.98	99.97	99.98	99.95	99.97	99.98	99.97	99.97	0.00
Harare City Centre	Success Rate of Intra-RAT Cell Outgoing Handover (%)	99.26	99.78	99.59	99.84	99.39	99.52	99.69	99.54	99.61	0.07
Norton	DL Throughput(Mbps)	27.13	25.71	24.56	39.45	43.58	40.62	40.31	25.80	40.99	58.9
Norton	LTE PDSCH Data Vol (GB)	8,501	7,175	7,407	9,371	8,200	12,305	12,855	7,694	10,683	38.8
Norton	DL PRB Utilization Rate (%)	60%	58%	56%	48%	42%	46%	48%	58%	46%	12.1%
Norton	ERAB Drop Rate(%)	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00
Norton	ERAB Establishment Success Rate(%)	99.91	99.9	99.9	99.89	99.88	99.87	99.9	99.90	99.89	-0.02
Norton	Success Rate of Intra-RAT Cell Outgoing Handover (%)	98.71	99.25	99.85	98.6	98.71	98.74	98.97	99.27	98.76	-0.51

Figure 34: Summary of LTE DSS KPIs.

5.3 Performance Evaluation

In this chapter, the results for the simulated technologies are presented. Metrics are depicted as averages across the entire simulation area throughout the duration of 7 days. The initial 3 days entail observing the outcomes of the currently implemented fixed spectrum strategy, succeeded by the simulation of DSS on the 4th day and observation for the subsequent 4 days. Additionally, a comparative analysis of the two study areas is provided through various KPI graphs for both 2G and 4G, spotlighting the effects on performance during busy hour conditions. Furthermore, voice call dropping and quality indicators for the entire areas are also encompassed in the analysis.

5.3.1 Harare City Centre

The simulation results illustrated in Figures 31-34 exhibit considerable LTE gains in average DL user throughput, showcasing a substantial 65% increase when DSS is utilized. These improvements primarily occur during voice off-peak hours (0000-0900 and 1600-2359 hrs) as more spectrum is made available from DCS. However, during

voice busy hours (0900-1600 hrs), characterized by high volumes of voice calls due to concentrated user activity in the Central Business District (CBD), opportunities for reallocating spectrum to LTE are restricted. This limitation results in negligible LTE gains from DSS compared to fixed spectrum allocation (FSA) during these hours. Notably, around 1600hrs, as most users depart from the CBD to residential areas, more spectra become accessible for LTE until the subsequent morning, when commercial activities resume. This benefits LTE while having marginal impact on DCS.

Additionally, DSS demonstrates a notable 29% surge in LTE Data Traffic, largely driven by enhancements during voice off-peak hours where more resources (PRBs) are allocated to LTE. This increase in LTE Data Traffic is accompanied by a 33% improvement in PRB utilization, indicating enhanced spectrum efficiency.

In contrast, the performance of DCS voice traffic exhibits a slight advantage of FSA over DSS, primarily due to a 7% decrease in overall voice traffic following DSS activation. This decline is attributed to increased interference within the shared spectrum area between DCS TCHs and LTE PRBs, leading to increased SINR. As a result, there is a 6% drop in DL quality samples (DL Rq), resulting in a 0.16% increase in voice call drops post-DSS activation. The detrimental impact of DSS on most DCS metrics is visible, particularly during off-peak hours. However, the substantial benefits of DSS in enhancing LTE performance outweigh these adverse impacts on DCS.

In summary, in urban areas, DSS demonstrates clear advantages during off-peak hours by enhancing spectrum efficiency and improving the LTE user experience. Despite its adverse effects on DCS voice call quality and traffic, DSS offers superior LTE performance, potentially leading to an increase in market share and providing greater benefits to user experience compared to FSA.

5.3.2 Norton

In summary, the performance outcomes for the suburban area of Norton, as illustrated in Figures 29-34, emphasize the effectiveness of DSS in augmenting LTE performance, particularly during voice off-peak hours. With DSS implementation, there is a notable 58% increase in average LTE DL throughput, resulting in a 38% increase in data traffic. Furthermore, there is a 12% improvement in DL PRB utilization, leading to enhanced spectrum efficiency. It's important to note that Norton primarily comprises residential areas with minimal commercial activity, resulting in voice peak hours occurring between 1600-2100 hrs when users are mostly indoors. During this period, minimal LTE gains are observed due to most of the shared spectrum being occupied by DCS traffic channels.

The impact of DSS on DCS voice call performance is negligible, with only a slight decline in overall voice traffic of around 2%. However, FSA maintains a slight edge of 1.7% in DL signal quality over DSS, although this advantage is marginal due to the presence of a

guard band reducing interference between DCS channels and LTE PRBs. Consequently, there are fewer voice call drops with FSA.

In the suburban area, owing to the overall low DCS traffic load, there is almost no discernible detrimental effect on DCS voice traffic with either DSS or FSA. Voice call quality and call setup success rate remain nearly identical for both approaches, indicating no degradation in user experience. Consequently, DSS tends to outperform FSA in suburban areas due to the heightened benefits of enhanced user experience on LTE, traffic increase and improved spectrum efficiency.

6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

6.1.1 Reflection on Dissertation Objectives

The Dissertation was guided by five primary objectives, each aimed at evaluating the effectiveness of DSS between DCS and LTE networks. Below is a detailed reflection on how each objective was addressed and the insights gained from the research:

1. Validate 3GPP Assumptions on DSS

The first objective sought to validate the 3GPP assumption that spectrum sharing could increase network throughput without negatively impacting the performance of traditional systems like DCS. Through extensive simulations using real-world network data, the study confirmed that DSS significantly improves LTE throughput, particularly during off-peak hours when DCS traffic is low. However, the findings also revealed that during peak voice traffic hours, the benefits of DSS are limited due to high DCS utilization. While LTE throughput improved by up to 65% in urban areas and 58% in suburban areas, DCS performance experienced a slight degradation, particularly in urban environments where interference in shared spectrum areas increased. This validates the 3GPP assumption but also highlights the need for careful implementation to mitigate interference effects on legacy systems.

2. Quantify User Throughput Improvements

The second objective aimed to measure and quantify the enhancement in user throughput resulting from DSS implementation. The results demonstrated substantial improvements in LTE user throughput, with average downlink throughput increasing by 65% in urban areas and 58% in suburban areas during off-peak hours. These improvements were directly attributed to the reallocation of spectrum from DCS to LTE, which provided additional bandwidth for LTE users. The study also highlighted that the extent of throughput improvement is highly dependent on the network environment, with suburban areas benefiting more consistently due to lower DCS traffic loads. This objective was successfully addressed, providing concrete evidence of the throughput gains achievable through DSS.

3. Assess Environmental Impact on DSS Performance

The third objective focused on examining how different network environments (urban vs. suburban) influence the benefits and challenges of DSS implementation. The study revealed significant differences in DSS performance between urban and suburban areas. In urban environments, DSS provided substantial LTE throughput gains but also led to a

7% reduction in DCS voice traffic due to increased interference. In contrast, suburban areas experienced minimal impact on DCS performance while still achieving significant LTE throughput improvements. This underscores the importance of considering environmental factors when implementing DSS, as the benefits and trade-offs vary depending on the network context.

4. Develop and Test a DSS Algorithm

The fourth objective involved designing and evaluating a DSS algorithm tailored for intra-operator scenarios. The proposed algorithm, which leverages a Centralized Self-Organizing Node (CSON) to dynamically allocate spectrum between DCS and LTE, was successfully implemented and tested. The algorithm utilized traffic load prediction, time bitmap updates, and frequency pool calculations to optimize spectrum reallocation. Simulations demonstrated that the algorithm effectively balanced spectrum utilization, improving LTE performance while minimizing negative impacts on DCS. This objective was fully addressed, with the algorithm proving to be a practical solution for intra-operator spectrum sharing.

5. Evaluate Key Performance Indicators (KPIs)

The final objective aimed to analyse the impact of DSS on critical network metrics, including LTE throughput, PRB utilization, and DCS performance metrics such as voice call drops and Rx signal quality. The study evaluated a comprehensive set of KPIs, revealing that DSS significantly improved LTE metrics such as downlink throughput (up to 65% in urban areas), PRB utilization (33% improvement), and data traffic volume (29% increase). However, DCS metrics showed slight degradation, particularly in urban areas, with a 0.16% increase in voice call drops and a 6% decline in DL quality samples. These findings highlight the trade-offs involved in DSS implementation and provide valuable insights for network operators seeking to optimize spectrum utilization.

6.1.2 Overall Assessment of Objectives

The Dissertation successfully addressed all five objectives, providing a comprehensive evaluation of DSS in real-world network scenarios. The findings validate the potential of DSS to enhance LTE performance while also highlighting the need for careful implementation to mitigate negative impacts on legacy systems. The study demonstrated that DSS is particularly effective in suburban areas, where lower DCS traffic loads allow for more consistent spectrum reallocation opportunities. In urban areas, while DSS offers significant LTE throughput gains, the trade-offs in DCS performance must be carefully managed.

The development and testing of the DSS algorithm represent a significant contribution to the field, offering a practical solution for intra-operator spectrum sharing. The algorithm's ability to dynamically adjust spectrum allocation based on real-time traffic

conditions ensures optimal resource utilization, making it a valuable tool for network operators.

To address the challenges identified and further enhance DCS performance in DSS scenarios, the following future work is proposed:

6.2 Future Work

1. Reducing Transmit Power in Shared Spectrum Areas

One of the key strategies to minimize interference between DCS channels and LTE PRBs is to reduce the transmit power of LTE resource elements in the shared spectrum area. By lowering the transmit power, the interference caused by LTE signals to DCS channels can be significantly reduced, thereby improving DCS performance. However, this approach may lead to reduced LTE coverage in the shared spectrum areas. To mitigate this issue, the following steps can be taken:

- **Site-to-Site Distance Optimization:** In urban areas, the smaller site-to-site distance ensures contiguous LTE coverage, even with reduced transmit power in shared spectrum areas. Network operators can leverage this characteristic to maintain seamless coverage while minimizing interference.
- **Dynamic Power Control:** Implementing dynamic power control mechanisms that adjust LTE transmit power based on real-time interference levels can further optimize performance. For example, during periods of low DCS traffic, LTE transmit power can be increased to maximize throughput, while during peak DCS traffic, power can be reduced to minimize interference.

2. Advanced Interference Mitigation Techniques

In addition to reducing transmit power, advanced interference mitigation techniques can be employed to enhance DCS performance in DSS scenarios. These techniques include:

- **Frequency Guard Bands:** Introducing guard bands between DCS and LTE frequencies can reduce interference by providing a buffer zone between the two systems. While this approach may reduce the amount of spectrum available for reallocation, it can significantly improve DCS performance.
- **Interference Cancellation Algorithms:** Leveraging advanced signal processing techniques, such as interference cancellation algorithms, can help mitigate the impact of interference on DCS channels. These algorithms can be implemented at the receiver end to filter out unwanted LTE signals, thereby improving DCS signal quality.

3. Enhanced Traffic Load Prediction Algorithms

Improving the accuracy of traffic load prediction algorithms can enhance the effectiveness of DSS by enabling more precise spectrum reallocation decisions. Future

work can explore the use of machine learning (ML) and artificial intelligence (AI) techniques to develop predictive models that account for complex traffic patterns and user behaviour. AI techniques, particularly supervised and unsupervised machine learning, can be used to analyse historical traffic data and identify complex patterns in user behaviour, network usage, and traffic load fluctuations. For example, recurrent neural networks (RNNs) and long short-term memory (LSTM) models are well-suited for time-series data and can predict traffic load with high accuracy by learning from temporal dependencies in the data enabling more efficient spectrum allocation.

Blockchain can also aid through decentralized data sharing for improved predictions. It can enable secure and transparent sharing of traffic data among multiple stakeholders (e.g., network operators, service providers) without compromising data integrity. This shared data can be used to train more robust and generalizable AI models, improving prediction accuracy across diverse network environments. Blockchain-based smart contracts can incentivize users and network operators to contribute traffic data by rewarding them with tokens or credits. This can increase the volume and diversity of data available for training AI models.

4. Multi-RAT Coordination and Optimization

Extending the DSS framework to include coordination between multiple RATs, such as UMTS and 5G, can further enhance spectrum efficiency. Future research can explore the development of multi-RAT coordination AI algorithms that optimize spectrum utilization across heterogeneous networks. These algorithms can dynamically allocate spectrum resources based on the traffic load, interference levels and performance requirements of each RAT, ensuring optimal resource utilization and user experience. For example, multi-agent reinforcement learning (MARL) can be used to coordinate spectrum sharing among heterogeneous networks, ensuring fair and efficient resource utilization. AI models can predict the optimal RAT for each user based on their location, device capabilities, and application requirements. For instance, a user in a dense urban area might be assigned to 5G for high-speed connectivity, while a user in a rural area might be assigned to LTE for broader coverage. These predictions can be updated in real-time as network conditions change.

Future research can also focus on Blockchain contribution to decentralized spectrum sharing. Blockchain can facilitate decentralized spectrum sharing among multiple RATs by providing a secure and transparent platform for negotiating and enforcing spectrum access agreements. Smart contracts can automate the allocation of spectrum resources based on predefined rules and real-time network conditions. In multi-operator environments, blockchain can enable trust less coordination by ensuring that all parties adhere to agreed-upon spectrum sharing policies without the need for a central authority. This is particularly useful in scenarios where operators use different RATs and need to share spectrum dynamically.

5. Field Trials and Real-World Deployment

To validate the findings of this research and assess the practical feasibility of DSS, future work should include field trials and real-world deployment in operational networks. These trials can provide valuable insights into the performance of DSS under real-world conditions, including the impact of environmental factors, user behaviour, and network configuration. The results of these trials can inform further refinements to the DSS algorithm and implementation strategies.

In conclusion, the Dissertation provides strong evidence supporting the feasibility and benefits of DSS, while also identifying key challenges and areas for further improvement. The findings offer actionable insights for network operators, paving the way for more efficient spectrum management in multi-RAT environments. By addressing the challenges associated with interference, spectrum reallocation opportunities, and real-time spectrum management, future work can further enhance the performance of DSS and unlock its full potential. The proposed strategies, including reducing transmit power, advanced interference mitigation techniques, enhanced traffic load prediction AI driven algorithms, and multi-RAT coordination, provide a roadmap for optimizing DSS implementation and ensuring its success in real-world networks.

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