Comparison of Dynamic Spectrum Access schemes in a common system model

S Rananga

orcid.org/0000-0003-0984-7331

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Supervisor: Prof ASJ Helberg
Co-supervisor: Dr M Ferreira
Co-supervisor: Dr MT Masonta

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DEDICATION

I dedicate this dissertation to my parents – to my father, Dr Rananga Ntshengedzeni Collins, and my mother, Mrs Rananga Namadzavho Esther – for their continuous support of my education and for investing in my personal growth. Your daily prayers, motivation and faith in me kept me focused and helped me attain this degree.
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ABSTRACT

The fourth generation (4G) and fifth generation (5G) mobile networks performance have been predicted through a broad consensus that they will not come close to meeting the demands that networks will face in the next decade. The increasing demand for new services within mobile networks like new mobile applications overburdens and restricts the electromagnetic radio spectrum and, as such, national regulatory authorities (NRAs) are urged to promote more efficient spectrum usage. To this effect, dynamic spectrum management (DSM) provides new ways of managing spectrum by utilising dynamic spectrum access (DSA) technologies to dynamically reassigning their use.

According to Literature, most DSA schemes do not follow a standard set of performance parameters, metrics or evaluation methodology for analysing and assessing a scheme’s performance. As such, regardless of what the given scheme’s performance is, it cannot be directly compared to other schemes in the existing body of knowledge, which poses challenges in solving the problem of inefficient spectrum usage. As such, there exists a need to outline and impose a standard set of performance parameters and DSA scheme evaluation methodology.

In light of the need mentioned above, this study performed a comparative study on the selected DSA schemes under a common DSA scheme evaluation methodology thereby determining the scheme that is best suited for improving spectrum utilisation or spectral efficiency (SE) and data rate (DR) under varying system model conditions. The findings of this study serve as a baseline for comparing performances of DSA schemes.

**Keywords:** Dynamic spectrum access (DSA), DSA schemes, performance parameters, DSA scheme performance, spectral efficiency (SE) and data rate (DR), dynamic spectrum management (DSM)
# TABLE OF CONTENTS

Dedication ......................................................................................................................... i
Acknowledgements ........................................................................................................... ii
Abstract ............................................................................................................................... iii
Table of Contents ............................................................................................................... iv
List of Acronyms ................................................................................................................ ix
List of Figures .................................................................................................................... x
List of Tables ....................................................................................................................... xi
CHAPTER 1  Introduction ................................................................................................. 1
  1.1  Background ................................................................................................................. 1
    1.1.1  Characteristics of the electromagnetic spectrum ............................................... 2
  1.2  Motivation .................................................................................................................... 3
  1.3  Research problem ....................................................................................................... 3
  1.4  Research objectives .................................................................................................... 4
  1.5  Research methodology ............................................................................................... 4
  1.6  Research scope ........................................................................................................... 5
    1.6.1  Delimitations ......................................................................................................... 5
    1.6.2  Limitations ........................................................................................................... 5
  1.7  The significance of the study ..................................................................................... 6
  1.8  Dissertation outline ................................................................................................... 7
  1.9  Chapter conclusion .................................................................................................... 7
CHAPTER 2  Literature review ......................................................................................... 8
  2.1  Chapter overview ...................................................................................................... 8
  2.2  Cognitive radio (CR) overview .................................................................................. 8
  2.3  Dynamic spectrum access (DSA) architecture overview .......................................... 9
2.3.1 Dynamic exclusive use model ................................................................. 10
2.3.2 Open sharing model ............................................................................. 11
2.3.3 Hierarchical access model .................................................................. 11
2.4 Dynamic spectrum management (DSM) .................................................. 12
  2.4.1 Spectrum sensing ................................................................................ 13
  2.4.2 Spectrum decision .............................................................................. 13
  2.4.3 Spectrum sharing ................................................................................ 13
  2.4.4 Spectrum mobility .............................................................................. 14
2.5 Dynamic spectrum access (DSA) approaches ......................................... 14
  2.5.1 Centralised spectrum access ................................................................. 14
  2.5.2 Distributed Spectrum access ............................................................... 15
  2.5.3 Multi-channel selection ...................................................................... 16
  2.5.4 Primary user (PU) or secondary user (SU) ......................................... 16
  2.5.5 Common control channel (CCC) ......................................................... 16
  2.5.6 Segment-based .................................................................................. 17
  2.5.7 Cluster-based ..................................................................................... 18
2.6 Dynamic spectrum access (DSA) standards ............................................. 18
  2.6.1 European Telecommunications Standards Institute (ETSI) reconfigurable
        radio system (RRS) ........................................................................... 19
  2.6.2 European Computer Manufacturers Association (ECMA) .................... 19
  2.6.3 IEEE 802.22 standard for wireless regional area networks (WRANs) ... 19
  2.6.4 IEEE 802.11af .................................................................................. 20
  2.6.5 IEEE 802.11y .................................................................................. 20
  2.6.6 IEEE 802.16h ................................................................................. 20
  2.6.7 IEEE 802.19 .................................................................................... 20
2.7 Dynamic spectrum access (DSA) schemes ............................................. 20
  2.7.1 Non-dominated sorting genetic algorithm-II ...................................... 21
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7.2</td>
<td>Energy spectral efficiency (SE) trade-off in downlink orthogonal frequency-division multiple access (OFDMA) network</td>
</tr>
<tr>
<td>2.7.3</td>
<td>Quality of service aware white space allocation (QAWSA)</td>
</tr>
<tr>
<td>2.7.4</td>
<td>Dynamic open spectrum sharing medium access control (MAC) scheme for ad-hoc wireless networks</td>
</tr>
<tr>
<td>2.7.5</td>
<td>Interference avoidance white space allocation (IAWSA)</td>
</tr>
<tr>
<td>2.7.6</td>
<td>Ad-hoc secondary medium access control scheme</td>
</tr>
<tr>
<td>2.7.7</td>
<td>Rule-based allocation scheme</td>
</tr>
<tr>
<td>2.7.8</td>
<td>Increase in capacity of multiuser orthogonal frequency-division multiplexing (OFDM) system using dynamic subchannel allocation</td>
</tr>
<tr>
<td>2.7.9</td>
<td>Game theory</td>
</tr>
<tr>
<td>2.7.10</td>
<td>Multi-hop cognitive wireless scheme</td>
</tr>
<tr>
<td>2.7.11</td>
<td>Distributed channel assignment in cognitive radio networks (CRNs)</td>
</tr>
<tr>
<td>2.7.12</td>
<td>Proposed approach based on generalised frequency division multiplexing (GFDM) for maximising throughput in underlay cognitive radio network (CRNs)</td>
</tr>
<tr>
<td>2.8</td>
<td>Dynamic spectrum access (DSA) performance parameters</td>
</tr>
<tr>
<td>2.8.1</td>
<td>Interference and power</td>
</tr>
<tr>
<td>2.8.2</td>
<td>Spectral efficiency (SE)</td>
</tr>
<tr>
<td>2.8.3</td>
<td>Data rate/throughput of secondary users (SUs)</td>
</tr>
<tr>
<td>2.8.4</td>
<td>Fairness</td>
</tr>
<tr>
<td>2.8.5</td>
<td>Delay</td>
</tr>
<tr>
<td>2.8.6</td>
<td>Energy efficiency</td>
</tr>
<tr>
<td>2.8.7</td>
<td>Network connectivity</td>
</tr>
<tr>
<td>2.9</td>
<td>Comparison of the dynamic spectrum access (DSA) performance parameters with their schemes</td>
</tr>
<tr>
<td>2.10</td>
<td>Chapter summary</td>
</tr>
<tr>
<td>3.1</td>
<td>Overview</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>3.2</td>
<td>Research design and methodology</td>
</tr>
<tr>
<td>3.3</td>
<td>Performance parameter selection</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Spectral efficiency (SE)</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Data rate</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Common assumptions on spectral efficiency (SE) and data rate</td>
</tr>
<tr>
<td>3.4</td>
<td>Selection of DSA schemes for comparison</td>
</tr>
<tr>
<td>3.4.1</td>
<td>(Scheme One) energy spectral efficiency (SE) trade-off in downlink orthogonal frequency-division multiple access (OFDMA) network</td>
</tr>
<tr>
<td>3.4.2</td>
<td>(Scheme Two) distributed channel assignment in cognitive radio networks (CRNs)</td>
</tr>
<tr>
<td>3.4.3</td>
<td>(Scheme Three) proposed approach based on generalised frequency division multiplexing (GFDM) toward maximising throughput in underlay cognitive radio network (CRN)</td>
</tr>
<tr>
<td>3.5</td>
<td>Chapter summary</td>
</tr>
<tr>
<td>CHAPTER 4</td>
<td>Verification</td>
</tr>
<tr>
<td>4.1</td>
<td>Overview</td>
</tr>
<tr>
<td>4.2</td>
<td>Verification methodology</td>
</tr>
<tr>
<td>4.3</td>
<td>System model/results verification</td>
</tr>
<tr>
<td>4.3.1</td>
<td>General verification methodology</td>
</tr>
<tr>
<td>4.4</td>
<td>Verification results for scheme one: energy Spectral efficiency (SE) trade-off in downlink orthogonal frequency-division multiple access (OFDMA) network</td>
</tr>
<tr>
<td>4.5</td>
<td>Verification results for scheme two: distributed channel assignment in cognitive radio networks (CRNs)</td>
</tr>
<tr>
<td>4.6</td>
<td>Verification results for scheme three: proposed approach based on generalised frequency division multiplexing (GFDM) for maximising throughput in underlay cognitive radio network (CRN)</td>
</tr>
<tr>
<td>4.7</td>
<td>Verification analysis metrics</td>
</tr>
<tr>
<td>4.8</td>
<td>Chapter summary</td>
</tr>
<tr>
<td>CHAPTER 5</td>
<td>Comparison of selected DSA schemes</td>
</tr>
</tbody>
</table>
5.1 Chapter overview ........................................................................................................56
5.2 System model ................................................................................................................56
5.3 Comparison of the schemes.........................................................................................58
5.4 Comparison scenario one ............................................................................................64
  5.4.1 Data rate versus power scenario one.................................................................64
  5.4.2 Spectral efficiency (SE) versus power scenario one..........................................66
5.5 Comparison scenario two ............................................................................................69
  5.5.1 Data rate versus bandwidth scenario two.........................................................69
  5.5.2 Spectral efficiency (SE) versus bandwidth for scenario two.........................71
5.6 Chapter summary .........................................................................................................73

CHAPTER 6 Conclusion ....................................................................................................74
  6.1 Study conclusion .........................................................................................................74
  6.2 Future research ............................................................................................................77

Bibliography .....................................................................................................................78
Appendices .........................................................................................................................84
## LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4G</td>
<td>Fourth generation mobile technology</td>
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<tr>
<td>5G</td>
<td>Fifth generation mobile technology</td>
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<tr>
<td>AWGN</td>
<td>Additive white Gaussian noise</td>
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<tr>
<td>BS</td>
<td>Base station</td>
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<tr>
<td>CDMA</td>
<td>Code division multiple access</td>
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<tr>
<td>CPE</td>
<td>Customer premises equipment</td>
</tr>
<tr>
<td>CR</td>
<td>Cognitive radio</td>
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<tr>
<td>CRN</td>
<td>Cognitive radio network</td>
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<tr>
<td>DSA</td>
<td>Dynamic spectrum access</td>
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<td>DSM</td>
<td>Dynamic spectrum management</td>
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<tr>
<td>EE</td>
<td>Energy efficiency</td>
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<tr>
<td>GFDM</td>
<td>Generalised frequency division multiplexing</td>
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<tr>
<td>GSM</td>
<td>Global System for Mobile communications</td>
</tr>
<tr>
<td>ICASA</td>
<td>Independent Communications Authority of South Africa</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>ISPs</td>
<td>Internet service providers</td>
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<tr>
<td>ITUR</td>
<td>International Telecommunications Union-Radio</td>
</tr>
<tr>
<td>LTE</td>
<td>Long-term evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium access control</td>
</tr>
<tr>
<td>M-QAM</td>
<td>M-ary quadrature amplitude Modulation</td>
</tr>
<tr>
<td>NRA</td>
<td>National regulatory authority</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal frequency-division multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal frequency-division multiple access</td>
</tr>
<tr>
<td>PU</td>
<td>Primary user</td>
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<tr>
<td>QoS</td>
<td>Quality of service</td>
</tr>
<tr>
<td>SE</td>
<td>Spectral/Spectrum efficiency</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to interference plus noise ratio</td>
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<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
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<tr>
<td>SO</td>
<td>Spectrum opportunity</td>
</tr>
<tr>
<td>SU</td>
<td>Secondary user</td>
</tr>
<tr>
<td>WRAN</td>
<td>Wireless regional area network</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1.1: DSA network communication functionalities [8] ................................................................. 6
Figure 2.1: SO at a specific geographic location as a function of frequency (MHz) and time (s) [8] ........................................................................................................................................ 9
Figure 2.2: The DSA taxonomy [17]. ........................................................................................................ 10
Figure 3.1: Venn diagram of the scheme selection characteristics with the selected schemes 40
Figure 4.1: SE (bits/sec/Hz) (a) the graph on the left reflects the original results and (b) on the right is the regenerated results for Scheme Two...................................................................................... 49
Figure 4.2: Data rate (bps) varies with transmit power (dBm) (a) left is the original results, and (b) right are the regenerated results in this study ............................................................................................. 51
Figure 4.3: Data rate (bps) for (a) on the left is OFDM-PS for the original results (b) on the right is the regenerated results for Scheme Three ........................................................................................................... 53
Figure 5.1: System model defined for this study ........................................................................................ 58
Figure 5.2: Comparison of the schemes’ data rate (bps) against power in dBm ...................... 66
Figure 5.3: Comparison of SE (bits/sec/Hz) of the schemes against power in dBm ............ 68
Figure 5.4: Comparison of the data rate (bps) of the schemes against bandwidth \( kHz \) ....... 70
Figure 5.5: Comparison of SE (bits/sec/Hz) of the schemes against bandwidth in \( kHz \) ........ 72
LIST OF TABLES

Table 1.1: Dissertation outline summary .................................................................7
Table 2.1: Comparison of the selected existing DSA schemes against different performance parameters ..................................................................................................................32
Table 3.1: DSA schemes versus the characteristics for selection of schemes for modelling in this study ..................................................................................................................................................38
Table 3.2: Mathematical model for Scheme One [45] ..................................................41
Table 3.3: Mathematical models for Scheme Two [26] ..................................................42
Table 3.4: Mathematical model for Scheme Three [52] ..................................................43
Table 4.1: Mathematical models of the selected schemes ..............................................46
Table 4.2: Original parameter definitions and their values for the selected schemes ....46
Table 4.3: Spectral efficiency (bits/sec/hertz) for the original and regenerated values ...48
Table 4.4: Original data rate (bps) versus regenerated data rate of channels ..........50
Table 4.5: Data rate (bps) for the original and regenerated values for Scheme Three ....52
Table 4.6: Verification metrics equations ......................................................................54
Table 4.7: Statistical parameters for the absolute error .................................................55
Table 5.1: Mathematical models for the schemes .........................................................59
Table 5.2: Simulation parameters for comparing the three schemes ............................60
Table 5.3: Simulation parameter values .........................................................................62
Table 5.4: Data rate (bps) comparison of schemes against power (dBm) ..................65
Table 5.5: SE (bits/sec/Hz) comparison of schemes against power (dBm) .................67
Table 5.6: Data rate (bps) comparison for Scenario Two .............................................69
Table 5.7: Spectral efficiency comparison for Scenario Two .......................................71
Table 6.1: Summary of the outcomes for the three scheme’s comparison of SE and Data rate performance against power (dBm) and bandwidth (kHz). ..........................76
CHAPTER 1
INTRODUCTION

This chapter serves as an introduction to the research that has been done for this study. It provides a brief background of the research problem; research objectives and methodology are outlined, followed by the significance, relevance of this study. An overview of this dissertation concludes this chapter.

1.1 BACKGROUND

The electromagnetic radio spectrum is a natural resource with most of its transmitters and some receivers being licensed by national regulatory authorities (NRAs) [1]. The Federal Communications Commission (FCC) of the United States published a report that was prepared by the Spectrum-Policy Task Force, which aimed at improving spectrum management practices in the United States [2].

On 19 October 2015, the Independent Communications Authority of South Africa (ICASA) published a discussion document on the draft framework for dynamic and opportunistic spectrum management [3]. This discussion document investigated ways to promote effective and efficient use of the radio frequency spectrum [4].

A brief inspection of the various radio spectrum portions [5] [6] [6], which includes the revenue-rich urban areas revealed that:

1. some of the frequency bands in the spectrum are mainly unoccupied most of the time;
2. some of the other frequencies are found to be partially occupied, and
3. the remaining frequency bands are heavily used.
The underutilisation of the electromagnetic spectrum led to the coining of the term spectrum hole [5], which many other authors in the field refer to as a spectrum opportunity (SO) and white space (WS) among others [7]-[9]. This study will adopt the term SO. SO can be defined as an opportunity during which a band of frequencies is assigned to a primary user (PU) at a particular time and in a specific geographical location, where this band is not being used by that PU [5].

1.1.1 CHARACTERISTICS OF THE ELECTROMAGNETIC SPECTRUM

Spectrum utilization can be improved significantly through the possibility of giving a secondary user (SU) or unlicensed user) access to the SO that is unoccupied by the PU or licensed user at the right location and the time in question [1], [10]. The following sections elaborate on the terms licensed and unlicensed spectrum.

1.1.1.1 LICENSED SPECTRUM

A licensed spectrum band is for exclusive use by the designated users that are called PUs. In this spectrum band, appropriate mechanisms have already been proposed, thereby enabling the license-free wireless devices to make efficient use of the licensed spectrum [1].

1.1.1.2 UNLICENSED SPECTRUM

Any user can freely access unlicensed spectrum by following a specific rule (for example, not exceeding a defined limit of power transmission) [1], [8]. The unlicensed spectrum includes the industrial, scientific and medical (ISM) and unlicensed national information infrastructure (U-NII) frequency bands.

The ISM frequency band uses technologies like the Institute of Electrical and Electronics Engineers (IEEE) 802.11 and IEEE 802.11g. U-NII includes frequency bands used by IEEE 802.11 technology and by internet service providers (ISPs). Several wireless technologies must operate and coexist on the same frequency bands where devices compete with neighbours for
the same spectrum resources. This study will adopt the term secondary user (SU) because it can be used for an unlicensed user and can adopt a primary user (PU).

Section 1.2 below gives a brief overview of dynamic spectrum access (DSA) and cognitive radio (CR), which have emerged as the key concept in addressing the inefficient use of the radio spectrum that does not require the allocation of new frequency bands. CR, which includes software-defined radio (SDR), has been proposed to promote the efficient use of the spectrum by exploiting the SO [11], [12].

1.2 Motivation

Mobile wireless traffic has grown rapidly over recent years as a result of increasing data-hungry mobile applications on various mobile devices. As application scenarios extend from traditional real-time voice communication to social networks, entertainment, and e-commerce, the number of devices and data rates keeps growing exponentially. A broad consensus anticipates that the fourth generation (4G) and fifth generation (5G) mobile networks will not come close to meeting the demands that networks will face in the next decade [13]. The limited spectrum limits mobile network applications due to the increasing demand for new services. As such, NRAs are urged to promote a more efficient spectrum usage. DSA technologies provide new ways of managing spectrum by dynamically reassigning underused spectrum.

In this context, this study details the benefits of performing a comparative study on selected DSA schemes under a common system model and common DSA scheme evaluation methodology. The study also highlights the key strengths and weaknesses of each scheme, providing answers to which scheme is best suited to improve spectrum usage under varying system model conditions. The work serves as a baseline for comparing the performance of DSA schemes.

1.3 Research problem

According to literature, most existing DSA schemes do not follow a standard set of performance parameters, metrics or evaluation methodologies for analysing and assessing a
scheme’s performance. As such, regardless of what the scheme’s performance is, it cannot be directly compared with schemes in the existing body of knowledge. This problem necessitates an outlining and imposition of a standard set of performance parameters and a DSA scheme evaluation methodology.

Since the performance parameters used for the comparison of DSA schemes in a common system model are unknown, this study will identify and advise on which performance parameters can be best used for comparing the performance of DSA schemes.

1.4 Research objectives

In light of the problem statement above, this study seeks to attain the following objectives:

1. To select the DSA scheme performance parameters for comparing the performance between DSA schemes;
2. To select the DSA schemes that will be best used for comparing said performance;
3. To define a common set of performance parameters for the DSA schemes that will be best suited to comparing the performance of the DSA schemes;
4. To compare the performance of the selected DSA schemes against the selected performance parameters in MATLAB;
5. Conclude on which scheme performs best on the mathematical simulation (MATLAB).

1.5 Research methodology

Toward attaining the research objectives, this study will employ the following steps to form its methodology:

1. Conduct a comprehensive literature review on the existing DSA schemes to understand the characteristics, advantages, disadvantages among different schemes;
2. DSA schemes with common performance parameters are categorised/grouped together and then compared to each other under similar scenarios;
3. The results of the selected DSA schemes were regenerated using MATLAB for verification;
4. Once the schemes were verified individually, they were then compared against the identified parameters in (2), to understand their performance.

1.6 Research scope

While several areas fall within the scope of this research, they serve different purposes. As such, the delimitations and limitations of this study are presented below.

1.6.1 Delimitations

The following activities fall beyond the scope of this work:

1. Spectrum sensing

The existence of spectrum sensing techniques that provide accurate white space detection results is acknowledged and assumed.

2. Spectrum sensing and mobility

Spectrum mobility is assumed to have been carried out successfully and that the last step for consideration is spectrum sharing, which is the focus of this study.

1.6.2 Limitations

The scope of this work will have the following focus:

Link layer/ media access control (MAC) [8]: Figure 1.1 below illustrates the Open Systems Interconnection model (OSI) layers. The elements in the DSM are sectioned and placed on the layer on which they operate.

The following limitations have been identified for this study:

1. This study focuses on spectrum sharing, represented by the link layer, as shown in Figure 1.1. All other layers in Figure 1.1 are assumed as fully functional and active.
2. The geo-location spectrum database (GLSD) provides available SU channels that do not interfere with the PUs. Therefore, channel sensing is not required. Additionally, no mobility on SUs is assumed.

![Diagram of DSA network communication functionalities](image)

Figure 1.1: DSA network communication functionalities [8]

1.7 The significance of the study

This study conducts a comparative study on selected DSA schemes under a common system model and common DSA scheme evaluation methodology to identify the key strengths and weaknesses of each scheme and determine which scheme is best suited to improve spectrum usage under varying system model conditions. The work serves as a baseline for comparing the performance of DSA schemes.
1.8 DISSERTATION OUTLINE

This study’s main contributions are captured in Chapters 3, 4 and 5. These chapters offer a detailed outline of the research method and the functionalities used in selecting the performance parameters and DSA schemes to model. Chapter 4 verifies and reaffirms the implementation of the schemes that were chosen by modelling them in the MATLAB simulation environment.

Chapter 5 defines the system model that was used to compare the performance of the schemes that were selected in Chapter 3. The related literature in Chapter 2 shows selected existing DSA schemes and their performance parameters. Table 1.1 below provides a layout of this dissertation.

Table 1.1: Dissertation outline summary

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1</td>
<td>Introduction</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>Literature review</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Research method</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Verification</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Comparison of Selected DSA schemes</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Conclusion and future work</td>
</tr>
</tbody>
</table>

1.9 CHAPTER CONCLUSION

This chapter has outlined the background of this study and served to illustrate the prevalent underlying concepts that are important for understanding the purpose of this study. Next followed an outline of the research problem, research objectives and the research purpose, followed by the research scope, delimitations, limitations and the significance of this study. This chapter has provided a scope of the aspects that this study does not cover to facilitate understanding of this research.
The focus of this chapter is to provide an overview of the literature applicable to the research problem.

2.1 CHAPTER OVERVIEW

This chapter provides a comprehensive overview of cognitive radio (CR) and illustrates the link between CR and DSA. It further provides a detailed overview of DSA and how it can be managed (DSM). Section 2.5 briefly outlines the different DSA approaches, followed by an overview of existing DSA standards in Section 2.6. A review of existing DSA schemes is outlined in Section 2.7, after which an analysis of DSA and the associated performance parameters is presented in Section 2.8. The final section compares the DSA schemes with performance parameter values provided in a table.

2.2 COGNITIVE RADIO (CR) OVERVIEW

CR can change its transmission parameters through interactions with the environment it is operating from [14]. CR enables DSA networks to use spectrum dynamically. CR exploits the unused licensed radio frequencies, which are designated as SOs as shown in Figure 2.1, thereby opening them for SU. If the SU is using the spectrum band, and the PU appears and attempts to use that spectrum band, then the SU must move to another SO or stay in the same band while altering its transmit power level or modulation scheme to avoid interference [8].

SUs can opportunistically use SOs to increase performance for the users without causing any harmful interference for the PUs, as shown in Figure 2.1. The operating spectrum band, other transmission parameters and the access technology are intelligently and dynamically chosen based on availability by SUs [8].

CR depends on the availability of SDRs, which define a kind of radio that can be dynamically reconfigured by software. SDRs, also known as software radio, “Is generally a multiband radio
that supports multiple air interfaces and protocols and is reconfigurable through software running on general-purpose microprocessors” [15]. Depending on the level of sophistication of the SDR device, many parameters may be reconfigurable; for example, the operating frequency, bandwidth, the modulation scheme and the transmission power.

SDRs perform operations, often designated as DSA, opportunistic spectrum allocation (OSA), spectrum allocation access, or spectrum agile radio. Ultimately, a CR is an SDR with the ability to intelligently adapt its spectrum usage to the changing radio frequency environment and according to predefined objectives, for example performance, availability and reliability.

![Image of spectrum usage](image)

Figure 2.1: SO at a specific geographic location as a function of frequency (MHz) and time (s) [8]

### 2.3 Dynamic Spectrum Access (DSA) Architecture Overview

DSA allows the SU (cognitive radio user) to operate on the best available channel. Existing wireless network architectures employ network heterogeneity when it comes to both spectrum policies and communication technologies [16]. Most portions of the wireless spectrum are already licensed for different purposes, while some bands remain unlicensed.
DSA provides new ways to manage spectrum by dynamically reassigning the underused spectrum (i.e. SO) [8]. This study adopts DSA represented by the term dynamic spectrum access, not dynamic spectrum allocation or assignment. Figure 2.2 broadly explains the DSA strategies, which are categorised under three models, namely: the dynamic exclusive use model, open sharing model, and hierarchical access model.

The following subsection gives a brief explanation of the elements in the model illustrated in Figure 2.2.

2.3.1 DYNAMIC EXCLUSIVE USE MODEL

The dynamic exclusive use model maintains the basic structure of the current spectrum regulation policy; therefore, spectrum bands are licensed to services for exclusive use. This model introduces flexibility to improve spectrum efficiency. This study proposes two approaches for use in this model: Spectrum property rights and dynamic spectrum allocation.

The first approach allows licensees to sell and trade spectrum and to choose technology freely. While licensees have the right to lease or share the spectrum for profit, such sharing is not delegated by the regulation policy [17]. The second approach, DSA, was brought forth by the
European DRiVE project [18], which aimed to improve SE through dynamic spectrum assignment by exploiting the spatial and temporal traffic statistics of different services.

This allocation differs from the first approach because it is based on an exclusive-use model. This approach cannot eliminate white space in the spectrum, thus resulting in the burst-like nature of wireless traffic [17].

2.3.2 OPEN SHARING MODEL

This model employs open sharing among peer users as a basis for managing spectral regions [19]. The model advocates support from the success of wireless services operating from the unlicensed industrial, scientific, and medical radio (ISM) band. Centralised and distributed spectrum sharing strategies have been investigated to address the technological challenges under this spectrum management model.

2.3.3 HIERARCHICAL ACCESS MODEL

This model was built on a hierarchical structure with PUs and SUs. This model is intended to serve an open-licensed spectrum to SUs while limiting interference of the PUs (licensed spectrum) [17]. Spectrum underlay and spectrum overlay are two approaches used in spectrum sharing between PUs and SUs. The following subsections give explanations on spectrum overlay and underlay:

2.3.3.1 SPECTRUM OVERLAY

Spectrum overlay was first envisioned by Mitola [11] under the term spectrum pooling, then investigated by the Defense Advanced Research Projects Agency (DARPA) Next Generation program, where they termed spectrum overlay as opportunistic spectrum access [11]. Spectrum overlay does not restrict the transmission power of SUs, but it controls when and where the SU should transmit [17]. In overlay spectrum sharing, a node accesses the network portion of the spectrum not in use by the licensed users, thus minimising interference in the PU [11].
2.3.3.2 Spectrum Underlay

Spectrum underlay exploits the spread spectrum techniques developed for cellular networks [20]. Unlike overlay techniques, spectrum underlay requires sophisticated spread spectrum techniques to attain increased usage of bandwidth. It “imposes severe constraints on the transmission power of SU s so that they operate below the noise floor of PUs. By spreading transmitted signals over an ultra-wide band (UWB), SU s can potentially achieve a short-range high data rate with extremely low transmission power” [17].

This study considers using the hierarchical spectrum-sharing model since it is more compatible with the current spectrum sharing, management policies and legacy wireless systems [17]. The following section explains the dynamic spectrum management.

2.4 Dynamic Spectrum Management (DSM)

Cognitive radio network (CRN) pose unique challenges caused by their coexistence with primary networks together with diverse QoS requirements. This produces new spectrum management functions, which are required for the CRN to overcome the following critical design challenges [8]:

1. Interference avoidance (it is crucial that the CRNs avoid interference with primary networks at all times);
2. QoS awareness (for SU s to decide on an appropriate spectrum band to use, the CRN should support the QoS-aware communication while it considers the dynamic and heterogeneous spectrum environment); and
3. Seamless communication (regardless of the appearance of the PUs, the CRNs should provide seamless communication).

The spectrum management process in CRNs has four major functionalities to address the aforementioned critical design challenges. These functionalities are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility, which are explained in the next subsections [8]:
2.4.1 SPECTRUM SENSING

A SU can only allocate the portion of the spectrum that is unused; thus, a SU must monitor the available spectrum bands, then capture their information and then detect their spectrum opportunity. Spectrum sensing is essential to the realisation of CRNs; as such, CR is designed to detect all the changes in its surroundings. Spectrum sensing enables SUs to adapt to the environment through the detection of SOs selected without interfering with the primary network. Spectrum sensing can be accomplished through a real-time wideband sensing capability, which is used to detect the weak primary signals in a broad-spectrum range.

2.4.2 SPECTRUM DECISION

A SU can allocate a channel based on spectrum availability. Allocation does not only depend on the spectrum availability but is also governed by internal (and possibly external) policies. CRNs require the capability to decide on the best spectrum to use among the available bands. The QoS requirements of the applications describe this notion as a spectrum decision. Spectrum decisions comprise two steps in selecting the most appropriate spectrum – each spectrum band is characterised, after which one spectrum band is based not only on local observations of SUs but also statistical information of primary networks.

The most appropriate spectrum band should be selected after the available spectrum bands have been characterised, having taken into consideration the QoS requirements and the spectrum characteristics. The transmission mode and bandwidth can be reconfigured accordingly. The SUs may detect many single spectrum bands to meet the user’s requirements. Thus, multiple non-contiguous spectrum bands can be used simultaneously for transmission in the CRNs. This procedure generates a signal that is not only capable of high data throughput but also immune to interference and the PUs’ activity. The spectrum handoff occurs in one of the current spectrum bands followed by the remaining spectrum bands that maintain the current transmissions.

2.4.3 SPECTRUM SHARING

CRN access should be coordinated to prevent multiple users from colliding in the overlapping portions of the spectrum because of multiple potential SUs trying to access the spectrum. The
shared nature of the wireless channel requires coordination of transmission attempts that occur between the SUs, which proves that spectrum sharing should include a broad scope of functionality from the medium access control (MAC) protocol. A unique feature of SUs is their coexistence with licensed users while having a wide range of the available spectrum.

2.4.4 SPECTRUM MOBILITY

In spectrum mobility, the SUs are recognised as visitors to the spectrum, where they use a specific portion of the spectrum used by the PU. However, the SUs communication must continue in another vacant portion of the spectrum.

PU activity on the selected spectrum may necessitate the SU changing its operating band after the SU has captured the best available spectrum and is referred to as mobility. Spectrum mobility leads to a rise in handoffs in CR networks, which is known as spectrum handoff. Various protocols for different layers on the network stack should adapt to the channel parameters of the operating frequency. These protocols should also be transparent to spectrum handoff and latency.

Every time a SU changes its frequency of operation, the network protocol might require modification of the operating parameters. The purpose of spectrum mobility in the CR networks is to ensure a smooth, fast transition, thereby minimising performance degradation during a spectrum handoff. Information about the spectrum handoff duration is one crucial requirement of mobility management. This information can be attained through a sensing algorithm – when the latency information is available, ongoing communication can be preserved with minimal performance degradation.

2.5 DYNAMIC SPECTRUM ACCESS (DSA) APPROACHES

2.5.1 CENTRALISED SPECTRUM ACCESS

The centralised approach requires the existence of a central node, because most actions are performed there. The central node is involved in making decisions for assigning channels to the SU, and collecting spectrum information for those users. In literature, the central node is
also referred to as “spectrum server or spectrum broker” [8] or “central base station” [21]. This approach is widely used in literature [22]-[25] because of its advantage of having a global view of the spectrum’s network. Thus, making it easier to maximise the overall network performance while minimising interference between the SUs.

The centralised approach integrates topology control [20]; using conflict graphs to minimise the interference between the SUs. The advantage of having a central node is that it provides a global view of the network and maintains connectivity to avoid the user disconnections.

The primary disadvantage of the centralised approach is inducing signal overheads due to exchanging measurements amid the spectrum broker and the SUs. Spectrum assignment to SUs ceases when the spectrum broker fails due to crashes or power failures, this results in SUs choosing their channel(s) independently, causing unfair assignment, PU interference and contention.

2.5.2 DISTRIBUTED SPECTRUM ACCESS

Distributed spectrum access is an approach where there is no central entity or spectrum broker responsible for channel assignment to the SUs [26]-[28]. SUs make decisions either by themselves or through cooperating with neighbours and exchange measurements and channel assignment within the specified range, or within two or three hops. In traditional wireless networks, each node selects the channel having less interference to its neighbour [29].

Distributed spectrum access reduces signal overloading because only neighbouring nodes interchange messages. Resolutions are quicker, due to transmission to neighbouring nodes only. As such, fairness is only accomplished locally to a set of neighbouring SUs but not inclusive of the entire network.

Decisions on distributed schemes are based on the exchange of measurements between the SUs, which could mislead and affect the results significantly. Where decisions in cases of traffic load are concerned, the distributed approach makes adequate decisions in low traffic. Thus, having knowledge of the traffic in the entire network results in better decisions.
2.5.3 Multi-channel selection

Traditional channel access assigns channels with a central frequency and specific bandwidth around that frequency. Thus, traditional channels are contiguous in the spectrum, where each one consists of contiguous spectrum fragments. In cases of multi-radio devices, each radio interface is assigned a separate channel as described in [30], where a multi-radio cognitive mesh network is considered.

CR allows simultaneous access to various spectrum fragments through using discontinuous orthogonal frequency division multiplexing (DOFDM), which aggregates the fragments into one channel while increasing bandwidth of each SU [31]. Moreover, using a multi-radio device in a cognitive mesh network gives access to multiple spectrum fragments simultaneously and increases the networks performance. The span of the aggregation bands is limited since transceivers cannot aggregate spectrum fragments that are out of their range, which implies that a maximum span is specified for each of the transceivers. One way to prevent SUs from selecting multiple channels is through overheads from frequent channel switching [32].

2.5.4 Primary User (PU) or Secondary User (SU)

A common dilemma in spectrum assignment in CR involves deciding on whether an algorithm should consider the presence of PUs in their system model or not [33]. One fundamental requirement of CR is ensuring that SU should not interfere with the performance of PU. However, most of the existing literature does not include an assumption of SUs having a fixed set of channels that is separate from the PU channels [28], [34], [35]. This assumption underlines the target objectives of DSA schemes that ensure distribution of a fixed set of SU channels based on a set criteria defined. PUs are mostly not regarded because they are only used for limiting the number of channels that SUs should use.

2.5.5 Common Control Channel (CCC)

The most common requirement for DSA in the CRN is the existence of a CCC that is used for coordinating channel assignment amongst the SUs [33]. “CCC is a pre-defined channel used for controlling information exchange between SUs” [33]. CCC can either be a global or local
channel. The global CCC is the equivalent for all the SUs in the CRN, although for a local CCC it is only devoted to a small topographical region.

In [33], spectrum allocation approaches have two types related to the CCC: those assuming the presence of the CCC for management amid the SUs, and the one not requiring CCC presence. Known CCCs are vulnerable to various forms of attacks, for example, denial of service (DoS) or jamming. CCCs with limited or no functionality can degrade network performance. As such, the execution of an efficient CCC scheme is required for finding the optimum control channel in the physical region of the network.

A few approaches described in the literature [36], [37] avoid using CCC for cognitive spectrum access. Shortcomings of intra-channel channel assignment in 802.22 for CRNs are investigated in [36], where no devoted CCC is assumed. A heuristic approach for channel allocation is assumed in free channels for exchanging control messages between the SUs. DSA is executed by the cognitive base station, which informs the SUs when there is an available channel to use; it uses the beacon broadcasts communication in all the available channels.

2.5.6 SEGMENT-BASED

In [38], the segment based approach was used for the DSA problem and was defined as the maximum set of all nodes connected that has access to at least one CCC. This approach assigns the same channel to all the nodes within a segment – this is called the operational channel. The nodes exchange the operational channel during the initial handshake and the available channel lists, availability of information in a round robin manner; but no information is given on how this exchange is done and whether or not a control channel is used.

DSA schemes are integrated with channel access, segment formation and route discovery. Segment formation is performed together with channel assignment as a result of variable spectrum usage. This method entails less channel switching and improved performance when compared with the traditional link-based and flow-based approaches of CR. Moreover, an assumption that the CR nodes have a single radio interference is made, even though this is not always the case [38].
2.5.7 CLUSTER-BASED

The cluster-based method is a crossbreed solution that combines centralised and distributed approaches on spectrum access, effectively eliminating the disadvantages of each approach. In the cluster-based method, the network contains fixed mesh routers and mobile mesh clients. Schemes using the cluster-based approach have several advantages, including:

1. achieving improved bandwidth use through grouping users into clusters and distributing loads into many channels;
2. decreasing the rate of communication overheads for the distributed method resulting from the message exchanges taking place in each of the clusters and not in the entire network;
3. enabling reusing the bandwidth similar to GSM networks.

The weakness of this approach [26] is the congestion of mesh routers easily when forwarding heavy traffic from their clusters to other clusters. Clustering must be performed wisely, adapting to the load dynamically, to avoid mesh router congestion.

2.6 DYNAMIC SPECTRUM ACCESS (DSA) STANDARDS

Technology forecasts predict that CR will become integral for future radio systems and networks. Regulatory bodies like the Federal Communications Commission (FCC) in the United States, Office of Communications (OFCOM) in the United Kingdom, and Independent Communications Authority of South Africa (ICASA) in South Africa are already considering the use of CR technologies [4], [39].

A fundamental introduction to DSA entails regulators unambiguously redefining usage rights for each user (PUs and SUs) in each usage scenario. An example of such a regime is OFCOM’s introduction known as special usage rights (SURs). In this regime, the rights of a license holder are defined by the maximum levels of interference, rather than the maximum power levels that they are permitted to transmit on. This step involves enabling technical standards for DSA. The IEEE 802.18-radio regulatory technical advisory group (RR-TAG) is one initiative developed toward achieving this goal [40]. Primarily, it serves as an intermediary to the International Telecommunications Union-Radio sector (ITU-R), national spectrum regulators, and various
stakeholders dealing with regulatory issues, especially the ones based on the existing 802 families of wireless technology [40].

Many standardisation organisations, such as the SDR Forum and the ITU-R work in this area, and numerous DSA standards have been proposed and developed by different bodies of the DSA based technologies. The next subsection discusses some of the standards of interest in the context of this study.

2.6.1 EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (ETSI) RECONFIGURABLE RADIO SYSTEM (RRS)

This standard considers the feasibility of possible operations of the long-term evolution (LTE) standard in the ultra-high frequency band (UHF) band between 470 to 790 MHz over television white spaces (TVWS) [41]. TVWS is largely available in rural areas where broadband connectivity and availability are rare. LTE uses time division duplexes (TDDs) for SU operations over TVWS in rural areas, since it employs unpaired spectrum bands and does not require duplexing equipment, thereby limiting costs.

2.6.2 EUROPEAN COMPUTER MANUFACTURERS ASSOCIATION (ECMA)

This standard serves to accommodate low-power homes and portable devices operating over TVWS in the UHF band [40]. The Cognitive Network Alliance (CogNea) and ECMA international have jointly developed this standard.

2.6.3 IEEE 802.22 STANDARD FOR WIRELESS REGIONAL AREA NETWORKS (WRANs)

This is the first IEEE standard that focuses on rural broadband wireless access [42]. This standard allows SUs to reuse TVWS without causing harmful interference to the PUs. It specifies the air interface, which includes media access control (MAC) and physical (PHY) layers of the fixed point to multipoint WRANs that operate in the very-high-frequency (VHF) and ultra-high-frequency television broadcast bands.
2.6.4 IEEE 802.11AF

This standard extends the traditional Wi-Fi (802.11) to TVWS. This standard can be described as a wireless network with access points (AP) and enabled DSA and CR, operating over TVWS through the spectrum sharing mechanisms [40].

2.6.5 IEEE 802.11Y

The objective of this standard is to allow for high-power co-primary and secondary Wi-Fi like operations in the 5 GHz radar and the 3.65-3.7 GHz earth satellite bands [39].

2.6.6 IEEE 802.16H

This standard enables the co-existence of licence-exempt systems based on 802.16 standards and licensed systems (PUs) [39]. This co-existence is facilitated by the application of CR techniques in coordinated co-existence (CX) and uncoordinated co-existence (UCP).

2.6.7 IEEE 802.19

This standard describes the methods for assessing the coexistence of the wireless networks and defines recommended coexistence metrics and methods for computing these coexistence metrics [39]. The primary focus is on IEEE 802 wireless networks, even though methods developed may apply to other standards development organisations and most development communities.

Section 2.7 provides a brief explanation of the DSA performance parameters.

2.7 DYNAMIC SPECTRUM ACCESS (DSA) SCHEMES

DSA determines the optimal mapping between the available licensed channels and cognitive radio to achieve optimal performance. Many existing DSA schemes are available in literature for solving the DSA problem, as shown in [8]. The DSA schemes under review in this study are the ones that focus on providing users with access to wireless broadband.
The schemes for this study are selected according to the following objectives:

1. The schemes should be able to assign available channels to SUs to achieve spectrum assignment for all the users;
2. The schemes should cause little or no interference between the SU and PU;
3. The schemes should fall on the link layer or the MAC layer.

In the following subsections, the schemes are described in detail, outlining the advantages and disadvantages (if any available).

**2.7.1 Non-dominated Sorting Genetic Algorithm-II**

The Non-dominated Sorting Genetic Algorithm-II (NSGA-II) addresses the multi-objective problem (MOP) by combining a genetic scheme and the concept of non-dominance that is introduced by [43]. The advantage of this scheme is that, it maximises throughput and SE by defining cases and solving them using a spectrum assignment algorithm that is based on the protocol that searches for the Pareto optimal solutions [44]. The characteristics of the problem that is being solved focus on rapidly assigning a small set of the Pareto optimal solutions to the service provider, thereby consuming fewer function evaluations.

The simulation results of this protocol revealed that the searchability of the protocol offers solutions in the Pareto front, which is affected by increasing QoS requirements for the network in spectrum sharing. Another simulation finding is the improved throughput at the expense of SE. This serves a guideline to the service provider in maintaining a high level of customer satisfaction between the SUs and the PUs of the network in spectrum sharing. The service provider ensures that the communication performed by the PUs is not affected by the operations from the SUs.

**2.7.2 Energy Spectral Efficiency (SE) Trade-off in Downlink Orthogonal Frequency-Division Multiple Access (OFDMA) Network**

This scheme [45] investigates an energy efficiency-SE trade-off (EST) problem in a downlink OFDMA single cell network. The problem is formulated as a multi-objective optimisation
problem (MOP), after which its Pareto optimal set is analysed. Next, the weighted linear sum method is used to convert the MOP to a single-objective optimisation problem (SOP). Finally, a novel algorithm is proposed using particle swarm optimization (PSO) to solve the SOP. The advantage of this scheme is that the simulation results reveal that the proposed algorithm could efficiently reduce total transmitting power and improve energy efficiency (EE), although this comes at the expense of some SE. Yet, its effects could be used in the design of a flexible, energy efficient network in future.

2.7.3 QUALITY OF SERVICE AWARE WHITE SPACE ALLOCATION (QAWSA)

QAWS scheme disadvantage is that it allocates the spectrum opportunity (SO) channels to all spectrum opportunity devices (SODs) under a certain bandwidth constraint [46]. Authors [46] considered channel bandwidth as the QoS metric, where each channel was evaluated and then classified based on its spectrum attributes. The advantage of this scheme, as illustrated in [46], is to ensure that every SOD would receive an SO channel to meet the minimum required bandwidth while avoiding any potential oversupply and wastage of the bandwidth. Thus, each SO channel was matched to a SOD based on its characteristics, which are SU quality of service requirements and the operational capabilities of the SODs.

2.7.4 DYNAMIC OPEN SPECTRUM SHARING MEDIUM ACCESS CONTROL (MAC) SCHEME FOR AD-HOC WIRELESS NETWORKS

This study describes a dynamic open spectrum sharing (DOSS) MAC protocol for ad-hoc wireless networks. DOSS MAC allows users to access arbitrary spectrum subject to their availability [47]. The advantage of this scheme is that, it does not require new centralised infrastructure, and it allows users to coexist with legacy users while avoiding hidden and exposed terminal issues.

This protocol involves the setup of operational bands: the control channel that allows users to negotiate or communicate based on their transmission frequencies while eliminating the hidden or exposed node issues. This allows the actual data transmission channel and allows the busy tone band users to find the occupied bands. The designed protocol allows for both unicast and multicast communication, for which the band sizes and data rates vary depending on the
spectrum availability together with the channel conditions. The performance of the proposed MAC protocol allows for enhanced spectrum utilization.

2.7.5 INTERFERENCE AVOIDANCE WHITE SPACE ALLOCATION (IAWSA)

This interference avoidance white space allocation (IAWSA) scheme advantage is based on its ability to allocate the SO channels to the heterogeneous SOD under a given interference constraint. According to [46], the objective of this scheme is reusing and sharing fewer channels among the high number of coexisting heterogeneous SODs while minimizing the interference. Graph-colouring heuristics are used to model the interference-free allocation.

2.7.6 AD-HOC SECONDARY MEDIUM ACCESS CONTROL SCHEME

An ad-hoc secondary MAC (AS-MAC) protocol was developed, which allowed secondary systems to operate with GSM cellular systems in a non-intrusive manner [48]. AS-MAC protocols advantage is assuming that SUs uses the multi-hop system and are constrained only to operate on the bandwidth that is unused by the primary system, as this causes no interference to the primary system.

The other advantage of the proposed MAC scheme is that it detects the spectrum and maintains a picture of the primary spectrum usage. A control channel is then used to coordinate of unused spectrum among the SUs. Simulations of this scheme show that the proposed MAC scheme allows SUs to use spectrum efficiently.

2.7.7 RULE-BASED ALLOCATION SCHEME

This scheme is aimed at addressing the conflicting objectives that were found on the Quality of Service Aware White Space Allocation (QAWSA) and the Interference Avoidance White Space Allocation (IAWSA) scheme. As discussed in [46], this rule based allocation scheme balances the QoS and the interference of using the channel partitioning (CP) or the channel bonding (CB). Another advantage of this scheme is that it avoid spectrum wastage through partitioning the SO channels into mini-channels that are allocated to the SODs.
Thus, if the channels are fewer than the bandwidth requirement, then the CB rule is used to bond the number of channels to meet the minimum required bandwidth size. A rule-based allocation scheme will search for the presence of any white space channel first, which can be allocated without channel bonding and partitioning. If there is no white space channel, then the channel-partitioning rule has priority over the channel-bonding rule. To meet the QoS requirements of SUs, this scheme searches the white space channels that are most suitable among the list of channels discovered. This scheme allocates channels that meet the QoS requirements instead of merely allocating white space channels that do not interfere with each other.

2.7.8 INCREASE IN CAPACITY OF MULTIUSER ORTHOGONAL FREQUENCY-DIVISION MULTIPLEXING (OFDM) SYSTEM USING DYNAMIC SUBCHANNEL ALLOCATION

This scheme [49] addresses the problem of dynamic multiuser sub channel allocation in the downlink of OFDM systems. This study assumed that the BS transmits perfect channel information with the channel model that is quasi-static [49]. This scheme results in a small group of users having poor channel gains caused by the large path loss and random fading due to sub channel allocations that are not optimised. This problem can be solved by deriving a multiuser convex optimisation problem to find the optimal allocation of sub channels and by proposing a low complexity adaptive sub channel algorithm [49]. Simulation results show that the proposed algorithm performs almost as well as the optimal solution. The advantage of this scheme is that there is multi-user diversity enables higher SE for a larger number of users in a cell.

2.7.9 GAME THEORY

Game theory has been used in performance evaluations of DSA schemes, especially in comparisons between cooperative and non-cooperative approaches as presented in [50] through game theoretical analysis. In [50], game theory was used to analyse the behaviour of the CRN for distributed adaptive channel allocation. The study assumed that users deploy code division
multiple access (CDMA) to determine operating channels and coding rates by maintaining a constant transmission power.

The cooperative case can be modelled as an exact potential game, and it converges to a pure strategy of the Nash equilibrium solution [50]. Conversely, this framework is not applicable for non-cooperative spectrum. Therefore, a sharing learning algorithm was proposed. The evaluations revealed that the Nash equilibrium point for cooperative users was reached soon, resulting in a certain degree of fairness and improved throughput.

On the other hand, the advantage of this scheme is that, the learning algorithm for non-cooperative users resulted in convergence towards a mixed strategy allocation. Moreover, the non-cooperative approach resulted in degrading fairness and slightly poorer performance, although the information exchange obtained by selfish users was significantly low.

2.7.10 MULTI-HOP COGNITIVE WIRELESS SCHEME

The DSA is presented in multi-hop cognitive wireless networks with multiple PUs and multiple SUs. This scheme advantage is that it proposes an effective algorithm to enhance spectrum usage and reliable communications between licensed users and cognitive users. The Pareto distribution was used to characterise the activities of licensed users [51]. The spectrum sensing method was presented to detect the idle and busy channel statuses in the CRN with multiple PUs and SUs [51].

The available channels in the system and the interference condition between users were extracted as a binary matrix by dynamically allocating the channel resources from a global point of view. Based on graph theory, time and frequency division multiplexing technologies were used to bring forth the channel allocation strategies and switch mechanism. Simulation results indicated that the proposed algorithm could effectively reduce the number of channel sensing and switch, thereby improving spectrum utilization.
2.7.11 DISTRIBUTED CHANNEL ASSIGNMENT IN COGNITIVE RADIO NETWORKS (CRNs)

In [26], distributive channel assignment in CRNs, of which one target objective is maximising the aggregate data rate of the SUs by using M-QAM, is proposed. This scheme disadvantage is that, it uses an ad-hoc CRN and presents channel assignment methods that can be used by a CR node for selecting a channel for communication. The proposed channel assignment methods aim to maximise SE, minimise transmit power, or maximise data rate. When several available channels are detected, based on the proposed methods, a SU can select a suitable channel to use.

2.7.12 PROPOSED APPROACH BASED ON GENERALISED FREQUENCY DIVISION MULTIPLEXING (GFDM) FOR MAXIMISING THROUGHPUT IN UNDERLAY COGNITIVE RADIO NETWORK (CRNs)

This scheme’s [52] advantage is that it proposed an approach based on a pattern search (PS) algorithm in GFDM to maximise the total throughput or data rate for the SUs without affecting the QoS of the PUs under power and interference constraints in downlink underlay CRNs. The proposed algorithm was compared with other optimisation techniques. Some parameters, such as the number of PUs, SUs and subcarriers, were studied for their effect. Furthermore, the scheme investigated a comparison between the suggested GFDM system and the OFDM system. The corresponding results showed that the overall throughput or data rate for all SUs had increased, which rendered the new proposed approach more useful for practical applications.

2.8 DYNAMIC SPECTRUM ACCESS (DSA) PERFORMANCE PARAMETERS

Several performance parameters are used for DSA to SUs in the CRNs [33], [53]. These performance parameters differ according to the purposes of each scheme. This section discusses the performance criteria for DSA.
2.8.1 INTERFERENCE AND POWER

CRNs constrain SUs to create little or no interference for the licensed users and to maximise CRN performance the interference between the SUs should always be kept to a minimum [33]. In designing efficient cognitive spectrum access schemes, interference is the most common criterion [22], [34], [54], [55]. Past literature has focused on the interference of SUs to the PUs. Conversely, other literature disregarded PUs while considering interference that is initiated to other SUs in both directions.

Many approaches to limiting interference or power to PUs are centred on the interference temperature limit (ITL), where channels are assigned to the SUs to retain the ITL under a predefined threshold. To limit interference temperatures below a certain threshold, the power is controlled to minimise the transmit power and the interference at PUs [56].

A joint framework for spectrum assignment and power control has been explored in different sources [26], [57], [58] towards solving the DSA problem. However, in most cases, these approaches do not always guarantee overall network performance and spectrum usage, and they do not consider QoS.

Several methods were proposed in [26] for channel access. One method is based on minimising the transmit power under various data rate values. To minimize transmission power, SUs with large amount of data rates must utilize channels with larger bandwidths and lower interference levels, as these channels would interfere least with bandwidth ratios.

2.8.2 SPECTRAL EFFICIENCY (SE)

SE can be described as the rate of information that is transferred from a BS to SUs in a network over a given bandwidth [59]. SE is measured in bits per second per hertz [53], which means that the number of bits received without error is given by the SE. SE is a common criterion for DSA schemes [23], [26], [31].

One of the proposed methods for maximising SE is presented in [26], which assumes the use of M-QAM in the SUs. This method has a function that can overcome the challenge of
maximising the SE by maximising the transmit power allocated to each CR node instead. This method only works where CR nodes have shared their maximum allowed transmission power.

SE can be maximised through the fair allocation of idle spectrum to SUs [25]. To consider fair allocation of spectrum for DSA schemes, the authors in [25] propose a method for removing possible starvation effects in spectrum. While this approach may improve SE, although optimal fairness is not always achieved. The authors in [33] explained that the complexity of maximising the SE increases when the multi-radio and multi-channel CRNs are involved.

2.8.3 DATA RATE/THROUGHPUT OF SECONDARY USERS (SUS)

Traditional wireless networks and CRNs have a common criterion of maximisation throughput for channel access schemes [31], [35], [60]. The main aim is to maximise the throughput of each SU and the overall network throughput. This is characterised by the following features:

1. The maximum transmit power that is used for each SU on each channel [26];
2. Shannon theorem that is used for the link capacity [57], [61];
3. Maximum interference linked to signal to interference ratio (SINR) [24];
4. Requirements of the quality of service [61];
5. Minimum impact on the PU [24].

Many existing works focus on attempts of maximising throughput of each SU, using distributed DSA approach for instances where SUs do not liaise with each other [62]. Other research [26] focuses on having throughput for SUs as a performance parameter, performing both distributed and centralised spectrum access for maximising network performance, but this resulted in unfairness, leaving some SUs starved.

In [26], one target objective for maximising data rate of the SUs is M-QAM. In this instance, the overall data rate of the SU has an objective function, subjective to the constraints that the transmit power should be lesser compared to the given value. Result for this objective is that, each user uses its maximal allowed transmit power to maximise the data rate.

The authors in [63] used a different approach to throughput maximisation by considering the OFDMA-based CRN. By assuming that the CR nodes borrow uplink subcarriers from a primary network, a maximised throughput is achieved through a target objective function for
all CR users. Therefore, optimisation is achieved under several constraints like maximum bit error rate, minimising SINR and the bits per SU.

2.8.4 FAIRNESS

The performance parameter for maximising the user or network throughput results in the distribution of spectrum unfairly among SUs. For example, in some instances one SU can choose multiple channels while others are left with no spectrum available i.e. starvation. Many works in [25], [28], [60] have avoided this occurrence by considering maximising throughput fairness between SUs for several utility functions. To illustrate maximising the minimum average throughput per SU will attain fairer results.

A centralised approach can be considered for achieving throughput fairness – the aim is assigning channels to SUs to distribute the spectrum fairly. While this approach does not consider minimising throughput requirements of high-demand users, it can still solve problems of starvation and unfairness.

The problem of fairness can also be solved by considering separate groups of SUs according to their QoS requirements, or by using user priorities according to the different throughput requirements. However, [33] holds that this work has not been fully investigated and is still being investigated.

The authors in [64] focus on infrastructure-based CRNs to maximise SE and fairness. Proportional fairness is the interchange of throughput and fairness during transmission [64]. The target goals for proportional fairness includes maximising the sum of the logarithmic utility functions and assigning data rate to each user that is inversely proportional to its predicted resource consumption [64], [65], [66].

2.8.5 DELAY

Delay is another QoS criterion used for DSA. Previous work in the literature on DSA in CRNs focused on end-to-end delay and the switching delay when selecting which spectrum bands to use. End-to-end delay can be defined as the overall time for delivering information and the information delivered is measured from the source to the destination node. CR considers an
end-to-end delay in several approaches combining spectrum access with routing. An example of this feature is multi-hop CRNs, where routing is essential.

Switching delay occurs when the transmission or the reception of information to the SU is interrupted, which then introduces more delay in information flow. In [67], the order of the times for the switching delay is 10ms for a 10MHz change for frequencies of up to 3GHz. The maximum delay of information flow to the SU is measured by the total delay of the prevailing flows including of the new flow, as shown in [68], [69].

Authors in [63] presented a framework for spectrum decisions in the CRNs while taking into account the spectrum switching delay. They then proposed a metric for calculating the capacity of the SU. In [70], a joint framework for channel assignment and routing was proposed, which considered the metrics that combine interference and channel switching. These authors present minimum cumulative interference and channel switching delay (MISD) metrics that allow for an interchange amid the interference and the switching delay. Channels and paths are assigned to each channel hop; however, the sum of channel switches is the subject of consideration and not the actual switching delay in the flow path. This approach is only feasible and useful where the spectrum bands have the same bandwidth.

2.8.6 ENERGY EFFICIENCY

Energy efficiency is a comparative concept that considers the power consumption of a base station. It can be defined as the ratio of the total data rate (i.e. system capacity) to the total power consumed [53]. This performance parameter aims to minimise the energy consumption of the SUs [28], [71]. In [71] an approach of distributed energy is introduced where a system is assumed operating in timeslots where the SUs with new traffic demands senses the whole spectrum and find the vacant frequencies at each timeslot.

Another energy efficient spectrum allocation approach is described in [28], known as CR ad-hoc networks (CRAHNs). This approach formulates a channel assignment and channel optimisation problem, aiming to maximise the overall channel capacity and minimise the system’s transmission power.
The problem of energy efficiency has resulted in a way to minimise the transmit power of the selected channel by using the constraints of not causing interference to the PUs. This is done by limiting the transmit power on a channel’s power mask link; as such, it does not select the channel that is used by another SU that exceeds the maximum battery power.

2.8.7 NETWORK CONNECTIVITY

Maintaining network connectivity for traditional ad-hoc and mesh networks is important for improving QoS to the users. A study by [72] investigated the spectrum assignment effect on the connectivity of the CR ad-hoc networks. The CRN was modelled using a graph or graph colouring rules according to which the authors could evaluate resulting network connectivity. The results showed that interference among the SUs had an observable impact on the network connectivity of CR ad-hoc networks.

The disadvantage of the existing network connectivity use based approaches is that most focus exclusively on network connectivity maintenance, with little to no consideration of other criteria. Even though network connectivity maintenance is important, QoS should also be considered for delivery of flows for a high QoS.

2.9 COMPARISON OF THE DYNAMIC SPECTRUM ACCESS (DSA) PERFORMANCE PARAMETERS WITH THEIR SCHEMES

This section presents a tabulated summary of the DSA schemes that were reviewed against their performance parameters in Section 2.8. The findings in Table 2.1 reveal several schemes that follow various performance parameters. No defined baseline criteria presently exist to guide the selection of performance parameters for a baseline in any DSA scheme. Therefore, this study aims to identify and propose a comparative system model that DSA schemes could follow for comparative analysis. Other performance parameters can be added depending on what the schemes want to achieve.
**PS:** notation N/M in the table means not mentioned.

Table 2.1: Comparison of the selected existing DSA schemes against different performance parameters

<table>
<thead>
<tr>
<th>DSA schemes</th>
<th>Criteria</th>
<th>Channel model</th>
<th>Link type</th>
<th>Noise type</th>
<th>Modulation type</th>
<th>Ref</th>
</tr>
</thead>
</table>
| NSGA-II     | • Throughput/data rate  
• SE          | Randomly assigned | Downlink  | SINR       | N/M             | [44] |
| QAWSA       | • SE                   | Randomly assigned | Downlink  | SNR        | OFDMA           | [46] |
| Game theory | • Fairness  
• Throughput  | Randomly assigned | Downlink  | SNR        | N/M             | [50] |
| Proposed approach based on GFDM for maximising throughput in underlay cognitive radio network | • Throughput/data rate  
• Power  
• Interference | Randomly assigned | Downlink  | AWGN    | OFDMA & GFDM | [52] |
| IAWSA       | • Interference        | Randomly assigned | Downlink  | SNR        | OFDMA           | [46] |
| Multi-hop cognitive wireless | • Spectrum utilization | Randomly assigned | Downlink  | SNR        | N/M             | [51] |
| Energy spectral efficiency trade-off in downlink OFDMA network | • Energy efficiency  
• Power  
• SE  
• cost | Randomly assigned | Downlink  | AWGN    | OFDMA           | [45] |
| Rule-based allocation scheme | • SE  
• Spectrum utilization  
• Interference | Randomly assigned | Downlink  | SNR        | OFDMA           | [46] |
<table>
<thead>
<tr>
<th>Method</th>
<th>Parameters</th>
<th>Channel Assignment</th>
<th>SNR</th>
<th>N/M</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS-MAC</td>
<td>• SE</td>
<td>Randomly assigned</td>
<td></td>
<td></td>
<td>[48]</td>
</tr>
<tr>
<td></td>
<td>• Spectrum utilization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOSS</td>
<td>• Spectrum utilization</td>
<td>Randomly assigned</td>
<td></td>
<td></td>
<td>[47]</td>
</tr>
<tr>
<td>Increase in capacity of multiuser OFDM system using dynamic sub channel allocation</td>
<td>• SE</td>
<td>Randomly assigned</td>
<td></td>
<td></td>
<td>[49]</td>
</tr>
<tr>
<td></td>
<td>• Data rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• SE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed channel assignment in CRN</td>
<td>• Data rate</td>
<td>Randomly assigned</td>
<td></td>
<td></td>
<td>[26]</td>
</tr>
<tr>
<td></td>
<td>• Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• SE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**2.10 CHAPTER SUMMARY**

This chapter offered a brief overview of DSA and CR terminology existing in the literature. Measures of managing DSA, DSA approaches and the IEEE standards mostly used with DSA schemes were outlined from the literature. A brief literature review of the existing DSA schemes was shown in Section 2.7 and the performance parameters summary for DSA schemes was shown in Section 2.8. A tabulated summary is given in table 2.1. This summary gave in-depth detail of different DSA schemes, illustrating the use of different performance parameters. Evidently, this review proves that DSA schemes do not follow any criteria while selecting the schemes to model. The selection of DSA schemes and performance parameters that will be modelled in this study is outlined in the following chapter, Chapter 3.
CHAPTER 3
RESEARCH METHOD

The systematic approach to answering or solving the research problem is outlined in this chapter. The procedures, techniques, and process for solving the research problem are described.

3.1 OVERVIEW

This chapter outlines the research design and methodology for selecting: (1) parameters for comparing scheme performance and (2) the DSA schemes for the performance comparison. The selection of these performance parameters and their schemes is based on the knowledge gained from Chapter 2, Section 2.9, and Table 2.1.

3.2 RESEARCH DESIGN AND METHODOLOGY

This section discusses the overall approach that was followed in addressing the research problem. The following methodology was followed as summarised in chapter 1:

1. Step One: the first step of the research methodology involves conducting a comprehensive literature review on existing DSA schemes and their performance parameters, which has been done in Chapter 2.
2. Step Two: the second step of the methodology entails selecting performance parameters that can be used in a comparison of the selected schemes’ performances.
3. Step Three: the third step is selecting DSA schemes for comparison, which follow in this chapter.
4. Step Four: the fourth step involves verifying the selected DSA schemes on MATLAB by reaffirming that the schemes have been correctly implemented, which follows in Chapter 4.
5. Step Five: the fifth step is carried out in Chapter 5, where it (1) defines the common system model for comparing selected DSA schemes, (2) compares scenarios in which
selected DSA schemes and their performance parameters can be compared, and (3) compares the performance of the selected DSA schemes with the selected performance parameters on MATLAB.

6. Step Six: the final step in the methodology follows in Chapter 6, which offers a discussion on the findings and a conclusion to this dissertation regarding scheme performance comparison with the selected parameters.

Literature offers many existing research design techniques like survey, simulation/statistical modelling, case studies, comparative analysis performance parameters, experiments and content analysis, among others [73]. This study employs a simulation modelling research design technique and implements it using MATLAB.

MATLAB is a language for technical computing that incorporates a programming environment for algorithmic development, data analysis, visualisation, and numeric computation [45]. It combines a desktop environment tuned for iterative analysis and design processes with a programming language that directly expresses matrix and array mathematics. MATLAB’s toolboxes are professionally developed, rigorously tested, and fully documented.

3.3 PERFORMANCE PARAMETER SELECTION

Table 2.1 compares the selected DSA schemes and their respective performance parameters. The table further reveals that, on average, the selected DSA schemes have either data rate or SE as their performance parameters [26]. SE can be used to measure how many bits per seconds per hertz are transmitted over the network, and the data rate can help measure how many bits per second are transmitted over the network [59].

The radio spectrum available for wireless data services and systems is becoming increasingly scarce as the demand for these services continues to grow rapidly. As such, SE is a primary concern to the design of future wireless data communications systems. Considering that the number of bits per second per hertz is transmitted over a given bandwidth in a specific communication system [49], SE is an ideal performance parameter for DSA schemes. SE will make it easier to measure the level of efficiency that a limited frequency spectrum uses [45].
On the other hand is data rate, which is a common criterion in traditional wireless networks and CRNs, and is used to maximise channel allocation in the DSA schemes [31], [35], [60]. Channel capacity is equal to the maximum data rate for a channel. In theory [74], channel capacity and data rate are defined as the speed at which bits are transmitted over a communication channel in the network per second [74]. The data rate enables determining the speed at which data is transferred between the BS and the SU in megabits per second or bits per second [42].

The following subsections define the performance parameters according to how they are used in this study.

3.3.1 SPECTRAL EFFICIENCY (SE)

Authors define SE differently, depending on the target goals of their study. For this study, SE is defined as the rate of information that can be transferred from a BS to SUs in the network over a given bandwidth [59]. SE usually is expressed in the format “bits per second per hertz”, abbreviated as bits/s/Hz. The primary aim of deploying CRNs is to attain a more efficient use of available spectrum bands. When designing efficient DSA schemes, maximising the SE is vital [23], [26], [31].

3.3.2 DATA RATE

Authors also define data rate differently depending on the target goals of their study. For this study, data rate is defined as the speed at which data is transferred between the BS and the SU and is measured in bits per second, abbreviated as bits/s [42]. Data rate is a common criterion that is used in traditional wireless networks and CRNs to maximise channel allocation in the DSA schemes [31], [35], [60].

3.3.3 COMMON ASSUMPTIONS ON SPECTRAL EFFICIENCY (SE) AND DATA RATE

The performance parameters reviewed in section 2.8 focus on providing users with sufficient access to wireless broadband networks. As such, the common assumptions of this study towards maximising SE and data rate are:
1. the usage of single radio devices, thus no channel aggregation;
2. channels should be fixed and SUs should have the ability to select which channel to use;
3. the users must share the maximum allowed transmit power and not be greedy to other users;
4. a fixed modulation scheme;
5. no physical mobility of secondary user nodes.

3.4 SELECTION OF DSA SCHEMES FOR COMPARISON

This section explains the selection procedure of the DSA schemes to be modelled for this study. Table 2.1 in Section 2.9 summarises the DSA schemes in Section 2.7 with their performance parameters. Section 2.7 briefly outlined the DSA schemes that will be reviewed for this study, which focuses on providing wireless broadband access network to users.

Three schemes were selected to model in this study, based on the following characteristics:

1. The scheme should have at least data rate or SE as its designed performance parameters. SE in wireless broadband access will enable the measurement of the information rate between a BS and SUs in the network over a given bandwidth [59]. Data rates in wireless broadband access will enable measurement of the speed at which data is transferred between a BS and SUs in the network over a given bandwidth [42].

2. The scheme should at least include Additive White Gaussian Noise (AWGN) as a parameter in the mathematical model. In this study, noise is measured to ensure that the noise transmission is regulated, since too much noise during transmission interferes with packet transmission, which limits the availability of broadband network to users.

3. The scheme should model power; since the ability to measure the total transmit power could reduce power consumption during transmission, resulting in flexible energy efficient wireless broadband networks for users [45].
4. The scheme should have randomly distributed users, as this gives SUs flexibility of choice for use during transmission. According to [8], schemes perform better under the assumption of randomly distributed users.

5. The scheme uses downlink transmission because the 3GPP Long Term Evolution (LTE) uses downlink access for the wireless broadband network, which is why this study’s focus is on schemes providing the same wireless network [46].

Table 3.1 presents a summary of the selection characteristics, together with the schemes that were reviewed in Chapter 2. The rows in grey represent the schemes, which meet all the characteristics defined for a scheme to be selected for modelling in this study.

Table 3.1 shows that only three schemes (grey rows) meet the characteristic requirements defined for the selection of schemes to model in this study. The three schemes to be modelled for this study are:

1. (Scheme One) energy SE trade-off in downlink OFDMA network [45];

2. (Scheme Two) distributed channel assignment in CRNs [26] and

3. (Scheme Three) a proposed approach based on GFDM for maximising throughput in underlay CRN [52].

Table 3.1: DSA schemes versus the characteristics for selection of schemes for modelling in this study

<table>
<thead>
<tr>
<th>DSA schemes</th>
<th>Downlink transmission</th>
<th>AWGN</th>
<th>Randomly assigned</th>
<th>Power</th>
<th>Data rate</th>
<th>SE</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSGA-II</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>[44]</td>
</tr>
<tr>
<td>QAWSA</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>[46]</td>
</tr>
<tr>
<td>Game theory</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>[50]</td>
</tr>
<tr>
<td>Proposed approach based on GFDM for</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>[52]</td>
</tr>
<tr>
<td>Function</td>
<td>Rule-based allocation scheme</td>
<td>AS-MAC</td>
<td>DOSS</td>
<td>Increase in capacity of multiuser OFDM system using dynamic sub channel allocation</td>
<td>Distributed channel assignment in CRN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>------------------------------</td>
<td>---------------------------------</td>
<td>--------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>--------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IAWSA</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-hop cognitive wireless</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy SE trade-off in downlink OFDMA network</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rule-based allocation scheme</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS-MAC</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOSS</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase in capacity of multiuser OFDM system using dynamic sub channel allocation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed channel assignment in CRN</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following figure 3.1 is a Venn diagram that summarises the scheme selection characteristics together with the selected schemes and their performance parameters.
Figure 3.1: Venn diagram of the scheme selection characteristics with the selected schemes

Illustrated in Figure 3.1 are the common parameters for all the schemes, which are the downlink, AWGN, randomly assigned, and power parameters. These common parameters inform the scheme selection characteristics defined in this study, which include the performance parameters – either data rate or SE or both.

Scheme One and Scheme Two share SE as common performance parameter. Scheme One and Scheme Three share channel gain and path loss as common parameters. Scheme Two and Scheme Three have bit rate and data rate in common. These common parameter sets for each pair of schemes include the scheme selection characteristics. Consequently, the prerequisites for a scheme to be selected for modelling in this study are that (1) the scheme should include the performance parameters from Section 3.3, and (2) they should include the scheme selection characteristic that was defined.

The three selected schemes are discussed in detail, together with their mathematical models in the following sections.
3.4.1 (Scheme One) Energy Spectral Efficiency (SE) Trade-off in Downlink Orthogonal Frequency-Division Multiple Access (OFDMA) Network

In this scheme [45], an energy efficiency-SE trade-off (or EST) problem in downlink OFDMA single cell network was investigated. To solve this problem, the system model was made up of the BS and user equipment’s (UEs). However, there is only one transmit antenna and one receive antenna, with the radius of the circular cell being R.

Table 3.2: Mathematical model for Scheme One [45]

<table>
<thead>
<tr>
<th>Performance parameter</th>
<th>Mathematical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE (bits/sec/Hz)</td>
<td>( SE = \sum_{m=1}^{M} \log_2 (1 + \frac{p_m f_m \sqrt{G} \beta d_m^{-\alpha} s_m}{\delta_z^2}) )</td>
</tr>
</tbody>
</table>

M denotes the set of UEs, while \(|M|\) denotes the number of UEs. \(p_m\) represents the transmit power, \(\delta_z^2\) which denotes the complex additive white Gaussian noise power. \(f_m\) is the small-scale fading channel that contains a zero-mean circularly symmetric complex Gaussian random variable of variance \(\frac{1}{2}\). \(G\) stands for the product of the power gain for the transmit and the receive antenna. \(d_m\) is the distance between UE \(m\) and the BS. \(\alpha\) represents the path loss exponent, which determines how rapidly the signal attenuates with distance, while \(\beta\) is the path loss constant, which depends on the average channel attenuation and the antenna characteristics. \(s_m\) is a log-normal shadow fading variable, and \(10\log s_m\) is a zero-mean Gaussian random variable with a standard deviation \(\delta_{sh}\).

3.4.2 (Scheme Two) Distributed Channel Assignment in Cognitive Radio Networks (CRNs)

This scheme’s [26] target objective is to use M-QAM to maximise data rate and SE for the SUs. This scheme’s system model considered an ad-hoc CR network consisting of multiple clusters. In each cluster, the SU senses the available channels and share the channel information through CCCs. The channel condition for all SUs in a cluster is assumed the same. For a CR
node, the information on each available channel includes the interference level (interference plus noise) and bandwidth. Downlink transmission from BS to SU is considered. The SUs are considered as static.

The following table shows the scheme’s mathematical models.

Table 3.3: Mathematical models for Scheme Two [26]

<table>
<thead>
<tr>
<th>Performance parameter</th>
<th>Mathematical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE (bits/sec/Hz)</td>
<td>( SE = \sum_{j=1}^{L} \log_2 \left( 1 + \frac{1}{k_b} \frac{p_{t,j}}{I_k^{(j)} d^{\alpha(j)}} \right) \text{ where } k_b = -\frac{2}{3} \ln \frac{P_b}{2} )</td>
</tr>
<tr>
<td>Data rate (bps)</td>
<td>( DR = \sum_{j=1}^{L} W_k^{(j)} \log_2 \left( 1 + \frac{1}{k_b} \frac{p_{t,j}}{I_k^{(j)} d^{\alpha(j)}} \right) \text{ where } k_b = -\frac{2}{3} \ln \frac{P_b}{2} )</td>
</tr>
</tbody>
</table>

\( I_k \) is defined as the interference level, which is the statistical average value of interference plus noise in channel \( k \). SUs obtain \( I_k \) by monitoring channel \( k \). \( P_b \) is the bit error probability for an AWGN channel with MQAM modulation and is set to be constant for all SUs. \( P_{t,j} \) is the transmit power of the source node; \( I \) is the interference plus noise; \( d \) is the distance between the source node and its one-hop destination node, and \( \alpha \) is the decay rate (it is equal to 2 in free space). \( d^{-\alpha(j)} = C \) where \( C \) is the constant. \( W_k^{(j)} \) denotes the bandwidth level of channel \( k \) used by source-destination pair \( j \). \( N \) source CR nodes share \( K \) available channels in a cluster.

3.4.3 (SCHEME THREE) PROPOSED APPROACH BASED ON GENERALISED FREQUENCY DIVISION MULTIPLEXING (GFDM) TOWARD MAXIMISING THROUGHPUT IN UNDERLAY COGNITIVE RADIO NETWORK (CRN)

This scheme’s [52] objective is to maximise the total throughput or data rate for the SUs without affecting the QoS of the PUs under power and interference constraints in downlink underlay CRNs. Their system model has a BS and AP, where the BS serves the PUs; on the other hand, the AP serves the SUs, sharing the same spectrum of PUs. All users are randomly
distributed in the circuit area over a radius of 1 km. The information on the channel state is assumed perfect.

Table 3.4: Mathematical model for Scheme Three [52]

<table>
<thead>
<tr>
<th>Performance parameter</th>
<th>Mathematical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (bps)</td>
<td>[ dr = \max \sum_{n=1}^{N} \delta_n W_s \log_2 \left[ 1 + \frac{P_{i,n} h_{i,i}}{\Gamma \left( \sum_{M \neq i} P_{M,n} h_{i,M} + \rho_i P_p h_{p,i} + \epsilon N_0 W_s \right)} \right] ]</td>
</tr>
</tbody>
</table>

The bandwidth of the sub channels is \( W_s \). \( \delta_n \) is the sub channel activity, \( P_{i,n} \) refers to the optimum power transmitted for SU \( i \) through sub channel \( n \), \( h_{i,i} \) is the power gain of data channel of SU \( i \), \( \Gamma \) is a factor related to the bit error rate of QAM mapper. \( P_{M,n} \) is the optimum power transmitted by SU \( M \) over subchannel \( n \) and \( h_{i,M} \) is the channel power gain between SU \( i \) transmitter and other SU \( M \) receiver. \( \rho_i \) is the PU activity \( P_p \) is the power transmitted by PU and \( h_{p,i} \) is the channel power gain between the PU transmitter and SU receiver \( i \). \( \epsilon \) is a noise factor, \( N_0 \) is the noise power density of additive white Gaussian noise with zero mean and variance.

3.5 CHAPTER SUMMARY

This chapter illustrated in detail the research design and methodology for selection that this study will use to answer the research problem. Definitions were given of the selected performance parameters according to how they will be used in this study. Moreover, the characteristics for the selection of the schemes to be modelled were discussed, in addition to providing a brief explanation of the reasons for which schemes to be modelled. Chapter 4 serves as verification of the three schemes that were selected to model in this study.
CHAPTER 4
VERIFICATION

Verification affirms that a proposed solution is correctly implemented. Therefore, upon verifying the schemes selected in Chapter 3 through simulation, the scheme results should provide the expected results as published.

4.1 OVERVIEW

This chapter entails verifying the published results of the schemes selected in Chapter 3. The verification was done by simulating the schemes on the MATLAB simulation tool; thus affirming that the proposed published scheme results have correctly been implemented. Regenerating these results in this study offers a deeper understanding of scheme modelling, which is for the benefit of Chapter 5 since it will compare the performance of schemes with the performance parameters defined in Section 3.3. Comparison of the scheme performance is done with the MATLAB simulation tool.

The three schemes to be modelled for this study are namely: energy spectral efficiency trade-off in downlink OFDMA network (Scheme One) [45], distributed channel assignment in CRNs (Scheme Two) [26], and proposed approach based on GFDM for maximising throughput in underlay CRN (Scheme Three) [52].

4.2 VERIFICATION METHODOLOGY

Verifying the system model is a procedure that is as adopted from [75]; to verify the processes of ensuring that, the system models and the results of the schemes are correctly implemented. In [75], methodologies and techniques were developed for verifying and validating the implementation of simulation models.
The steps for the methodology verification are as follow:

1. **Practising good programming:** good practice of programming and modularity should be followed, as advised by the practice of software engineering.

2. **Simulation model outputs:** Intermediate outputs of the simulation model should be verified through tracing and/or statistical testing.

3. **Simulation outputs comparison:** Uses statistical tests to compare final simulation outputs with analytical results.

The authors of [75] advocate the use of statistical tests for verification. However, some argue that the statistical method is not required for verifying the correctness of the system model, should the model have only deterministic inputs [75]. For models that adhere to this criterion, their system model or output should be identical to the theoretically determined response, with the numerical inaccuracy expectations being determined through computation.

### 4.3 SYSTEM MODEL/RESULTS VERIFICATION

The process that was used to verify the published system model/results of the schemes is described in this section. Statistical testing for the three schemes is not important since a deterministic model is regarded. The steps for the verification procedures are described in the following subsections.

#### 4.3.1 GENERAL VERIFICATION METHODOLOGY

During the execution of the system model and generating the results of the simulation, overall rules of good programming practice were perceived as a reference to the first step of the verification methodology in Section 4.2 above. The mathematical models are presented in Table 4.1 below for the schemes selected in Section 3.4. The outputs of the schemes were compared with the theoretically determined results, respectively, as highlighted in the second step of the verification methodology in Section 4.2.
After the verification that all the schemes have been implemented appropriately, then the verification of the final output of the system model of published results is done. Once again, input parameters are chosen for the verification of the logical path flow of the system model. For correctness verification of the system model outputs, these outputs are compared with the theoretical analytical results, thus fulfilling the third step of the verification methodology. The steps for verification methodology in Section 4.2 were implemented for each of the three selected schemes.

Table 4.1: Mathematical models of the selected schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Performance metric</th>
<th>Mathematical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme One [45]</td>
<td>Spectral efficiency (bits/sec/Hz)</td>
<td>( SE = \sum_{m=1}^{M} \log_2 (1 + \frac{p_m f_m \sqrt{G^* B^* d_m^{-\alpha} s_m}}{\delta_z^2}) )</td>
</tr>
<tr>
<td>Scheme Two [26]</td>
<td>Data rate (bps)</td>
<td>( DR = \sum_{j=1}^{L_j} W_k^{(j)} \log_2 (1 + \frac{1}{k_b \frac{P_{t,(j)}}{k} d^{(j)})} \text{ where } k_b = -\frac{2}{3} \ln \frac{p_b}{2} )</td>
</tr>
<tr>
<td>Scheme Three [52]</td>
<td>Data rate (bps)</td>
<td>( dr = \max \sum_{n=1}^{N} \delta_n W_s \log_2 [1 + \frac{P_{i,n} h_{i,i}}{\Gamma (\sum_{M\neq i} P_{M,n} h_{i,M} + \rho_i P h_{P,i} + \xi N_0 W_s)]} )</td>
</tr>
</tbody>
</table>

The definitions of the parameters used for the mathematical models shown in Table 4.1 above are defined in Table 4.2 below. Furthermore, the parameter definitions in the table are inclusive of their original paired parameter values as depicted in the schemes.

Table 4.2: Original parameter definitions and their values for the selected schemes

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Parameter symbol</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme One [45]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of UE</td>
<td>( m )</td>
<td>10</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>( p_m )</td>
<td>20(dBm)</td>
</tr>
<tr>
<td>Complex additive white Gaussian noise power</td>
<td>( \delta_z^2 )</td>
<td>-100 dBm</td>
</tr>
<tr>
<td>Small scale fading channel</td>
<td>( f_m )</td>
<td>0,5</td>
</tr>
<tr>
<td>Power gain</td>
<td>$G$</td>
<td>$8 , dB$</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Distance between UE $m$ and the BS</td>
<td>$d_m$</td>
<td>$1000 , meters$</td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>$\alpha$</td>
<td>$3.76$</td>
</tr>
<tr>
<td>Path loss constant</td>
<td>$\beta$</td>
<td>$12.81$</td>
</tr>
<tr>
<td>Lognormal shadow fading variable</td>
<td>$s_m$</td>
<td>$6.31$</td>
</tr>
</tbody>
</table>

**Scheme Two [26]**

| CR source node | $i$ | $4$ |
| Source-destination pair (BS pair with CR node) | $j$ | $4$ |
| channel | $k$ | $4$ |
| bit error probability (given as constant value) | $P_b$ | $10^{-6}$ |
| Transmit Power | $P_{t,i}^{(j)}$ | $10 \, to \, 30 \, (dBm)$ |
| Interference level | $I_{k}^{(j)}$ | $-120 \, to \, -40 \, (dBm)$ |
| Power decay factor (given as constant value) | $d_{\alpha(i)}$ | $10^{-6}$ |
| Bandwidth | $W_{k}^{(j)}$ | $32 \, to \, 256 \, (kHz)$ |

**Scheme Three [52]**

| Sub channel activity | $\delta_n$ | $10^7$ |
| Subcarrier distance | $W_s$ | $0.3 \, (MH_{z})$ |
| Power transmitted for SU | $P_{i,n}$ | $20 \, to \, 30 \, dBm$ |
| Channel power gain between SU $i$ transmitter and other SU $M$ receiver | $h_{i,M}$ | $1$ |
| Power transmitted by PU | $P_p$ | $30 \, dBm$ |
| Channel power gain between PU transmitter and SU receiver | $h_{p,i}$ | $35 \, dBm$ |
| Noise factor | $\varepsilon$ | $0.1$ |
| Noise power density of AWGN | $N_0$ | $0.1$ |
The following section verifies the scheme selection by duplicating the original results from the schemes to offer an understanding of how these schemes were implemented for the benefit of the scheme performance comparison in Chapter 5. Also, a simulation environment was prepared for scheme comparison by duplicating the original results.

4.4 Verification results for scheme one: Energy Spectral efficiency (SE) trade-off in downlink orthogonal frequency-division multiple access (OFDMA) network

This section presents the regenerated results of the algorithm on the energy SE trade-off in downlink OFDMA network [45]. The results that were regenerated using the simulation tool are illustrated and further compared with the original results of the algorithm. The parameters used in this study’s simulation reflect the original paper and can be seen in Table 4.2 above. The following two graphs and the table below show the original results and the regenerated results from this study, respectively.

Table 4.3: Spectral efficiency (bits/sec/hertz) for the original and regenerated values

<table>
<thead>
<tr>
<th>Power(dBm)</th>
<th>Original spectral efficiency (bits/sec/hertz)</th>
<th>Regenerated spectral efficiency (bits/sec/hertz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>6</td>
<td>49.5</td>
<td>50.2</td>
</tr>
<tr>
<td>8</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>10</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>12</td>
<td>61</td>
<td>61</td>
</tr>
<tr>
<td>14</td>
<td>65</td>
<td>65.8</td>
</tr>
<tr>
<td>16</td>
<td>70.2</td>
<td>70.3</td>
</tr>
<tr>
<td>18</td>
<td>75.2</td>
<td>75.3</td>
</tr>
<tr>
<td>20</td>
<td>79.9</td>
<td>79.9</td>
</tr>
</tbody>
</table>
Figure 4.1: SE (bits/sec/Hz) (a) the graph on the left reflects the original results and (b) on the right is the regenerated results for Scheme Two

The first graph in Figure 4.1 (a) on the left illustrates the original results, and (b) the graph on the right contains the regenerated values from this study. Both graphs show a power increase that is met with an increase in SE per channel in bits per second per hertz. The original SE of SE-max from the graph (a) is compared with the verified graph (b) of SE-max on the right. The power in dBm ranges from 0 to 20 dBm, as seen in the graph of Figure 4.1 and from Table 4.4, and as the power in dBm increases, more bits are transmitted per second (SE).
4.5 VERIFICATION RESULTS FOR SCHEME TWO: DISTRIBUTED CHANNEL ASSIGNMENT IN COGNITIVE RADIO NETWORKS (CRNs)

This section verifies the results by regenerating the results of the algorithm on distributed channel assignment in CRNs [26]. The parameters used and values used in the regeneration of the results are the same as in the original results and are shown in Table 4.2.

The following table and graphs show the original values and regenerated values from the simulation tool. The graph in Figure 4.2 reveals that the original and regenerated values are similar.

Table 4.4: Original data rate (bps) versus regenerated data rate of channels

<table>
<thead>
<tr>
<th>Power (dBm)</th>
<th>Channel One</th>
<th>Channel Two</th>
<th>Channel Three</th>
<th>Channel Four</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original data rate values (bps)</td>
<td>Regenerate data rate values (bps)</td>
<td>Original data rate values (bps)</td>
<td>Regenerate data rate values (bps)</td>
</tr>
<tr>
<td>30</td>
<td>$1.2 \times 10^5$</td>
<td>$1.2 \times 10^5$</td>
<td>$3.3 \times 10^5$</td>
<td>$3.3 \times 10^5$</td>
</tr>
<tr>
<td>25</td>
<td>$0.5 \times 10^5$</td>
<td>$0.55 \times 10^5$</td>
<td>$1.55 \times 10^5$</td>
<td>$1.6 \times 10^5$</td>
</tr>
<tr>
<td>20</td>
<td>$0.25 \times 10^5$</td>
<td>$0.3 \times 10^5$</td>
<td>$0.6 \times 10^5$</td>
<td>$0.65 \times 10^5$</td>
</tr>
<tr>
<td>15</td>
<td>$0.1 \times 10^5$</td>
<td>$0.1 \times 10^5$</td>
<td>$0.3 \times 10^5$</td>
<td>$0.3 \times 10^5$</td>
</tr>
<tr>
<td>10</td>
<td>$0.2 \times 10^5$</td>
<td>$0.2 \times 10^5$</td>
<td>$0.1 \times 10^5$</td>
<td>$0.1 \times 10^5$</td>
</tr>
</tbody>
</table>
Figure 4.2: Data rate (bps) varies with transmit power (dBm) (a) left is the original results, and (b) right are the regenerated results in this study

The first graph (a) on the left of Figure 4.2 is the original results, and the second graph (b) on the right is the regenerated results from this study. Both graphs show that the power increases as the data rate from each channel increases in bits per seconds. The power ranges from 10 dBm to 30 dBm. As such, the availability of more power causes an increase in data rate; thus, more bits are transmitted with more power.
4.6 Verification Results for Scheme Three: Proposed Approach Based on Generalised Frequency Division Multiplexing (GFDM) for Maximising Throughput in Underlay Cognitive Radio Network (CRN)

This section provides the regenerated results of the scheme on the proposed approach, based on GFDM for maximising throughput in underlay CRN [52]. The results that were regenerated are presented using the simulation tool and compared with the original results of the algorithm. The parameters used in this simulation reflect the values in the original paper and are shown in Table 4.2.

The following two graphs and the table show the original results and the regenerated results from this study.

Table 4.5: Data rate (bps) for the original and regenerated values for Scheme Three

<table>
<thead>
<tr>
<th>Power (dB)</th>
<th>Original data rate (bps)</th>
<th>Regenerated data rate (bps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−20</td>
<td>0.1 × 10^6</td>
<td>0.1 × 10^6</td>
</tr>
<tr>
<td>−15</td>
<td>1 × 10^6</td>
<td>1 × 10^6</td>
</tr>
<tr>
<td>−10</td>
<td>2.3 × 10^6</td>
<td>2.3 × 10^6</td>
</tr>
<tr>
<td>−5</td>
<td>5 × 10^6</td>
<td>5 × 10^6</td>
</tr>
<tr>
<td>0</td>
<td>8.3 × 10^6</td>
<td>8.3 × 10^6</td>
</tr>
<tr>
<td>5</td>
<td>11.5 × 10^6</td>
<td>11.5 × 10^6</td>
</tr>
<tr>
<td>10</td>
<td>12 × 10^6</td>
<td>12 × 10^6</td>
</tr>
<tr>
<td>15</td>
<td>12.5 × 10^6</td>
<td>12.5 × 10^6</td>
</tr>
<tr>
<td>20</td>
<td>12.8 × 10^6</td>
<td>12.8 × 10^6</td>
</tr>
<tr>
<td>30</td>
<td>12.9 × 10^6</td>
<td>12.9 × 10^6</td>
</tr>
</tbody>
</table>
Figure 4.3: Data rate (bps) for (a) on the left is OFDM-PS for the original results (b) on the right is the regenerated results for Scheme Three

The first graph (a) on the left represents the original results noted OFDM-PS, and the second graph (b) on the right contained the regenerated values from this study. The original graph’s comparison is the first graph in the red dotted graph, denoted OFDM-PS. Both graphs illustrate that the power increases with an increase in the data rate in bits per seconds.

4.7 VERIFICATION ANALYSIS METRICS

Table 4.6 shows the order of statistics metrics for evaluating if the results have been verified correctly. The results of the metrics considered are shown in Table 4.7. The results show that the predicted values and reference values of the mean absolute error and median absolute error are similar.
Table 4.6: Verification metrics equations

<table>
<thead>
<tr>
<th>Equation name</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute error</td>
<td>$\epsilon_i =</td>
</tr>
<tr>
<td></td>
<td>$x_i$ is the predicted value, $x_j$ is the corresponding reference value, $n$ is the number of samples</td>
</tr>
<tr>
<td>Maximum error</td>
<td>$\epsilon_{max} = \max{\epsilon_i}$, $i = 1, ..., n$</td>
</tr>
<tr>
<td>Mean absolute error $\epsilon_{mae}$</td>
<td>$\epsilon_{mae} = \frac{1}{n}\sum_{i=1}^{n}</td>
</tr>
<tr>
<td></td>
<td>$x_i$ is the predicted value, $x_j$ is the corresponding reference value, $n$ is the number of samples</td>
</tr>
<tr>
<td>Pearson’s correlation coefficient $r_e$</td>
<td>$r_e = \frac{\sum_{i=1}^{n}(x_i - \bar{x}_i)(x_j - \bar{x}<em>j)}{\sqrt{\sum</em>{i=1}^{n}(x_i - \bar{x}<em>i)^2}\sqrt{\sum</em>{j=1}^{n}(x_j - \bar{x}_j)^2}}$</td>
</tr>
<tr>
<td></td>
<td>$x_i$ is the predicted value, $x_j$ is the corresponding reference value, $\bar{x}_i$ is the predicted mean value, $\bar{x}_j$ is the reference value mean and $n$ is the number of samples</td>
</tr>
</tbody>
</table>

There are no causes of large error that can be attributed to the results and verified results. The differences of standard deviation attributes its implementation, as shown in Table 4.7. Pearson’s correlation $r$ shows a resilient progressive linear relationship, which is statistically substantial meaning ($p < 0.05$). Coefficient of determination $r^2$ shows a good linear fit between the original results and the regenerated results. Therefore, the schemes are concluded to have been verified and the implementation was done correctly.
Table 4.7: Statistical parameters for the absolute error

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>5,338</td>
</tr>
<tr>
<td>Median $\epsilon$</td>
<td>0,678</td>
</tr>
<tr>
<td>$r$</td>
<td>0,9997</td>
</tr>
<tr>
<td>P-value</td>
<td>$&lt; 0,05$</td>
</tr>
<tr>
<td>$r^2$</td>
<td>0,9994</td>
</tr>
</tbody>
</table>

4.8 **CHAPTER SUMMARY**

This chapter’s main purpose was to verify the implementation of the schemes. Verification is the process of checking whether the schemes have been implemented correctly. This is important to know before implementing those schemes in an independent study such as this. In this chapter, verification methodologies were shown and the process for verification was briefly outlined. In addition, the results of the selected schemes were regenerated using the MATLAB simulation tool to gain a deeper understanding of the process to model these schemes for the benefit of the next chapter, which will compare the performance of these schemes against the selected performance parameters, namely data rate and SE.
CHAPTER 5
COMPARISON OF SELECTED DSA SCHEMES

The focus of this chapter is to compare the performance of the three schemes selected in Chapter 3 with the selected performance parameters: data rate and SE as shown in Section 3.3.

5.1 CHAPTER OVERVIEW

This chapter compares the performance of the three schemes and measures the data rate and SE used by these schemes during transmission. After measuring the data rate and SE of the three schemes, the three schemes were compared on the same set of axes to determine which scheme performs better. For simplicity in determining the schemes’ performance and for ease of comparison, two comparison scenarios are defined in this chapter for comparing the performance of the three schemes, and these scenarios are defined in Section 5.4.

The three schemes are described below:

1. Scheme One is the algorithm on energy spectral efficiency trade-off in downlink OFDMA networks [45];
2. Scheme Two is the algorithm on distributed channel assignment in CRNs [26]; and
3. Scheme Three is the algorithm on the proposed approach based on GFDM for maximising throughput in underlay CRN [52].

The following section describes the system model that was used to compare the performance of the schemes on the same set of axes.

5.2 SYSTEM MODEL

This section defines the system model used to compare the three schemes’ performance. The system is defined such that all three schemes could be modelled on the same set of axes. Additionally, the designed system model is defined according to a brief study of the three
schemes system models. As such, the system is also able to model all performance parameters using the same scenarios and parameter values.

The system model should provide users with wireless broadband access networks since this is also the goal of this study. Consequently, the system model should have the following functions:

1. The system model should use downlink transmission because the 3GPP LTE uses downlink access for a wireless broadband network. Therefore, this study focuses on schemes providing the same wireless network [46].

2. The system model should have randomly distributed users, as this gives SUs the flexibility of usage choice during transmission. According to [8], schemes perform better under the assumption of random distribution of users.

3. The system model should model power since the ability to measure the total transmit power can reduce power consumption during transmission, which offers users flexible energy efficient wireless broadband networks [45]. Also, modelling low power can reduce cost since it requires less energy during the transmission.

4. The system model should model Additive White Gaussian Noise (AWGN) as a parameter in the mathematical model. Measuring noise in this study ensures that the noise transmission is regulated because too much noise during transmission interferes with packets transmission, which affects the availability of broadband network to users.

5. In addition, this system model will consider CRN with a single cell network as shown in Figure 5.1, with one base station (BS), a set of SUs, and radius R. A centralised DSA spectrum approach is the reason for considering one BS and different SUs (SUs have non-overlapping channels) [14]. The advantage of centralised spectrum access schemes is that they provide a global view of the spectrum broker’s network, making it simpler to maximise the whole throughput of the network and minimise the interference amid the SUs, thus preserving network performance.
6. The system model should model the two selected performance parameters that this study has selected namely, data rate and SE. SE and data rate are important for wireless broadband access because: (1) SE measures the information rate that is transferred from a BS to SUs in the network over a given bandwidth [59], and (2) consequently, data rate measures the speed at which data is transferred from the base station (BS) to the SU [42]. Then areas of improvement can be identified to eventually produce enough wireless broadband transmission over time.

Figure 5.1: System model defined for this study

5.3 COMPARISON OF THE SCHEMES

This section compares the performance of the three schemes. Two comparison scenarios were defined for a simpler interpretation of the scheme performances. The first comparison scenario was based on a comparison of SE and data rate with the power consumption by SUs during transmission. The second set of comparisons is based on a comparison of SE and data rate with the bandwidth used during transmission.
Table 5.1 outlines the original mathematical models of the schemes together with the variable names reflecting how they have been used in this study. This outline is essential for defining similar parameters for all schemes for compatibility in comparing all three in the same set of axes.

The following notation was used to refer to the three schemes in the graphs:

1. **Scheme One** is the algorithm on energy spectral efficiency trade-off in downlink OFDMA network [45]

2. **Scheme Two** is the algorithm for distributed channel assignment in CNRs [26]

3. **Scheme Three** is the algorithm on the proposed approach based on GFDM for maximising throughput in underlay CRN [52]

Table 5.1: Mathematical models for the schemes

<table>
<thead>
<tr>
<th>Scheme and performance metric</th>
<th>Original mathematical model</th>
<th>Mathematical model with variables defined in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme One [45] SE (bits/sec/Hz)</td>
<td>$SE = \sum_{m=1}^{M} \log_2(1 + \frac{P_m f_m \sqrt{G} \beta d_m - \alpha s_m}{\delta^2})$</td>
<td>$SE = \sum_{m=1}^{M} \log_2(1 + \frac{P_m f_m \sqrt{G} \beta d_m - \alpha s_m}{N_0})$</td>
</tr>
<tr>
<td>Scheme Two [26] DR (bps)</td>
<td>$DR = \sum_{k=1}^{L} W_k \log_2(1 + \frac{P_{tk}^{(i)} I_k^{(i)} d_w^{(i)}}{k_b})$ where $k_b = -\frac{2}{3} \ln\frac{P_b}{2}$</td>
<td>$DR = \sum_{m=1}^{M} W_m \log_2(1 + \frac{P_{tm}^{(m)} I_k^{(m)} d_w^{(m)}}{k_b})$ where $k_b = -\frac{2}{3} \ln\frac{P_b}{2}$</td>
</tr>
<tr>
<td>Scheme Three [52] DR (bps)</td>
<td>$dr = \max_{n=1}^{N} \sum_{i=1}^{M} \delta_n \log_2(1 + \frac{P_{ti,j} h_{i,j}}{\Gamma(\sum_{k \neq i} P_{k,j} h_{k,j} + \rho_i P_{p} + EN_0 W_s)})$</td>
<td>$dr = \max_{m=1}^{M} \sum_{i=1}^{N} \delta_m \log_2(1 + \frac{P_{ti,m} h_{i,j}}{\Gamma(\sum_{k \neq i} P_{k,m} h_{k,j} + \rho_i P_{p} + EN_0 W_s)})$</td>
</tr>
</tbody>
</table>

Table 5.2 illustrates all three schemes’ original parameters with their mathematical notation, parameter names and mathematical models used in this study for comparison.

From Table 5.2, the notation “N/A” means not applicable to that scheme or that parameter is not mentioned in that scheme.
Table 5.2: Simulation parameters for comparing the three schemes

<table>
<thead>
<tr>
<th>PARAMETER (Scheme One, Two, Three)</th>
<th>Parameter name in Scheme One [45]</th>
<th>Parameter name in Scheme Two [26]</th>
<th>Parameter name in Scheme Three [52]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node mobility</td>
<td>Stationary</td>
<td>Stationary</td>
<td>Stationary</td>
</tr>
<tr>
<td>Secondary users m</td>
<td>User equipment m</td>
<td>CR source node, i</td>
<td>Secondary user number n</td>
</tr>
<tr>
<td>Distance, (d_m)</td>
<td>Distance d_m</td>
<td>Distance d</td>
<td>N/A</td>
</tr>
<tr>
<td>Transmit power (p_m, P_{t,i}^{(m)}, P_{t,m})</td>
<td>Transmit power p_m</td>
<td>Transmit power P_{t,i}^{(j)}</td>
<td>Power transmitted for SU P_{t,n}</td>
</tr>
<tr>
<td>Bandwidth (W_k, W_s)</td>
<td>N/A</td>
<td>Bandwidth W_k^{(j)}</td>
<td>Subcarrier bandwidth W_s</td>
</tr>
<tr>
<td>Additive white Gaussian noise power, constant N_0</td>
<td>Additive white Gaussian noise power, δ^2</td>
<td>N/A</td>
<td>Noise power density of AWGN, N_0</td>
</tr>
<tr>
<td>Power gain, G, constant, h_{i,M}</td>
<td>Power gain, G</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Path loss exponent, constant α</td>
<td>Path loss exponent α</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Path loss constant β</td>
<td>Path loss constant β</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Interference level I_k^{(m)}</td>
<td>N/A</td>
<td>Interference level I_k^{(j)}</td>
<td>N/A</td>
</tr>
<tr>
<td>Bit error probability (constant) P_b</td>
<td>N/A</td>
<td>bit error probability P_b</td>
<td>N/A</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>Small-scale fading channel</td>
<td>$f_m$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Log-normal shadow fading variable constant</td>
<td>$s_m$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Power decay factor (given as constant value)</td>
<td>$d^\alpha$, $d^{\alpha(m)}$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sub channel activity</td>
<td>$\delta_m$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Power transmitted by PU</td>
<td>$P_p$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 5.3 shows the parameter values for all three schemes followed by the parameter values defined in this study (highlighted in grey in the table) for use in the scheme performance comparison. The selected parameters of this study are defined to include the ability to be modelled with the system model defined in Section 5.2. Table 5.3 illustrated how the parameter values were defined that were used in the simulations to compare the performance of the three schemes.
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Parameter value defined in this study</th>
<th>Parameter value in Scheme One [45]</th>
<th>Parameter value in Scheme Two [26]</th>
<th>Parameter value in Scheme Three [52]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node mobility</td>
<td>Stationary</td>
<td>Stationary</td>
<td>Stationary</td>
<td>Stationary</td>
</tr>
<tr>
<td>Simulation runs</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Secondary users $m$</td>
<td>10</td>
<td>10</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Distance $d_m$</td>
<td>$(0 \times 1000) \text{ m}$</td>
<td>1000 meters</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Power (PUs) $P_m$</td>
<td>$-25 \text{ to } 30 \text{ (dBm)}$</td>
<td>$-25 \text{ to } 30 \text{ (dBm)}$</td>
<td>$-25 \text{ to } 30 \text{ (dBm)}$</td>
<td>$-25 \text{ to } 30 \text{ (dBm)}$</td>
</tr>
<tr>
<td>Power (SUs) $P_m$</td>
<td>$-30 \text{ to } 30 \text{ (dBm)}$</td>
<td>$20 \text{ (dBm)}$</td>
<td>$10 \text{ to } 30 \text{ (dBm)}$</td>
<td>$20 \text{ to } 30 \text{ (dBm)}$</td>
</tr>
<tr>
<td>Bandwidth $W_m$</td>
<td>32 to 160 (kHz)</td>
<td>N/A</td>
<td>32 to 256 (kHz)</td>
<td>0.3 (MHz)</td>
</tr>
<tr>
<td>Additive white Gaussian noise power, constant $N_0$</td>
<td>0,1</td>
<td>$-100 \text{ dBm}$</td>
<td>N/A</td>
<td>0,1</td>
</tr>
<tr>
<td>Power gain, constant (for both SUs &amp; PUs), $G$</td>
<td>1</td>
<td>8 dB</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>Path loss exponent, constant $\alpha$</td>
<td>3.76</td>
<td>3.76</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Path loss constant</td>
<td>12.81</td>
<td>12.81</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Interference level $I_m$</td>
<td>$(-120 \text{ to } -40) \text{ dBm}$</td>
<td>N/A</td>
<td>$(-120 \text{ to } -40) \text{ (dBm)}$</td>
</tr>
<tr>
<td>-----</td>
<td>----------------------</td>
<td>-------------------------------------</td>
<td>-----</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Bit error probability, constant $P_b$</td>
<td>$10^{-6}$</td>
<td>N/A</td>
<td>$10^{-6}$</td>
<td>N/A</td>
</tr>
<tr>
<td>Small scale fading channel $f_m$</td>
<td>1</td>
<td>0,5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lognormal shadow fading variable, constant $s_m$</td>
<td>1</td>
<td>6.31</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sub channel activity, $\delta_m$</td>
<td>$10^7$</td>
<td>N/A</td>
<td>N/A</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

Table 5.3 reveals that Scheme One models small scale fading channels and log normal fading. From the mathematical model of Scheme One in Section 3.4.1, setting small scale fading and log normal fading to a factor of 1 means that there will be no fading during transmission, as shown on Scheme Two’s mathematical model [45]. This is because fading is set to a Gaussian random variable in Scheme One’s mathematical model [45], thus setting it to a constant. This means that there will be no variation during transmission since fading is the environmental influence during transmission. This implies that if Scheme One does not have a fading factor, it becomes comparable to the other schemes [26] [52] that do not have fading factors. For Scheme Three, the power transmission ranges from -25 to 30 dBm, since the PU should transmit with more power that SU to limit interference, hence the reason on why PU starts at -25 dBm power transmission. The power gain for the PU is set to a constant of one.
The base station and PU coordinates are allocated as follows; where the BS is centered to a fixed position of zero with a radius of 1000 meters. The PUs are randomly distributed inside the circle, but they are stationary, there is no node mobility.

A scheme having SE as a performance parameter as shown from the mathematical model of Scheme Two in [26] and Section 3.4.2 can be extended to model data rate by adding a bandwidth factor on its mathematical model, as done for Scheme Two [26]. As such, the aforementioned technique will be adopted for the scheme’s mathematical model in this study, as done in Scheme Two [26].

The following section defines the two comparison scenarios that were used in comparing the three schemes’ performances with data rate and SE performance parameters. The first scenario compares SE and data rate against power ranging from -30 dBm to 30 dBm. The second scenario compares SE and data rate against bandwidth ranging from 32 kHz to 160 kHz.

It is important to note that in Section 4.4, during the verification of Scheme One, this scheme had four transmitting channels. However, for a fair comparison of this scheme with the other two schemes, transmission will be done using one channel because the other schemes also transmit using one channel, resulting in the same transmission parameters for comparison.

5.4 COMPARISON SCENARIO ONE

This section presents the results for the first comparison scenario. This first scenario is defined by evaluating the performance of data rate and SE when the power ranges between -30 dBm to 30 dBm.

5.4.1 DATA RATE VERSUS POWER SCENARIO ONE

This section evaluates the performance of the three scheme’s data rate (bps) against power (dBm). From Table 5.3 and Figure 5.2 it is worth noticing that higher power (dBm) availability executes higher data rate (bps) for all three schemes.
Scheme One performs better than the other two schemes because it includes modelling data rate that is energy efficient [45]. This means that this scheme saves energy while transmitting at a higher data rate, resulting in more bits per second being transmitted for this scheme than the other two schemes.

Scheme Two transmits more data rate than Scheme Three, although when the power is above 25 dBm, Scheme Three transmits more data rate than Scheme Two. Scheme Two performs better than Scheme Three because it models a uniform constant interference level during its transmission. This means that catering for the presence of interference and setting the constant interference level parameters during transmission limits the presence of high interference during this transmission leading to higher data rate transmission.

Table 5.4: Data rate (bps) comparison of schemes against power (dBm)

<table>
<thead>
<tr>
<th>Power (dBm)</th>
<th>Data rate (Scheme One) (bps)</th>
<th>Data rate (Scheme Two) (bps)</th>
<th>Data rate (Scheme Three) (bps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−30</td>
<td>$0.0058 \times 10^5$</td>
<td>$0.0 \times 10^5$</td>
<td>$0.0 \times 10^5$</td>
</tr>
<tr>
<td>−23</td>
<td>$0.0149 \times 10^5$</td>
<td>$0.0 \times 10^5$</td>
<td>$0.0 \times 10^5$</td>
</tr>
<tr>
<td>−17</td>
<td>$0.0190 \times 10^5$</td>
<td>$0.0001 \times 10^5$</td>
<td>$0.0001 \times 10^5$</td>
</tr>
<tr>
<td>−10</td>
<td>$0.0259 \times 10^5$</td>
<td>$0.0004 \times 10^5$</td>
<td>$0.0004 \times 10^5$</td>
</tr>
<tr>
<td>−3</td>
<td>$0.0355 \times 10^5$</td>
<td>$0.0019 \times 10^5$</td>
<td>$0.0013 \times 10^5$</td>
</tr>
<tr>
<td>3</td>
<td>$0.1031 \times 10^5$</td>
<td>$0.0088 \times 10^5$</td>
<td>$0.0052 \times 10^5$</td>
</tr>
<tr>
<td>10</td>
<td>$0.1556 \times 10^5$</td>
<td>$0.0399 \times 10^5$</td>
<td>$0.0205 \times 10^5$</td>
</tr>
<tr>
<td>17</td>
<td>$0.4169 \times 10^5$</td>
<td>$0.1657 \times 10^5$</td>
<td>$0.0834 \times 10^5$</td>
</tr>
<tr>
<td>23</td>
<td>$0.9135 \times 10^5$</td>
<td>$0.5388 \times 10^5$</td>
<td>$0.3439 \times 10^5$</td>
</tr>
<tr>
<td>30</td>
<td>$1.6234 \times 10^5$</td>
<td>$1.2119 \times 10^5$</td>
<td>$1.4331 \times 10^5$</td>
</tr>
</tbody>
</table>
Scheme Three transmission includes the presence of the PUs, which means that SUs transmit in the presence of PUs. This limits the number of bits per second transmitted for this scheme compared to the other two schemes because for SUs and PUs to transmit on one channel, SUs need to transmit using less power than PUs. A result is that this scheme’s SU transmits with less power, making it have a lower data rate compared to the other two schemes.

In summary, Table 5.4 and Figure 5.2 showed that when comparing the performance of the three schemes’ data rate (bps) against power (dBm), Scheme One performs better than Scheme Two and Scheme Three.

5.4.2 SPECTRAL EFFICIENCY (SE) VERSUS POWER SCENARIO ONE

This section will evaluate the performance of the three scheme’s SE (bits/s/Hz) against power (dBm). Table 5.5 and Figure 5.3 investigate the total data rate for all SUs with the maximum power level used during packet transmission from the SU to the BS of the three schemes. It can
be noted that when increasing the maximum power level of SUs during packet transmission, the total SE increases simultaneously.

Scheme One transmits higher data rate starting from the time when power is -30dBm, but when power reaches 30dBm, Scheme Three performs better compared to Scheme One and Two.

Scheme Two transmits more SE compared to Scheme Three, although when the power is above 25 dBm, then Scheme Three transmits more SE than Scheme Two. Scheme Two performs better than Scheme Three because it models a constant uniform interference level during its transmission. This means that catering for the presence of interference and setting the constant interference level parameters during transmission limits the presence of high interference during transmission, leading to higher SE transmission.

Table 5.5: SE (bits/sec/Hz) comparison of schemes against power (dBm)

<table>
<thead>
<tr>
<th>Power (dBm)</th>
<th>SE (bits/sec/Hz) (Scheme One)</th>
<th>SE (bits/sec/Hz) (Scheme Two)</th>
<th>SE (bits/sec/Hz) (Scheme Three)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−30</td>
<td>0.0145</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>−23</td>
<td>0.0372</td>
<td>0.0000</td>
<td>0.0001</td>
</tr>
<tr>
<td>−17</td>
<td>0.0475</td>
<td>0.0002</td>
<td>0.0003</td>
</tr>
<tr>
<td>−10</td>
<td>0.0649</td>
<td>0.0010</td>
<td>0.0012</td>
</tr>
<tr>
<td>−3</td>
<td>0.0889</td>
<td>0.0048</td>
<td>0.0045</td>
</tr>
<tr>
<td>3</td>
<td>0.2577</td>
<td>0.0221</td>
<td>0.0173</td>
</tr>
<tr>
<td>10</td>
<td>0.3891</td>
<td>0.0999</td>
<td>0.0685</td>
</tr>
<tr>
<td>17</td>
<td>1.0423</td>
<td>0.4143</td>
<td>0.2780</td>
</tr>
<tr>
<td>23</td>
<td>2.2836</td>
<td>1.3470</td>
<td>1.1464</td>
</tr>
<tr>
<td>30</td>
<td>4.0584</td>
<td>3.0297</td>
<td>4.7771</td>
</tr>
</tbody>
</table>
Scheme Three includes the presence of the PUs during transmission, which means SUs transmit in the presence of PUs. As explained in the previous section. This limits the number of bits per second per hertz transmitted for this scheme compared to the other two schemes, because for SUs and PUs to transmit in the same channel, SUs should transmit using less power than PUs. As a result, this scheme’s SU transmitting has less power, which gives it a lower data rate than the other two schemes. Scheme Three includes the presence of the PUs, which means SUs transmit in the presence of PUs. Thus, at 30 dBm, Scheme Three transmits with more bandwidth meaning; there were few or no PUs transmitting at that time.

In summary, Table 5.5 and Figure 5.3 showed that when comparing the performance of the three scheme’s SE (bits/sec/Hz) against power (dBm), Scheme One performs better than Scheme Two and Scheme Three.
5.5 COMPARISON SCENARIO TWO

The second scenario is defined by evaluating the performance of data rate and SE when the bandwidth ranges between 32 kHz to 160 kHz.

5.5.1 DATA RATE VERSUS BANDWIDTH SCENARIO TWO

This section evaluates the performance of the three schemes’ data rate (bps) against bandwidth ranging from 32 kHz to 160 kHz. From Table 5.6 and Figure 5.4, it can be noticed that higher bandwidth (kHz) availability executes higher data rate (bps) for all three schemes.

Scheme One transmits a high data rate at a bandwidth of 32 kHz to 146 kHz as compared with other schemes. As the bandwidth level increases beyond 146 kHz, Scheme Three transmits at a higher data rate than other schemes. However, when transmitting with a bandwidth of 103 kHz to 146 kHz, Scheme Two transmits more bits per second than Scheme Three. In summary, Scheme One transmits a higher data rate between the base station (BS) and the SU, measured in bits per second.

Scheme Two transmits more data rate than Scheme Three because it models a uniform constant interference level during its transmission. This means that catering for the presence of interference and setting the constant interference level parameters during transmission limits the presence of high interference during this transmission, thereby leading to higher data rate transmission.

Table 5.6: Data rate (bps) comparison for Scenario Two

<table>
<thead>
<tr>
<th>Bandwidth (kHz)</th>
<th>Data rate for Scheme One (bps)</th>
<th>Data rate for Scheme Two (bps)</th>
<th>Data rate for Scheme Three (bps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>$0.0047 \times 10^5$</td>
<td>$0.0 \times 10^5$</td>
<td>$0.0 \times 10^5$</td>
</tr>
<tr>
<td>46</td>
<td>$0.0172 \times 10^5$</td>
<td>$0.0 \times 10^5$</td>
<td>$0.0001 \times 10^5$</td>
</tr>
<tr>
<td>60</td>
<td>$0.0287 \times 10^5$</td>
<td>$0.0001 \times 10^5$</td>
<td>$0.0002 \times 10^5$</td>
</tr>
</tbody>
</table>
During transmission, Scheme Three includes the presence of the PUs, which means SUs transmit in the presence of PUs. This limits the amounts of bits per second transmitted for this scheme compared to the other two schemes, because for SUs and PUs to transmit on one channel, SUs should transmit using less power than PUs. This resulted in this scheme’s SU transmitting with less bandwidth, which makes it have a lower data rate than the other two schemes.
In summary, Table 5.6 and Figure 5.4 has illustrated that when comparing the performance of the three schemes’ data rate (bps) with bandwidth (kHz), Scheme One and Scheme Three perform better than Scheme Two when the bandwidth is over 150 kHz.

5.5.2 SPECTRAL EFFICIENCY (SE) VERSUS BANDWIDTH FOR SCENARIO TWO

This section evaluates the performance of the three schemes’ SE (bits/s/Hz) against bandwidths ranging from 32 kHz to 160 kHz. Table 5.7 and Figure 5.5 show the SE comparison results of the three schemes with the bandwidths in kHz. The results show an increased bandwidth during transmission, which results in a total increase in SE for all SUs in bits per second per hertz. However, more bits per second per hertz appear to be transmitted in all schemes were the bandwidth ranges from 100 kHz to 160 kHz.

Scheme One performs better than the other schemes and transmits more bits per second as the bandwidth increases. This is because it includes modelling data rate that is energy efficient [45]. Scheme One performed better than the other two schemes, due to the inclusion of a SE model that renders it more energy efficient [45]. This means that this scheme transmits more data for the energy consumed, with the result that utilisation of the spectrum opportunity transmits more bits per second per hertz than the other two schemes.

Table 5.7: Spectral efficiency comparison for Scenario Two

<table>
<thead>
<tr>
<th>Bandwidth (kHz)</th>
<th>SE for Scheme One (bits/sec/Hz)</th>
<th>SE for Scheme Two (bits/sec/Hz)</th>
<th>SE for Scheme Three (bits/sec/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0.0145</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>46</td>
<td>0.0372</td>
<td>0</td>
<td>0.0001</td>
</tr>
<tr>
<td>60</td>
<td>0.0475</td>
<td>0.0002</td>
<td>0.0003</td>
</tr>
<tr>
<td>75</td>
<td>0.0649</td>
<td>0.0010</td>
<td>0.0012</td>
</tr>
<tr>
<td>89</td>
<td>0.0889</td>
<td>0.0048</td>
<td>0.0045</td>
</tr>
<tr>
<td>103</td>
<td>0.2577</td>
<td>0.0221</td>
<td>0.0173</td>
</tr>
<tr>
<td>117</td>
<td>0.3891</td>
<td>0.0999</td>
<td>0.0685</td>
</tr>
<tr>
<td>132</td>
<td>1.0423</td>
<td>0.4143</td>
<td>0.2780</td>
</tr>
</tbody>
</table>
Figure 5.5: Comparison of SE (bits/sec/Hz) of the schemes against bandwidth in kHz

When the bandwidth level ranges between 120 kHz to 146 kHz, Scheme One, Scheme Two and Scheme Three experience improved SE transmission. A bandwidth increase from 146 kHz to 160 kHz results in a significant increase in SE for Scheme One and Scheme Three when compared with Scheme Two. Scheme Three includes the presence of the PUs, which means SUs transmit in the presence of PUs. Thus, at 160 kHz, Scheme Three transmits more bandwidth, meaning they were few or no PUs transmitting on that at that time.

In summary, Table 5.5 and Figure 5.3 reveal that, when comparing the performance of the three scheme’s SEs (bits/sec/Hz) with power (dBm), Scheme One and Scheme Three performed better than Scheme Two for a bandwidth above 150 kHz.
5.6 CHAPTER SUMMARY

This chapter presented the results performance comparison of the three schemes selected in Chapter 3 for modelling in this study. The comparison of these schemes was divided into two scenarios. The first scenario compared the performance of both the data rate and the SU of the three identified schemes with the power range of -30 dBm to 30 dBm, and the second scenario considered the bandwidth range of 32 kHz to 160 kHz. The comparison results revealed that Scheme One performed better than the other two schemes. Reasons for Scheme One’s performance were also explained in this chapter.
CHAPTER 6
CONCLUSION

This chapter concludes this dissertation by assessing whether the research problem has been answered, followed by recommendations for further studies.

6.1 STUDY CONCLUSION

The literature review of this study introduced the statement “there is a common belief that we are running out of usable radio frequencies”. The overcrowded U.S. frequency allocation chart and the multibillion-dollar cost of a 20 MHz frequency band from the European third-generation (3G) spectrum auction have reinforced this belief [33]. This poses the question of whether consumers are truly approaching the capacity of the radio spectrum. However, actual spectrum usage measurements obtained by the FCC Spectrum Policy Task Force tell a different story: “At any given time and location, much of the prized spectrum lies idle” [76].

According to the FCC [76], the use of assigned spectra ranges from 15% to 85% within temporal and geographical variations. As the demand for advanced broadband wireless technologies and services increases, traditional static spectrum regulation policies are becoming outdated. As such, more efficient DSA technologies and regulatory approaches are required to keep up with the growing demand. Through DSA techniques, DSA networks together with CRNs, can offer mobile users access to high bandwidths. This can be achieved through the application or use of various schemes that have been developed for DSA to solve this problem.

Most existing DSA schemes in literature do not follow a standard set of performance parameters, metrics or evaluation methodology when analysing and assessing the scheme performance. Hence, no matter what the scheme’s performance, it cannot be directly compared
with schemes in the existing body of knowledge. As such, there is a need to outline and propose a standard set of performance parameters and a DSA scheme evaluation methodology.

The purpose of this study has been to conduct a comprehensive review of existing DSA performance parameters under applicable schemes. The comparison of the DSA schemes against the performance parameters under a common system model was done. These parameters and the common system model will contribute to the existing knowledge of improving dynamic spectrum sharing.

Chapter 3 outlined the research design and methodology that were used to select the performance parameters and the DSA schemes that were modelled. These selections were based on knowledge gained from Section 2.9, Table 2.1. The selected performance parameters are data rate and SE. The selected DSA schemes are (1) distributed channel assignment in CRNs (referred to as Scheme One), (2) energy SE trade-off in downlink OFDMA networks (referred to as Scheme Two) and (3) a proposed approach based on GFDM for maximising throughput in underlay CRNs (referred to as Scheme Three).

Chapter 4 verified the implementation of these schemes. The verification process affirmed whether the schemes had been implemented correctly. In addition, the results of the selected schemes were regenerated using a MATLAB simulation tool to facilitate a deeper understanding of modelling these schemes to compare their performance with the selected performance parameters that are the data rate and the SE.

Chapter 5 defined a common system model to models all three schemes on the same set of axes and conducted a comparison of the three schemes against data rate and SE through a MATLAB simulation tool. Table 6.1 below summarises the findings from the comparison. In summary, Scheme One performed better than the other three schemes, with the power and data rate during transmission ranging from -30 dBm to 30 dBm and 32 kHz to 160 kHz respectively. The improved performance was a result of energy efficiency, thus allowing the schemes to transmit higher data rate or SE with less power than the other two schemes. Scheme Two performed better than Scheme Three under conditions of higher bandwidths and data rate.
It is concluded that:

1. Scheme One performs better than Scheme Two and Scheme Three.

Table 6.1: Summary of the outcomes for the three scheme’s comparison of SE and Data rate performance against power (dBm) and bandwidth (kHz)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scheme One</th>
<th>Scheme Two</th>
<th>Scheme Three</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power (-30 to 30 dBm)</strong></td>
<td>Achieves a higher data rate and SE compared to Scheme One and Scheme Two</td>
<td>Achieves a lower data rate and SE compared to Schemes One and Two</td>
<td>Achieves a fair data rate and higher SE compared to Scheme Two</td>
</tr>
<tr>
<td><strong>Bandwidth (32 kHz to 160 kHz)</strong></td>
<td>Achieves a higher data rate and SE compared to Scheme One and Scheme Two</td>
<td>Achieves a lower data rate and SE compared to Schemes One and Two</td>
<td>Achieves a higher fair data rate and SE compared to Scheme Two</td>
</tr>
</tbody>
</table>

To date, a lot of research has been done on DSA schemes and their performance parameters. However, comparative studies on which performance parameters and DSA schemes can be categorised for use are lacking. As such, Section 2.9 in Chapter 2 contributed to categorising ways to select performance parameters and DSA schemes. This study selected data rate and SE as the performance parameters to compare the performance of the DSA selected schemes. Table 2.1 in Chapter 2 reveals other parameters that can be grouped with their schemes to conduct an extended comparative study. This table presents fair comparison possibilities since the comparison can be used for schemes and performance parameters with similar characteristics.

The comparison revealed that Scheme One, which is based on energy SE trade-offs in downlink OFDMA networks [45], executed more SE and a higher data rate than the other schemes when we are transmitting with less power as shown in section 4.2.3. This is because the schemes try to find ways of maximising SE at the same time minimising power.
The following gives more insight or practical examples of the interpretation of the results: In digital wireless networks today, having more SE and Data rate transmission means several users or services simultaneously transmits a limited radio frequency bandwidth in a specific geographic area at a certain time [3]. Based on the aforementioned, we can further define SE as the maximum aggregated throughput or goodput, meaning we sum over all users in the system, and divided by the channel bandwidth and by the covered area or number of base station sites being used. The transmission is affected by the single user and multiple access scheme, radio resource management transmission techniques used. Thus the fewer users, the higher the spectrum efficiency and the better the data rate.

6.2 FUTURE RESEARCH

1. Future research should be done on ways for Scheme Two and Scheme Three to execute more SE and data rate, to make them more energy efficient for them to transmit using less power.

2. This study considered static CR nodes. Therefore, the impact of node mobility on the channel assignment could be investigated.

3. More complex system models could be considered, for example, where there is more than one base station in the CRN.

4. Further research is required for channel models that are more complex than AWGN.

5. Different modulation schemes can be used for future work on this study.
BIBLIOGRAPHY


APPENDICES

Data rate (bps) & SE (bits/s/Hz) vs Bandwidth MATLAB code, as used to generate results for chapter 5.

% Author: Seani Rananga
% Date: 01 August 2018
% Algorithms name: Energy spectral efficiency tradeoff in downlink OFDMA network; Distributed channel assignment in cognitive radio network; Proposed Approach Based on GFDM for Maximizing Throughput in Underlay Cognitive Radio Network.
% found at: https://onlinelibrary.wiley.com/doi/abs/10.1002/dac.2725; https://dl.acm.org/citation.cfm?id=1582596:
% This program calculates the spectral efficiency and data rate the three algorithms against Power(dBm) and Bandwidth(dBm) for a downlink OFDMA single circular cell network with one base station (BS) and 10 user equipments (UE)
% Defining the network model with a circle of radius r= 1000m and having one BS centred at (0,0) and 10 UE randomly distributed

% This is the function of the circle and the radius
function circle_function = circle(x_BS,y_BS,x_UE,y_UE, n, radius)
%.....................................
x_BS = 0; % the Base station x coordinates
y_BS = 0; % the Base station y coordinates
figure(1)
hold on
x_UE = randn;
y_UE = randn;
TotalUE = 10; % number of UE's or secondary users
radius = 1000; % the radius of the circle in meters
%radius = 1, % to kilo meters
xunit = radius * cos(Circle_theta) + x_BS;
yunit = radius * sin(Circle_theta) + y_BS;
circle_function = plot(xunit, yunit);
%plotting the base station on the centre (0,0)
scatter(x_BS, y_BS, [], 'g');
% Plotting the random values for the user equipment’s
theta = rand(1,TotalUE)*(2*pi); % plotting the random variables
r = sqrt(rand(1,TotalUE))*radius;
x = x_UE + r.*cos(theta);
y = y_UE + r.*sin(theta);
plot(x, y, '.');
xlabel('X axis');
ylabel('Y axis');
% display('distance');
d = sqrt(((x_BS)-(x)).^2 + ((y_BS)-(y)).^2)
d = sort(d, 'descend')
% The link model
% Here we define variables that will be used to calculate SNR
% the maximal transmit power ranges form -30 to 30 dBm and we use step 2, we have 10
PowerDBM = linspace(-30,30,10)
PowerWatts = 10.^((PowerDBM/10)/1000)

% Pathloss constant
B = 12.81;
% Pathloss exponent constant
sigma = 3.76;
% Lognormal fading variable constant
sm = 1;
% Power gain constant of the transmit and receive antenna
G = 8; % dB
% Constant complex additive white Gaussian noise power
sigmaSquaredDBM = -100; % dBm
sigmaSquaredWatts = 1e-13; % Watts
% Small-scale fading channel constant
fm = 1;

% Available number of channels
K = 10;
% Transmit power of K channels is uniformly distributed between 10 dBm and 30 dBm
PowerDBM = linspace(-30,30,10)
PowerWatts = 10.^((PowerDBM/10)/1000) % converting DBm to watts
% The bandwidth of K channels is uniformly distributed between 32000 Hz and 160000 Hz
Bandwidth = linspace(32000,160000,10)
BandwidthKHz = linspace(32,160,10)
% Interference of K channels is uniformly distributed between -120 dBm and -40 dBm
InterferenceDBM = linspace(-120,-40,10);
InterferenceWatts = 10.^((InterferenceDBM/10)/1000); % converting DBm to watts
% Bit error probability
Pb = 10^-6;
% Constant
C = 10^-6;
% Power decay factor (d^-?)
d = 10^-6;
% Calculating kb
kb = (-2/3)*log2(Pb/2);
sg = 100000; % sub channel activity
Ws = 30000; % subcarrier distance in MHz
i = 0; % sub channel n
Hi = 1; % power gain of data channel of SU
b = 100; % factor of Qam mapper
Pm = 0; % optimum power transmitted by SU m over sub channel
Hm = 1; % channel power gain between SU i transmitter and other SU m receiver
phi = 1; % PU activity
Pp = linspace(-25,30,10); % power transmitted by PU
PowerWattsP = 10.^((Pp/10)/1000)
PowerWattsPm = 10.^((Pp/10)/1000)
Hp = 1; % channel power gain between PU transmitter and SU reciever i
NF = 0.1; % noise factor
No = 0.1; % noise power density of additive white Gaussian noise with zero mean and variance

% Calculating spectral efficiency for SU one 
sum1 = 0;
ssum1 = 0;
for i = 1:length(d)
    SpectraEfficiency_1 = log2(1 + ((PowerWatts(1)).*(fm^2.*(G.*B.*(845 .^(-sigma).*sm))/(sigmaSquaredWatts)))
    sum1 = sum1 + SpectraEfficiency_1
end
DR_1 = Bandwidth(1).*log2(1 + ((PowerWatts(1)).*(fm^2.*(G.*B.*(845 .^(-sigma).*sm))/(sigmaSquaredWatts)))
ssum1 = ssum1 + DR_1

%######Calculating spectral efficiency for SU two########
sum2 = 0;
for i = 1:length(d)
    SpectraEfficiency_2 = log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(988 .^(-sigma).*sm))/(sigmaSquaredWatts)))
    sum2 = sum2 + SpectraEfficiency_2;
end
DR_2 = Bandwidth(2).*log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(988 .^(-sigma).*sm))/(sigmaSquaredWatts)))
ssum2 = ssum2 + DR_2;

%######Calculating spectral efficiency for SU three#######
sum3 = 0;
for i = 1:length(d)
    SpectraEfficiency_3 = log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(925 .^(-sigma).*sm))/(sigmaSquaredWatts)))
    sum3 = sum3 + SpectraEfficiency_3;
end
DR_3 = Bandwidth(3).*log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(925 .^(-sigma).*sm))/(sigmaSquaredWatts)))
ssum3 = ssum3 + DR_3;

%######Calculating spectral efficiency for SU four#####
sum4 = 0;
for i = 1:length(d)
    SpectraEfficiency_4 = log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(850 .^(-sigma).*sm))/(sigmaSquaredWatts)))
    sum4 = sum4 + SpectraEfficiency_4;
end
DR_4 = Bandwidth(4).*log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(850 .^(-sigma).*sm))/(sigmaSquaredWatts)))
ssum4 = ssum4 + DR_4;

%######Calculating spectral efficiency for SU five######
sum5 = 0;
ssum5 = 0;
for i = 1:length(d)
SpectraEfficiency_5 = log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(780 .^-sigma).*sm))/(sigmaSquaredWatts)))
sum5 = sum5 + SpectraEfficiency_5;

DR_5 = Bandwidth(5).*log2(1 + ((PowerWatts(2)).*(fm^2.*(G.*B.*(780 .^-sigma).*sm))/(sigmaSquaredWatts)))
ssum5 = ssum5 + DR_5;
end
sum5
ssum5

%######Calculating spectral efficiency for SU six######
sum6 = 0;
ssum6 = 0;
for i = 1:length(d)
SpectraEfficiency_6 = log2(1 + ((PowerWatts(3)).*(fm^2.*(G.*B.*(870 .^-sigma).*sm))/(sigmaSquaredWatts)))
sum6 = sum6 + SpectraEfficiency_6;

DR_6 = Bandwidth(6).*log2(1 + ((PowerWatts(3)).*(fm^2.*(G.*B.*(870 .^-sigma).*sm))/(sigmaSquaredWatts)))
ssum6 = ssum6 + DR_6;
end
sum6
ssum6

%######Calculating spectral efficiency for SU seven######
sum7 = 0;
ssum7 = 0;
for i = 1:length(d)
SpectraEfficiency_7 = log2(1 + ((PowerWatts(3)).*(fm^2.*(G.*B.*(770 .^-sigma).*sm))/(sigmaSquaredWatts)))
sum7 = sum7 + SpectraEfficiency_7;

DR_7 = Bandwidth(7).*log2(1 + ((PowerWatts(3)).*(fm^2.*(G.*B.*(770 .^-sigma).*sm))/(sigmaSquaredWatts)))
ssum7 = ssum7 + DR_7;
end
sum7
ssum7

%######Calculating spectral efficiency for SU eight######
sum8 = 0;
ssum8 = 0;
for i = 1:length(d)
SpectraEfficiency_8 = log2(1 + ((PowerWatts(4)).*(fm^2.*(G.*B.*(835 .^-sigma).*sm))/(sigmaSquaredWatts)))
sum8 = sum8 + SpectraEfficiency_8;

DR_8 = Bandwidth(8).*log2(1 + ((PowerWatts(4)).*(fm^2.*(G.*B.*(835 .^-sigma).*sm))/(sigmaSquaredWatts)))
ssum8 = ssum8 + DR_8;
end
sum8
ssum8

%######Calculating spectral efficiency for SU nine######
sum9 = 0;
ssum9 = 0;
for i = 1:length(d)
    SpectraEfficiency_9 = log2(1 + ((PowerWatts(5)).*(fm^2.*(G.*B.*(890 .^(-sigma)).*sm))/(sigmaSquaredWatts)))
    sum9 = sum9 + SpectraEfficiency_9;
    DR_9 = Bandwidth(9).*log2(1+ ((PowerWatts(5)).*(fm^2.*(G.*B.*(890 .^(-sigma)).*sm))/(sigmaSquaredWatts)))
    ssum9 = ssum9 + DR_9;
end
sum9
ssum9

%######Calculating spectral efficiency for SU ten######
sum10 = 0;
ssum10 = 0;
for i = 1:length(d)
    SpectraEfficiency_10 = log2(1+ ((PowerWatts(6)).*(fm^2.*(G.*B.*(923 .^(-sigma)).*sm))/(sigmaSquaredWatts)))
    sum10 = sum10 + SpectraEfficiency_10;
    DR_10 = Bandwidth(10).*log2(1+ ((PowerWatts(6)).*(fm^2.*(G.*B.*(923 .^(-sigma)).*sm))/(sigmaSquaredWatts)))
    ssum10 = ssum10 + DR_10;
end
sum10
ssum10
figure(2)
% Total spectral efficiency for all SU users
TotalSpectralEfficiency = [sum1,sum2,sum3,sum4,sum5,sum6,sum7,sum8,sum9,sum10]
% PowerDBM = linspace(0,20,11)
figure(2)
%plotting total spectral efficiency against power
plot(Bandwidth, TotalSpectralEfficiency, 'rd-')
%labelling the X axis
xlabel('Bandwidth(KHz)');
%Labelling the Y axis
ylabel('SE (bits/s/Hz)');
legend('SE-Max ','Location','northwest')
grid on
grid minor
figure(5)
% Total spectral efficiency for all SU users
TotalDR = [ssum1,ssum2,ssum3,ssum4,ssum5,ssum6,ssum7,ssum8,ssum9,ssum10]
% PowerDBM = linspace(0,20,11)
%plotting total data rate against power
plot(Bandwidth, TotalDR, 'rd-')
%labelling the X axis
xlabel('Bandwidth(KHz)');
%xticks([32:5:160]);
%Labelling the Y axis
ylabel('Datarate(bits/s)');
legend('Datarate ','Location','northwest')
grid on
grid minor

%Data rate for channel 1 using Bandwidth of 34 kH(34000) and -50 dBm (1e-8 Watts) Interference
for i = 1:10
    Datarate_1 = Bandwidth(1)*log2(1 + ((1/kb) *(PowerWatts(1)/(1e-8*d))));
Datarate_2 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(2)/(1e-8*d)));
Datarate_3 = Bandwidth(3)*log2(1 + (1/kb) *(PowerWatts(3)/(1e-8*d)));
Datarate_4 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(4)/(1e-8*d)));
Datarate_5 = Bandwidth(5)*log2(1 + (1/kb) *(PowerWatts(5)/(1e-8*d)));
Datarate_6 = Bandwidth(6)*log2(1 + (1/kb) *(PowerWatts(6)/(1e-8*d)));
Datarate_7 = Bandwidth(7)*log2(1 + (1/kb) *(PowerWatts(7)/(1e-8*d)));
Datarate_8 = Bandwidth(8)*log2(1 + (1/kb) *(PowerWatts(8)/(1e-8*d)));
Datarate_9 = Bandwidth(9)*log2(1 + (1/kb) *(PowerWatts(9)/(1e-8*d)));
Datarate_10 = Bandwidth(10)*log2(1 + (1/kb) *(PowerWatts(10)/(1e-8*d)));

%SE for channel 1 using Bandwidth of 34 kHz(34000) and -50 dBm (1e-8 Watts) Interference
SE_1 = log2(1 + (1/kb) *(PowerWatts(1)/(1e-8*d)));
SE_2 = log2(1 + (1/kb) *(PowerWatts(2)/(1e-8*d)));
SE_3 = log2(1 + (1/kb) *(PowerWatts(3)/(1e-8*d)));
SE_4 = log2(1 + (1/kb) *(PowerWatts(4)/(1e-8*d)));
SE_5 = log2(1 + (1/kb) *(PowerWatts(5)/(1e-8*d)));
SE_6 = log2(1 + (1/kb) *(PowerWatts(6)/(1e-8*d)));
SE_7 = log2(1 + (1/kb) *(PowerWatts(7)/(1e-8*d)));
SE_8 = log2(1 + (1/kb) *(PowerWatts(8)/(1e-8*d)));
SE_9 = log2(1 + (1/kb) *(PowerWatts(9)/(1e-8*d)));
SE_10 = log2(1 + (1/kb) *(PowerWatts(10)/(1e-8*d)));
end

figure(3)
display('datarate(bps) for channel one');
Datarate1 = [Datarate_1,Datarate_2,Datarate_3,Datarate_4,Datarate_5,
Datarate_6,Datarate_7,Datarate_8,Datarate_9,Datarate_10]
plot(Bandwidth, Datarate1, '-rs')
hold on
xlabel('Bandwidth(KHz)');
ylabel('Data rate (bps)');

figure(6)
display('SE(bps/hz) for channel one');
SE1 = [SE_1,SE_2,SE_3,SE_4,SE_5, SE_6,SE_7,SE_8,SE_9,SE_10]
plot(Bandwidth, SE1, '-rs')
hold on
xlabel('Bandwidth(KHz)');
ylabel('Spectral efficiency(bits/sec/hz)');

%Data rate for channel 3 using Bandwidth of 105 kHz(105000) and -50 dBm (1e-8 Watts) Interference
for i = 1:10
Datarate_31 = Bandwidth(2) *log2(1 + (1/kb) *(PowerWatts(1)/(1e-8*d)));
Datarate_32 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(2)/(1e-8*d)));
Datarate_33 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(3)/(1e-8*d)));
Datarate_34 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(4)/(1e-8*d)));
Datarate_35 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(5)/(1e-8*d)));
Datarate_36 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(6)/(1e-8*d)));
Datarate_37 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(7)/(1e-8*d)));
Datarate_38 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(8)/(1e-8*d)));
Datarate_39 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(9)/(1e-8*d)));
Datarate_310 = Bandwidth(2)*log2(1 + (1/kb) *(PowerWatts(10)/(1e-8*d)));
end

figure(3)
display('datarate(bps) for channel one');
Datarate3 = [Datarate_1,Datarate_2,Datarate_3,Datarate_4,Datarate_5,
Datarate_6,Datarate_7,Datarate_8,Datarate_9,Datarate_10]
plot(Bandwidth, Datarate3, '-rs')
hold on
xlabel('Bandwidth(KHz)');
ylabel('Data rate (bps)');

figure(6)
display('SE(bps/hz) for channel one');
SE3 = [SE_1,SE_2,SE_3,SE_4,SE_5, SE_6,SE_7,SE_8,SE_9,SE_10]
plot(Bandwidth, SE3, '-rs')
hold on
xlabel('Bandwidth(KHz)');
ylabel('Spectral efficiency(bits/sec/hz)');
SE_34 = log2(1 + (1/kb) * (PowerWatts(4)/(1e-8*d)));  
SE_35 = log2(1 + (1/kb) * (PowerWatts(5)/(1e-8*d)));  
SE_36 = log2(1 + (1/kb) * (PowerWatts(6)/(1e-8*d)));  
SE_37 = log2(1 + (1/kb) * (PowerWatts(7)/(1e-8*d)));  
SE_38 = log2(1 + (1/kb) * (PowerWatts(8)/(1e-8*d)));  
SE_39 = log2(1 + (1/kb) * (PowerWatts(9)/(1e-8*d)));  
SE_310 = log2(1 + (1/kb) * (PowerWatts(10)/(1e-8*d)));  
end  
figure(3)  
display('datarate(bps) for channel three');  
Datarate3 = [Datarate_31,Datarate_32,Datarate_33,Datarate_34,Datarate_35, Datarate_36,Datarate_37,Datarate_38,Datarate_39,Datarate_310]  
plot(Bandwidth, Datarate3,'-bo')%Plotting total data rate for channel three against the Power  
hold on  
xlabel('Bandwidth(KHz)');  
ylabel('Data rate (bps)');  
figure(6)  
display('SE(bps/Hz) for channel three');  
SE3 = [SE_31,SE_32,SE_33,SE_34,SE_35, SE_36,SE_37,SE_38,SE_39,SE_310]  
plot(Bandwidth, SE3,'-rs')%Plotting total data rate for channel one against the Power  
hold on  
xlabel('Bandwidth(KHz)');  
ylabel('Spectral efficiency(bits/sec/Hz)');  

%Data rate for channel 2 using Bandwidth of 70 kHz(70000) and -50 dBm (1e-8 Watts)Interference  
for i = 1:10  
Datarate_21 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(1)/(1e-8*d)));  
Datarate_22 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(2)/(1e-8*d)));  
Datarate_23 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(3)/(1e-8*d)));  
Datarate_24 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(4)/(1e-8*d)));  
Datarate_25 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(5)/(1e-8*d)));  
Datarate_26 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(6)/(1e-8*d)));  
Datarate_27 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(7)/(1e-8*d)));  
Datarate_28 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(8)/(1e-8*d)));  
Datarate_29 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(9)/(1e-8*d)));  
Datarate_210 = Bandwidth(3) * log2(1 + (1/kb) * (PowerWatts(10)/(1e-8*d)));  
end  
figure(3)  
display('datarate(bps) for channel two');  
Datarate2 = [Datarate_21,Datarate_22,Datarate_23,Datarate_24,Datarate_25,Datarate_26, Datarate_27,Datarate_28,Datarate_29,Datarate_210]  
plot(Bandwidth, Datarate2,'-ko')%Plotting total data rate for channel two against the Power  
hold on
xlabel('Bandwidth(KHz)');
ylabel('Data rate (bps)');
figure(6)
display('SE(bps/hz) for channel two');
plot(Bandwidth, SE2, '-rs');%Plotting total data rate for channel one
hold on
xlabel('Bandwidth(KHz)');
ylabel('Spectral efficiency(bits/sec/hz)');

%Data rate for channel 3 using Bandwidth of 164 kHz(164000) and -50 dBm
%Watts)Interference
for i = 1:20
    Datarate_41 = Bandwidth(4) *log2(1 + (1/kb) *(PowerWatts(1)/(1e-8*d)));
    Datarate_42 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(2)/(1e-8*d)));
    Datarate_43 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(3)/(1e-8*d)));
    Datarate_44 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(4)/(1e-8*d)));
    Datarate_45 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(5)/(1e-8*d)));
    Datarate_46 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(6)/(1e-8*d)));
    Datarate_47 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(7)/(1e-8*d)));
    Datarate_48 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(8)/(1e-8*d)));
    Datarate_49 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(9)/(1e-8*d)));
    Datarate_410 = Bandwidth(4)*log2(1 + (1/kb) *(PowerWatts(10)/(1e-8*d)));
end
figure(3)
display('datarate(bps) for channel four');
Datarate4 = [Datarate_41,Datarate_42,Datarate_43,Datarate_44,Datarate_45,
    Datarate_46,Datarate_47,Datarate_48,Datarate_49,Datarate_410]
plot(Bandwidth, Datarate4, '-md');%Plotting total data rate for channel four
hold on
xlabel('Bandwidth(KHz)');

%SE for channel 3 using Bandwidth of 164 kHz(164000) and -50 dBm
%Watts)Interference
SE_41 = log2(1 + (1/kb) *(PowerWatts(1)/(1e-8*d)));
SE_42 = log2(1 + (1/kb) *(PowerWatts(2)/(1e-8*d)));
SE_43 = log2(1 + (1/kb) *(PowerWatts(3)/(1e-8*d)));
SE_44 = log2(1 + (1/kb) *(PowerWatts(4)/(1e-8*d)));
SE_45 = log2(1 + (1/kb) *(PowerWatts(5)/(1e-8*d)));
SE_46 = log2(1 + (1/kb) *(PowerWatts(6)/(1e-8*d)));
SE_47 = log2(1 + (1/kb) *(PowerWatts(7)/(1e-8*d)));
SE_48 = log2(1 + (1/kb) *(PowerWatts(8)/(1e-8*d)));
SE_49 = log2(1 + (1/kb) *(PowerWatts(9)/(1e-8*d)));
SE_410 = log2(1 + (1/kb) *(PowerWatts(10)/(1e-8*d)));
end
figure(6)
display('SE(bps/hz) for channel two');
plot(Bandwidth, SE4, '-rs');%Plotting total data rate for channel one
hold on
xlabel('Bandwidth(KHz)');

%xticks([0:5:30]);

91
%xticks([32:5:160]);
ylabel('Spectral efficiency(bits/sec/Hz)');
grid on
grid minor
legend('channel 1', 'channel 2', 'channel 3', 'channel 4',
'Location', 'northwest')

% calculating Datarate for SU one
DDatarate1 = sg .* (Bandwidth(1)).* log2(1 + (PowerWatts(1).* Hi)/(10.*((PowerWatts(1).*Hm) + (2.*PowerWatts(1).*Hp) + (NF.*No.*Ws)))))

% calculating Datarate for SU two
DDatarate2 = sg .* (Bandwidth(2)).* log2(1 + (PowerWatts(2).* Hi)/(20.*((PowerWatts(8).*Hm) + (10.*PowerWattsP(9).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU three
DDatarate3 = sg .* (Bandwidth(3)).* log2(1 + (PowerWatts(3).* Hi)/(30.*((PowerWatts(9).*Hm) + (30.*PowerWattsP(10).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU four
DDatarate4 = sg .* (Bandwidth(4)).* log2(1 + (PowerWatts(4).* Hi)/(40.*((PowerWatts(10).*Hm) + (8.*PowerWattsP(10).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU five
DDatarate5 = sg .* (Bandwidth(5)).* log2(1 + (PowerWatts(5).* Hi)/(50.*((PowerWatts(9).*Hm) + (phi.*PowerWattsP(8).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU six
DDatarate6 = sg .* (Bandwidth(6)).* log2(1 + (PowerWatts(6).* Hi)/(60.*((PowerWatts(6).*Hm) + (phi.*PowerWattsP(6).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU seven
DDatarate7 = sg .* (Bandwidth(7)).* log2(1 + (PowerWatts(7).* Hi)/(70.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(7).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU eight
DDatarate8 = sg .* (Bandwidth(8)).* log2(1 + (PowerWatts(8).* Hi)/(80.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(8).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU nine
DDatarate9 = sg .* (Bandwidth(9)).* log2(1 + (PowerWatts(9).* Hi)/(90.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(9).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU 10
DDatarate10 = sg .* (Bandwidth(10)).* log2(1 + (PowerWatts(10).* Hi)/(100.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(10).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU one
specEFF1 = sg.*log2(1 + (PowerWatts(1).* Hi)/(10.*((PowerWatts(1).*Hm) + (2.*PowerWatts(1).*Hp) + (NF.*No.*Ws))))

% calculating Datarate for SU two
specEFF2 = sg .* log2(1 + (PowerWatts(2).* Hi)/(20.*((PowerWatts(8).*Hm) + (10.*PowerWattsP(9).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU three
specEFF3 = sg .* log2(1 + (PowerWatts(3).* Hi)/(30.*((PowerWatts(9).*Hm) + (30.*PowerWattsP(10).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU four
specEFF4 = sg .* log2(1 + (PowerWatts(4).* Hi)/(40.*((PowerWatts(10).*Hm) + (30.*PowerWattsP(10).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU five
specEFF5 = sg .* log2(1 + (PowerWatts(5).* Hi)/(50.*((PowerWatts(9).*Hm) + (phi.*PowerWattsP(8).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU six
specEFF6 = sg .* log2(1 + (PowerWatts(6).* Hi)/(60.*((PowerWatts(6).*Hm) + (phi.*PowerWattsP(6).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU seven
specEFF7 = sg .* log2(1 + (PowerWatts(7).* Hi)/(70.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(7).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU eight
specEFF8 = sg .* log2(1 + (PowerWatts(8).* Hi)/(80.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(8).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU nine
specEFF9 = sg .* log2(1 + (PowerWatts(9).* Hi)/(90.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(9).*Hp) + (NF.*No.*Ws) )))

% calculating Datarate for SU 10
specEFF10 = sg .* log2(1 + (PowerWatts(10).* Hi)/(100.*((PowerWatts(10).*Hm) + (phi.*PowerWattsP(10).*Hp) + (NF.*No.*Ws) )))

% Total datarate for all SU users
TotalDatarate = [DDatarate1, DDatarate2, DDatarate3, DDatarate4, DDatarate5, DDatarate6, DDatarate7, DDatarate8, DDatarate9, DDatarate10]
figure(4)
% plotting total spectral efficiency against power
plot(Bandwidth,TotalDatarate, '--md')
% labelling the X axis
xlabel('Bandwidth (KHz)');
xlabel('Bandwidth (KHz)');
% labelling the Y axis
ylabel('Datarate (bps)');
%yticks([0:0.5:15*10^6]);
grid on
grid minor
legend('OFDM-PS ', 'Location','northwest')

figure(7)
TotalspecEFF = [specEFF1, specEFF2, specEFF3, specEFF4, specEFF5, specEFF6, specEFF7, specEFF8, specEFF9, specEFF10]
% plotting total spectral efficiency against power
plot(Bandwidth,TotalspecEFF, '--bd')
% labelling the X axis
xlabel('Bandwidth (KHz)');
%xticks([0:5:30]);
% Labelling the Y axis
ylabel('Spectral efficiency (bits/s/Hz)');
%yticks([0:0.5:15*10^6]);
grid on
grid minor
legend('OFDM-PS ','Location','northwest')

%*************************************************
%Comparison, thus plotting in the same axes
%*************************************************
figure(8)
plot(BandwidthKHz, TotalDR, '-rs')
hold on
plot(BandwidthKHz, Datarate1, '-gs')
hold on
plot(BandwidthKHz, Datarate2, '-ko')
hold on
plot(BandwidthKHz, Datarate3, '-yu')
hold on
plot(BandwidthKHz, Datarate4, '-md')
hold on
plot(BandwidthKHz, TotalDatarate, '-bd')
hold on
labelling the X axis
xlabel('Bandwidth(kHz)');
xticks([0:5:30]);
labelling the Y axis
ylabel('Datarate(bps)');
legend('Datarate ','Location','northwest')
grid on

%*************************************************
%Spectral efficiency********************************************
figure(9)
plot(BandwidthKHz, TotalSpectralEfficiency, 'rd-')
hold on
plot(PowerDBM, SE1, '-gs')
hold on
plot(PowerDBM, SE3, '-yo')
hold on
plot(PowerDBM, SE2, '-ko')
hold on
plot(BandwidthKHz, SE1, '-md')
hold on
plot(BandwidthKHz, TotalSpectEff, '-bo')
hold on
labelling the X axis
xlabel('Bandwidth(kHz)');
xticks([0:5:30]);
labelling the Y axis
ylabel('SE (bits/s/Hz)');
legend('SE-Max ','Location','northwest')
grid on
grid minor
legend('Scheme One','Scheme Two','Scheme Three', 'Location','northwest')
xlabel('P_m_a_x(dBm)');
axes('position',[0 4 8 10]);
box on
your_index = -10<x & x<10;
plot( PowerDBM(your_index), TotalspecEFF(your_index));
axis tight