Using Hypergraph Theory to Model Coexistence Management and Coordinated Spectrum Allocation for Heterogeneous Wireless Networks Operating in Shared Spectrum

A thesis submitted in partial fulfilment of the requirements
of the degree of
Doctor of Philosophy

Tawachi Nyasulu
Software Defined Radio Lab
Department of Electronic and Electrical Engineering
University of Strathclyde, Glasgow

May 10, 2022

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: **Tawachi Nyasulu**

Date: **May 2022**

Abstract

Electromagnetic waves in the Radio Frequency (RF) spectrum are used to convey wireless transmissions from one radio antenna to another. Spectrum utilisation factor, which refers to how readily a given spectrum can be reused across space and time while maintaining an acceptable level of transmission errors, is used to measure how efficiently a unit of frequency spectrum can be allocated to a specified number of users.

The demand for wireless applications is increasing exponentially, hence there is a need for efficient management of the RF spectrum. However, spectrum usage studies have shown that the spectrum is under-utilised in space and time. A regulatory shift from static spectrum assignment to DSA is one way of addressing this. Licence-exemption policy has also been advanced in Dynamic Spectrum Access (DSA) systems to spur wireless innovation and universal access to the internet. Furthermore, there is a shift from homogeneous to heterogeneous radio access and usage of the same spectrum band. These three shifts from traditional spectrum management have led to the challenge of coexistence among heterogeneous wireless networks which access the spectrum using DSA techniques.

Cognitive radios have the ability for spectrum agility based on spectrum conditions. However, in the presence of multiple heterogeneous networks and without spectrum coordination, there is a challenge related to switching between available channels to minimise interference and maximise spectrum allocation. This thesis therefore focuses on the design of a framework for coexistence management and spectrum coordination, with the objective of maximising spectrum utilisation across geographical space and across time. The amount of geographical coverage in which a frequency can be used is optimised through frequency reuse while ensuring that harmful interference is minimised. The time during which spectrum is occupied is increased through time-sharing of the same spectrum by two or more networks, while ensuring that spectrum is shared by networks that can coexist in the same spectrum and that the total channel load is not excessive to prevent spectrum starvation.

Conventionally, a graph is used to model relationships between entities such as interference relationships among networks. However, the concept of an edge in a graph is not sufficient to model relationships that involve more than two entities, such as more than two networks that are able to share the same channel in the time domain, because an edge can only connect two entities. On the other hand, a hypergraph is a generalisation of an undirected graph in which a hyperedge can connect more than two entities. Therefore, this thesis investigates the use of hypergraph theory to model the RF environment and the spectrum allocation scheme.

The hypergraph model was applied to an algorithm for spectrum sharing among 100 heterogeneous wireless networks, whose geo-locations were randomly and independently generated in a 50 km by 50 km area. Simulation results for spectrum utilisation performance have shown that the hypergraph-based model allocated channels, on average, to 8% more networks than the graph-based model. The results also show that, for the same RF environment, the hypergraph model requires up to 36% fewer channels to achieve, on average, 100% operational networks, than the graph model. The rate of growth of the running time of the hypergraph-based algorithm with respect to the input size is equal to the square of the input size, like the graph-based algorithm. Thus, the model achieved better performance at no additional time complexity.

Acknowledgements

I would like to acknowledge the funders of my research: the UK government through the Commonwealth Scholarships Commission, the Schlumberger Foundation through the Faculty of the Future Fellowships and the University of Strathclyde.

I am very grateful to my primary supervisor, Dr David Crawford, and to my secondary supervisor, Dr Louise Crockett, who guided me so positively throughout this research project, offered deep insight into the study and nurtured my professional development as a researcher. I also would like to thank the leader of our research group, Prof Robert Stewart, for providing me the opportunity to study for a PhD in the Strathclyde Software Defined Radio (StrathSDR) research group and for his guidance in my studies.

The support and friendship from friends and colleagues in the research group is greatly appreciated. I am grateful for the supportive atmosphere within the group. Special thanks go to Lakshmy, Dani, Youssif, Kenny and Shruthi. I am also grateful to my friend Inacio at University of Surrey for cheering me on and for being “a friend in need”.

I would like to sincerely thank my loving host family, David and Wilma, for being my family away from home. I am also grateful to my church family for praying for me and supporting me in various ways. I am particularly appreciative the following people: Elma, and Frances for the refreshing days out and Keswick Conventions/holidays; Sheila for the insightful advice; Joan for the PhD tips and books; Douglas and Janet for their hospitality; Dorothy Hayward for the spiritual talks over our routine coffee mornings.

I am forever grateful to my loving parents, brothers and sisters for their support and encouragement throughout my life and during this PhD. I am because you are!

Last but not least, I am grateful to my heavenly Father, the Sovereign of the universe who created me and sustains me. All the days ordained for me were written in His book before one of them came to be (Psalm 139:16). I therefore echo the words of this ancient hymn by Joachim Neander in praise to Him.

Praise to the Lord, who o'er all things so wondrously reigneth,
Shelters thee under His wings, yea, so gently sustaineth!
Hast thou not seen how thy desires e'er have been
Granted in what He ordaineth?

Contents

List of Figures

List of Tables

Acronyms

3GPP	3rd Generation Partnership Project
ABS	Almost Blank Subframe
ACK	Acknowledgement
ACLR	Adjacent Channel Leakage Ratio
AP	Access Point
ARNS	Aeronautical Radio-Navigation Services
ASA	Authorised Shared Access
BCU	Basic Channel Unit
BPSK	Binary Phase Shift Keying
BS	Base Station
CAP	Contention Access Period
CBP	Coexistence Beacon Protocol
CBRS	Citizens Broadband Radio Service
CBSD	CBRS device
CCG	Common Channel Group
CDIS	Coexistence Discovery and Information Server
CE	Coexistence Enabler
CEPT	European Conference of Postal and Telecommunications Administrations
CFP	Contention Free Period
CMRS	Commercial Mobile Radio Service
CNG	Common Node Group
COE	Coordination Enabler

COR	Channel Occupancy Rate
CPE	Customer Premise Equipment
CRP	Channel Reservation Protocol
CSAT	Carrier Sense Adaptive Transmission
CSMA-CA	Channel Sense Multiple Access/Collision Avoidance
CxG	Coexistence Group
CxM	Coexistence Manager
D2D	Device-to-Device
DCF	Distributed Coordination Function
DL	Downlink
DSA	Dynamic Spectrum Access
DSRC	Dedicated Short Range Communications
DSS	Dynamic Spectrum Sharing
DTP	Data Transfer Period
DTT	Digital Terrestrial Television
EB	Exabyte
ECC	Electronic Communications Committee
ECMA	European Computer Manufacturers Association
eICIC	enhanced Inter-Cell Interference Coordination
EIRP	Effective Isotropic Radiated Power
ESC	Environmental Sensing Capability
ETSI	European Telecommunications Standards Institute
EU	European Union
FBMC	Filter Bank Multi-Carrier
FBS	Femtocell Base Station
FCC	Federal Communications Commission
FWA	Fixed Wireless Access
GAA	General Authorised Access
GCO	Geo-location Capable Object
GDB	Geo-location Database

GDD	Geo-location Database Dependent
GHz	Gigahertz
GL	Geo-location
GLSD	Geo-location Spectrum Database
GOP	General Operating Parameter
GPS	General Positioning System
GSC	GAA Spectrum Coordination
GTS	Guaranteed Time Slot
H-CRN	Heterogeneous Cognitive Radio Network
HAAT	Height Above Average Terrain
HCF	Hybrid Coordination Function
HDTV	High Definition Television
ICG	Interference Coordination Group
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
ISM	Industrial, Scientific, Medical
LBT	Listen-Before-Talk
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-LAA	Long Term Evolution Licence Assisted Access
LTE-U	Long Term Evolution Unlicensed
MAC	Media Access Control
MACRA	Malawi Communications Regulatory Authority
MCF	Mesh Coordination Function
MHz	Megahertz
ML	Machine Learning
MNO	Mobile Network Operator
MVPD	Multi Video Programming Distributor
NBP	National Broadband Plan

NEG	No Edge Group
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
Ofcom	Office of Communication
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PAL	Priority Access Licence
PAWS	Protocol to Access White Space databases
PCA	Prioritised Contention Access
PHY	Physical
PLMRS	Private Land Mobile Radio Service
PMRS	Private Mobile Radio Service
PMSE	Programme Making and Special Events
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RAS	Radio Astronomy Service
RAT	Radio Access Technology
RF	Radio Frequency
RFC	Request for Comments
RLSS	Radio Location Secure Server
RRM	Radio Resource Manager
RSPP	Radio Spectrum Policy Programme
RTS/CTS	Request to Send/Clear to Send
RTSSM	Real-Time Secondary Spectrum Market
SAS	Spectrum Access System
SINR	Signal-to-Interference-plus-Noise-Ratio
SISO	Single Input Single Output

SM	Spectrum Manager
SMDB	Spectrum Management Database
SNR	Signal-to-Noise-Ratio
SOP	Specific Operating Parameter
SSA	Spectrum Sensing Automation
SSF	Spectrum Sensing Function
SSH	Secure Shell
STA	Station
SU	Secondary User
TCP/IP	Transmission Control Protocol/Internet Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TLS	Transport Layer Security
TPC	Transmission Power Control
TV	Television
TVBD	TV Band Device
TVHT	Television Very High Throughput
TVWS	Television White Space
UE	User Equipment
UHF	Ultra High Frequency
UKPM	United Kingdom Planning Model
UL	Uplink
V2X	Vehicle-to-Everything
VHF	Very High Frequency
WInnForum	Wireless Innovation Forum
WLAN	Wireless Local Area Network
WMTS	Wireless Medical Telemetry Service
WRAN	Wireless Regional Area Network
WSD	White Space Device
WSO	White Space Object

Glossary

cardinality The total number of elements in a set or subset.

coexistence The ability for two or more radio systems to operate in proximity without significantly impacting each other's performance

coexistence group A group of radio devices/networks that are managed by the same coexistence manager using the same interference management policy.

coexistence management The function that is responsible for managing coexistence between two or more radio devices/networks, which form a coexistence group, and which may operate using different wireless protocols with different coexistence mechanisms. This function could be implemented within a radio/network or by a logical entity that does not take part in the communication process.

coexistence mechanism The process by which a radio system design implements coexistence with different wireless devices and standards in the same frequency band.

connected set a set of vertices of a graph in which any two vertices are connected to each other through a path.

cubic time complexity Represents an algorithm whose running time has a rate of growth that is directly proportional to the cube of the input size, often as a result of three loops.

edge A line connecting two vertices in a graph and is represented by a subset of the two vertices that it connects.

graph A set of points (called vertices or nodes) and lines (called edges) connecting some pairs of the points.

heterogeneous radio environment Comprises independent radio systems that access the spectrum using different MAC/PHY designs or composite radio systems that comprises radio subsystems that have different MAC/PHY designs.

hyperedge A connection between any number vertices of a hypergraph, and can therefore be a non-empty subset of any cardinality other than just 2 as is the case of an ordinary graph.

hypergraph A hypergraph is a generalization of an undirected graph in which an edge can join any number of vertices. By contrast, in a traditional graph, an edge connects exactly two vertices.

interference coordination group A group of radio devices/networks that can coordinate access to shared bandwidth in order to manage interference among themselves.

quadratic time complexity Represents an algorithm whose running time has a rate of growth that is directly proportional to the square of the input size, often as a result of a nested loop.

RF environment All radio devices and networks that are operating in a given spectrum band in a given location at a given time.

RF environment model A representation, using well known data structures, of how the radio device/system parameters and spectral factors interact so as to affect each other's performance.

spectrum coordination This is a high-level method for reducing the potential of interference in shared spectrum through coordinated bandwidth allocation among different coexistence groups. Radio devices/networks in each coexistence group manage interference within their respective groups.

spectrum utilisation This is a measure of how readily spectrum can be reused by multiple independent radio communication systems across space and time.

time complexity This is an abstract way to represent the running time of an algorithm in terms of the rate of growth with respect to the size of the input.

Chapter 1

Introduction

1.1 Research Background

According to a report that was released by Ericsson in June 2021, global mobile network traffic per month is forecast to grow from 58 Exabytes (EBs) at the end of 2020 to 300 EBs in 2026, representing growth by a factor of 5 [1]. However, the Radio Frequency (RF) spectrum, the medium through which wireless traffic is transmitted, is a finite resource and is one of the major limitations on the growth of wireless infrastructure. Nonetheless, spectrum utilisation studies have shown that there exists chunks of licensed spectrum that are not in use at particular times and/or in particular geographical locations [2–6]. As such, wireless communications regulation and research has focused on efficient spectrum management to meet the growing demand for wireless applications.

Dynamic Spectrum Access (DSA) is regarded as a potential solution for increasing spectrum utilisation. DSA involves real-time adjustment of radio resources in response to changes in the availability of radio resources [7]. This enables dynamic spectrum sharing, thereby reducing the probability that spectrum will remain idle. Three technologies have been proposed for implementing DSA: spectrum sensing, beacon signal and geo-location combined with spectrum database [8, 9].

DSA policy was first approved in the Television (TV) band in the United States of America (USA) in 2008 [10]. Since 2015, Singapore, the United Kingdom (UK), Canada and South Africa have implemented DSA frameworks for operation in the vacant spectrum in this band, which is called Television White Space (TVWS) [11–14]. In order to further improve spectrum accessibility for wireless innovations, the regulators have embraced licence exemption or light licensing policies for access to TVWS.

Communications regulators in the USA and UK, Federal Communications Commission (FCC) and Office of Communication (Ofcom), respectively, have approved the geo-location combined with spectrum database method as the main method of implementing managed dynamic spectrum sharing between licensed TV stations and licence-exempt secondary user networks in such a manner that the licensed TV stations are protected from interference that may originate from the secondary user networks [10, 15]. While the regulations guarantee interference protection of primary users from secondary users, interference protection of secondary users from other secondary users is not guaranteed [16].

Following implementation of TVWS regulatory frameworks, heterogeneous Radio Access Technology (RAT) standards have been published to support development of radio systems that can operate in TVWS spectrum to provide diverse wireless communication services [17–21]. Interference management among heterogeneous secondary networks becomes a challenge when the available spectrum is not adequate for each network or for networks of the same RAT standard and configuration to operate exclusively in a channel. Without spectrum coordination and interference management, efficient utilisation of white space spectrum may not be realised [16, 22].

In 2017, the USA approved a DSA framework for the 3.5 Gigahertz (GHz) band, which is called the Citizens Broadband Radio Service (CBRS), and is based on a three-tier shared access model that is governed by a Spectrum Access System (SAS) [23]. The current incumbent users, which are federal radar systems and fixed satellite service earth stations, operate in the highest tier. Priority Access Licence (PAL) and General Authorised Access (GAA) users operate in the middle and lowest tiers, respectively.

GAA users are not guaranteed interference protection from higher tiers and from other GAA users. However the rules state that GAA users must coordinate in their spectrum access and usage in order to minimise interference and to increase spectrum utilisation [23]. The CBRS band does not mandate a common radio spectrum access procedure. CBRS spectrum has attracted various RAT standards such as 4G Long Term Evolution (LTE) and 5G New Radio (NR) mobile networks, Fixed Wireless Access (FWA) networks, and private enterprise networks. Thus, coordination of spectrum access among heterogeneous radio systems operating in the GAA tier is a challenge due to RAT compatibility issues.

In 2019, the UK's Ofcom released a statement on enabling wireless innovation through shared access licensing to 1800 MHz, 2300 MHz and 3.8-4.2 GHz spectrum bands and through local licensing to spectrum that is already licensed to Mobile Network Operators (MNOs) in the 800 MHz, 900 MHz, 1400 MHz, 1800 MHz, 1900 MHz, 2100 MHz, 2300 MHz, 2600 MHz and 3.4 GHz bands, but which is not being used or planned for use in a particular area within the next three years [24]. These spectrum bands are expected to support diverse use cases such as Fixed Wireless Access (FWA) networks, Internet of Things (IoT) applications, and enterprise networks. Hence, diverse RAT standards are expected to operate in these spectrum bands. In the statement, Ofcom announced future plans to consider the feasibility of transitioning towards a DSA approach to shared and local licensing, implemented by a fully automated central database.

Multiple wireless devices are said to "coexist" if they can operate in proximity without significantly impacting each other's performance [25]. Coexistence management starts with the design of the wireless protocol. However, inherent interference management mechanisms become less effective in heterogeneous environments due to incompatible wireless protocols, different scheduling modes, disparate bandwidth size and communication ranges [22, 26].

Cognitive radios are capable of spectrum agility, which is the ability of the radio to change its operating frequency in response to changes in the RF environmental conditions, in order to optimise its performance [7]. However, in the presence of two or more independent heterogeneous networks, without proper coordination, there is a challenge related to switching between available frequency bands to provide smooth spectrum access without interruption to service because of harmful interference among the networks and to arrive at a spectrum allocation that achieves the most efficient spectrum utilisation across all networks [22, 27]. Thus, coordinated spectrum access and coexistence management of heterogeneous secondary user devices is an important research challenge in DSA.

There are proposals in the literature for wireless protocols to implement coexistence mechanisms between heterogeneous radio systems [26, 28–32]. However, these approaches require modifications to the radio protocols and hardware. Furthermore, such radio-technology-dependent approaches might not be sustainable because technology is evolving at a fast rate and new radio standards are being introduced for operation in spectrum bands that are designated for access using DSA techniques. Therefore, standards bodies have published technology-agnostic wireless coexistence methods for heterogeneous networks. These methods can be implemented through a logical entity that does not take part in the communication process called a Coexistence Manager (CxM). The CxM is essentially a Radio Resource Manager (RRM) that frequency-isolates networks that cannot coexist in the same spectrum and manages other transmission characteristics to minimise interference. The Institute of Electrical and Electronic Engineers (IEEE) published the 802.19.1 Standard for Wireless Network Coexistence Methods in 2014, which was revised in 2017 and 2018 [33–35]. The Wireless Innovation Forum (WInnForum) published the GAA Spectrum Coordination Technical Report in 2019 [36–38]. The CBRS Alliance, which has now re-branded as the OnGo Alliance, published CBRS Coexistence Technical Specifications in 2020 [39]. However, actual implementation of coexistence management algorithms is left to the industry.

The DSA ecosystem is characterised by multiple independent operators, multiple independent Radio Access Networks (RANs), and heterogeneous RAT standards, operating in the same spectrum band. The nodes are expected to operate under different transmission policies according to regulatory policies, licence conditions and operator policies. The nodes are also expected to operate under different interference management policies depending on the coexistence management service or policy that they are subscribed to. Modelling of such RF environments for radio resource management or frequency planning is likely to involve complex multiple relationships such as network dependency of nodes, and membership of interference coordination groups and coexistence groups.

In radio resource allocation, graph theory is conventionally used to represent radio device/network relationships. However, the concept of an edge in a traditional graph, which is a two-element subset because an edge can only connect two vertices, is not sufficient to model multiple relationships which ought to be represented by subsets of cardinality that is greater than 2. On the other hand, a hypergraph is a generalisation of an undirected graph in which a hyperedge is a subset of arbitrary cardinality rather than just 2 as in traditional graphs. Hypergraph theory has found application in modelling of cumulative interference from secondary user devices to prevent harmful interference to licensed user devices [40–45]. Hypergraph theory has also been used to model network dependency in a heterogeneous radio environment [46]. The novelty in this thesis is that hypergraph theory is used to model spectral coexistence for coordinated spectrum allocation and for spectrum sharing in the time domain. To the best of the author's knowledge, hypergraph theory has not been applied before in modelling of interference and spectral coexistence-related information in the same data structure. To this end, this thesis seeks to investigate the use of hypergraph theory in modelling spectral coexistence management relationships of networks in a heterogeneous radio environment in order to implement efficient, coordinated radio resource allocation and coexistence management.

Use of hypergraph modelling will be investigated at two layers. At the storage layer, implementation of a hypergraph data model for a coexistence information system database will be investigated. At the application layer, the investigation will involve hypergraph modelling of the RF environment for radio resource allocation algorithms. It is envisioned that this novel RF environment modelling technique could be applied in coexistence mechanisms, automated network management, dynamic spectrum management, frequency planning and machine learning applications for proactive coexistence management.

1.2 Research Aims and Objectives

The main aim of this thesis is to contribute a solution to the aforementioned problem of coexistence among heterogeneous wireless networks in DSA systems by developing a radio resource management framework, RF environment modelling technique and requisite algorithms for efficient allocation of shared spectrum, while ensuring coexistence among heterogeneous secondary networks. Traditional graph theory has been widely used in network modelling, whereby a network is represented by a node in the graph and interference between a pair of networks is represented by an edge between the networks [47–50]. Graph colouring algorithms have been used to to solve the problem of radio resource allocation based on spatial coexistence. Radio resource management frameworks have therefore been developed around the properties of the graph data structure. However, the traditional graph model is insufficient to model spectral coexistence information. The concept of an edge in a traditional graph is a two-element subset, whereas a subset of coexistent networks may comprise more than two networks. Therefore, this thesis proposes the use of advanced graph theory, called hypergraph theory, to model interference and coexistence relationships of the RF environment. Furthermore the thesis proposes a novel radio resource management framework, which is designed according to the properties of the hypergraph data structure. The specific objectives of this thesis are as follows:

1. To analyse state-of-the-art coexistence mechanisms, coexistence management systems and spectrum coordination systems, with the goal of investigating how the performance of these systems can be improved through novel modelling techniques that are more efficient than the current modelling tools.

2. To develop a framework for radio resource management in DSA systems. The framework should be amenable to the modelling technique that is being investigated and should guide the design, implementation and evaluation of centralised RRM applications.

3. To derive a data model for representing interference and spectral coexistence

information of the RF environment in the same data structure. The data model should be amenable to channel allocation algorithms.

4. To develop radio resource allocation algorithms for the centralised RRM application. The algorithms should pass an accuracy test and upon rigorous testing, should outperform existing approaches when compared using an appropriate performance metric.

5. To demonstrate application of the developed framework and to suggest application use-cases.

1.3 Original Contributions

The following original contributions to knowledge

1. In Chapter 3, a survey of state-of-the-art heterogeneous coexistence mechanisms in TVWS and CBRS spectrum bands is presented. In comparison with previous surveys, this survey focuses on the TVWS and CBRS bands, which have different regulatory requirements than the 5 GHz unlicensed band, and discusses how hypergraph-based modelling technique can be applied to the proposed heterogeneous coexistence mechanisms. Preliminary work leading to this survey was published in [16] (peer-reviewed publication number 1 in Section 1.3.1). Through this contribution, the first specific objective that is described in Section 1.2 was met.

2. Chapter 4 presents a survey of the state-of-the-art, database-assisted spectrum coordination and coexistence management solutions. In contrast to the discussions in previous surveys, this survey provides a detailed analysis of the RF environment modelling techniques. This contribution meets the first specific research objective that is described in Section 1.2.

   Furthermore, a framework for radio resource management is derived. The novelty in the framework is that spectral coexistence information is included in the RF environment model, along with interference information, to enable spectrum time-sharing among two or more coexistent networks. This in in contrast to the traditional approach whereby network models have only represented interference relationships for spatial coexistence using a graph data structure. This output contributes sufficiently to the second specific research objective.

3. Chapter 5 proposes a novel technique for modelling the RF environment for spectrum sharing to realise efficient spectrum utilisation using hypergraph theory. To compare the performance of graph-based and hypergraph-based modelling techniques, these two techniques were applied in an IEEE 802.19.1 coexistence management system. Spectrum utilisation results show that the hypergraph-based modelling enables more networks to be allocated operating channels from a given set of available channels than when graph-based modelling is used. These results were published in [51, 52] (peer-reviewed publication numbers 2 and 3 in Section 1.3.1). This contribution exhaustively meets the third, fourth and fifth specific research objectives that are described in Section 1.2.

4. Finally, in Chapter 6, the computational cost of the proposed hypergraph-based spectrum sharing algorithms is analysed and is compared with that of the graph-based spectrum sharing algorithm. The design of the hypergraph model is not complex because computationally-complex hypergraph algorithms are not required in the computing the hypergraph representation, and the hypergraph is decomposed to the form of a traditional graph, without losing coexistence information, to make it amenable to a graph colouring algorithm for allocation of radio resources, which is less complex than hypergraph colouring. This is demonstrated by analytical and actual results which show that the rate of growth of the run time of the hypergraph-based algorithm, with respect to the size of the input, is comparable to graph-based algorithm.

   Chapter 6 also proposes a novel technique for modelling the RF environment to reduce the time-complexity of the bandwidth allocation procedure in spectrum coordination systems using hypergraph theory. The technique was applied in implementation of spectrum coordination in CBRS SAS using WInnForum GAA

Spectrum Coordination. This work was presented as an abstract at a conference [53] (abstract presentation number 1 in Section 1.3.1). This research output contributes to the third, fourth and fifth specific research objectives that are described in Section 1.2.

1.3.1 Research Outputs

The following are the publications and conference presentations that were used to disseminate the research that was carried out in this thesis.

Peer-Reviewed Publications

1. T. Nyasulu and D. H. Crawford, “Comparison of Graph-based and Hypergraph-based Models for Wireless Network Coexistence,” 2021 IEEE International Mediterranean Conference on Communications and Networking (MeditCom), 2021, pp. 203-208, doi: 10.1109/MeditCom49071.2021.9647587.
2. T. Nyasulu and D. H. Crawford, ”Hypergraph-Based Model for Coexistence Management of Heterogeneous Wireless Networks,” 2021 Wireless Days (WD), 2021, pp. 1-8, doi: 10.1109/WD52248.2021.9508293.
3. T. Nyasulu, D. H. Crawford and C. Mikeka, “Malawi’s TV white space regulations: A review and comparison with FCC and Ofcom regulations,” 2018 IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, Spain, 2018, pp. 1-6, doi: 10.1109/WCNC.2018.8377175.

Abstract Presentation

1. T. Nyasulu, “RF Environment Modelling Techniques for Heterogeneous Network Management, (Abstract)” WInnComm 2021, Virtual, USA, 2021.

   Available: https://conference.wirelessinnovation.org/winncomm-2021-top-ten

Poster Presentation

1. T. Nyasulu, D. Anderson, D.H. Crawford, R. Stewart and M. Brew, “TV White Space for Internet Access In The Developing World, (poster)” 2017 Turing Talks, Edinburgh, UK, 2017.

   Available: https://turingtalks.files.wordpress.com/2017/06/nyasulu.pdf

1.4 Thesis Organisation

The remainder of this thesis is organised as follows:

Chapter 2 introduces the general context of the research topic. It includes a background to the need for efficient spectrum utilisation and to the concept of DSA. The research problem of coexistence management among heterogeneous wireless networks in DSA systems is discussed. Hypergraph theory is introduced as the modelling technique that is to be investigated for implementing coexistence management and spectrum coordination applications.

Chapter 3 presents a survey of state-of-the-art technology-dependent coexistence mechanisms to solve the challenge of heterogeneous coexistence. The chapter argues that this approach is neither sufficient nor sustainable because such mechanisms are tailored for specific scenarios and technologies. Nonetheless, such coexistence mechanisms could be exploited in intelligent coexistence decision-making functions. Most importantly, the chapter discusses potential areas in which hypergraph modelling can be applied to improve performance of coexistence mechanisms.

Chapter 4 provides a survey of state-of-the-art modelling techniques for coexistence management and spectrum coordination schemes, and presents an argument that traditional graph theory is not sufficient to model relationships in spectrum coordination and coexistence management systems of heterogeneous wireless networks because such systems involve complex multiple relationships which are beyond the pairwise connections of a graph data structure. Finally, the chapter proposes a high-level solution framework for spectrum coordination and coexistence management which is based on hypergraph data structure.

Chapter 5 investigates spectrum utilisation of a hypergraph-based model for coexistence management through comparison of simulated performance between graph-based and hypergraph-based spectrum sharing techniques. A detailed design of the coexistence decision algorithm is presented. The controlled variables in the simulation are the level of interference and the number of available channels. The performance metric used is spectrum utilisation.

Chapter 6 investigates computational cost of the hypergraph-based model through time complexity analysis using the Big O notation. First, an analysis is done to compare the time complexity of the hypergraph-based and graph-based spectrum sharing algorithms that were developed in Chapter 5. Then a hypergraph-based model for bandwidth allocation in spectrum coordination schemes is proposed, and an analysis is carried out to compare its time complexity with that of a graph-based bandwidth allocation scheme.

Finally, Chapter 7 presents a summary, key results, further work and final remarks.

Chapter 2

Hypergraph Theory and Coexistence Management in DSA

2.1 Introduction

This chapter provides the context of the research. A background to DSA is given to highlight the over-arching objective of spectrum sharing, which is maximisation of spectrum utilisation. This is followed by a review of DSA frameworks in TVWS and CBRS spectrum bands and the challenge of coexistence among heterogeneous radio systems is discussed. Next, graph theory and hypergraph theory are introduced as mathematical tools for modelling the RF environment in coexistence management solutions. Finally, an argument is presented as to why hypergraph theory is more suitable than graph theory and why it is worth investigation in this thesis, in the light of comparison with previous work.

2.2 DSA Background

In a bid to ensure universal access to internet services, the US Congress directed the FCC to develop a National Broadband Plan (NBP) in early 2009 [54]. The plan was released in 2010 and four key objectives were identified. One of these objectives was to ensure efficient allocation, use and management of government-owned and governmentinfluenced resources such as radio spectrum. The plan indicated that the FCC at that time only had 50 MHz of spectrum in inventory, which was far much less than the amount of spectrum that was required to meet the growing demand. The plan therefore made several recommendations on spectrum policy including: to make 500 MHz of spectrum available within 10 years, to provide mechanisms and incentives to re-purpose spectrum to more flexible usage and to introduce innovative spectrum access models such as opportunistic and licence-exempt use of spectrum.

In 2012, the European Parliament and Council approved the first Radio Spectrum Policy Programme (RSPP), which contains strategic objectives for spectrum policy and harmonisation in accordance with the Europe 2020 Initiative and the Digital Agenda for Europe [55]. The programme identified several action points, including: to identify 1200 MHz of wireless spectrum to meet the demand for wireless data traffic, to promote spectrum sharing in order to ensure efficient use of spectrum and to improve spectrum access for innovative wireless applications.

Both the US and EU strategic plans underscore the need for efficient spectrum management in order to meet the demand for wireless spectrum. Wireless signals are conveyed through the electromagnetic spectrum, a finite resource that has become a scarce resource because, under the current static spectrum allocation policy, the demand for bandwidth is greater than the supply. While technologies have been developed to increase the amount of data that can be carried per unit of bandwidth, more bandwidth can be freed up through efficient and innovative spectrum management approaches.

2.2.1 Spectrum Occupancy Measurements

Inefficiencies in spectrum management came to light when findings from spectrum utilisation measurements confirmed that generally, a large amount of spectrum is not in use at all times and/or in all geographical locations. In July 2002, FCC's Spectrum Policy Task Force conducted a study to assess spectrum use below 1 GHz in Atlanta, Chicago, New Orleans, San Diego and in a suburb in Washington DC. The studies indicated that, while some frequency bands such as those used by mobile network base stations are heavily used, most frequency bands are not in use or are used only part of the time [56]. For instance, the usage data for a police dispatch channel in New York State showed that during the measurement period, typical occupancy was less than 15% and would rise close to 85% during peak periods [2]. Other spectrum utilisation measurements that were done in USA (2005), Singapore (2008), Czech Republic and France (2008-2009), Japan (2012) and Malawi (2012-2013) also concluded that licensed spectrum is underutilised [2–6].

Under the traditional policy of static spectrum allocation or *"command-and-control"*, large portions of allocated spectrum are underutilised and are unavailable to other users and services other than the licensed user and service. There is therefore a significant amount of "spectral holes" in frequency bands which have been allocated to a specific service or to a specific company or organisation. These "spectral holes" are called *"white spaces"*. This fallow spectrum could be put to use if the current regulation policy approach of allocating a particular band to a technology, service or operator could be transformed to a more flexible and efficient approach that allows other uses for these white spaces when not in use by the priority services.

2.2.2 Efficient Spectrum Management Initiatives

The IEEE 1900.1 standard defines Dynamic Spectrum Access (DSA) as the process of making continuously-changing spectrum assignments to radio access networks within a composite wireless network that is operating in a given location and time [7]. The physical aspects of spectrum utilisation that can be adjusted include the frequency range that can be accessed, and the transmission characteristics such as transmission power. The varying circumstances include, but are not limited to: changes in the environmental constraints such as spectrum availability or operational policies, and changes in the radio state such as its location. The changing objectives may include spectrum-usage efficiency, Quality of Service (QoS) and energy conservation targets.

This form of spectrum assignment is considered by regulators and operators as highly disruptive to the traditional model of spectrum assignment. The service and the company or organisation that has been assigned to operate in a particular spectrum band are referred to as *"primary service"* and *"primary user"*, respectively. *"Incumbent* *users"* is another term used to refer to primary users. *"Secondary users"* could be allowed to use the spectrum, when it is not in use by the primary users, for a service that could be different from the primary service. This kind of spectrum sharing is referred to as Dynamic Spectrum Sharing (DSS), which is an implementation of frequency sharing techniques on a changing basis in response to varying circumstances and objectives, possibly in real-time [7,57]. For instance, a radio system will have to check for frequency bands that are not being used by primary users before it starts transmitting and will have to immediately stop transmitting when the primary user signal occupies that frequency band. Dynamic spectrum sharing techniques are considered to be a subset of techniques for implementing DSA [7].

DSA can take place in various forms. First, primary users could be encouraged to share their spectrum with secondary users who can occupy white spaces in an opportunistic manner on licence-exemption or light-licensing basis. Second, two primary systems may share the same spectrum through real-time leasing and trading of spectrum between two or more operators. This has been termed Licensed Shared Access (LSA) or Authorised Shared Access (ASA). Third, within the same primary system, spectrum may be shared between heterogeneous subsystems, e.g. in 3G systems, macro cells and micro cells may share the same spectrum.

Dynamic channel assignment may be performed by one or more logical entities, within the radio system or network. An external logical entity or party that does not take part in the communications process, such as a spectrum management/assignment database system or a spectrum broker, may also perform the dynamic spectrum assignment process.

2.2.3 Enabling Technologies for DSS

To achieve interference protection of the primary services, three methods have been considered for detection and protection of Primary Users (PUs): beacon signals, spectrum sensing and geo-location combined with spectrum database [8,9]. These methods are used to provide an Secondary User (SU) device with a list of frequency bands or channels that are not being used by the primary services and are permissible for use by the SU device at its geographical location, under the provisions of the regulatory framework. There are other supporting technologies that are necessary for proper functioning of dynamic spectrum sharing. Location technologies, such as General Positioning System (GPS), are used for determination of the geo-location of an SU device in order to get location-specific operating parameters. Transmission Power Control (TPC) mechanisms enable an SU device to automatically adjust its transmission power, in response to a received command, to control interference. Information security features for SUs devices are also necessary to ensure that communication between the database and the device are secure, to prevent the device from accessing unauthorised databases and to ensure that unauthorised parties cannot modify the device to operate in a manner that is not consistent with the regulatory framework.

2.2.3.1 Beacons

In this method, a beacon is used as a controlling signal that implies that the channel is vacant. Secondary users can start transmitting in a channel only if they have detected a beacon signal in that channel. There are two proposals for operation and maintenance of the beacon signal. The beacon signal can be implemented by the primary user and transmitted by a PU transmitter (i.e. TV transmitters in the case of TVWS). However, this would require modifications to the radio hardware standards of primary services. Alternatively, it can be implemented by a third party and transmitted by a fixed transmitter, operating in the concerned spectrum band, and having capability to detect which frequency bands or channels are free [8] [9]. The major issue with this signal method is that beacon signals can be lost when there is a blockage between the beacon transmitter and the SU device as illustrated in Figure 2.1. Also, if an SU device is located in an area where there are no beacon signals, it would be prevented from transmitting even there are no PU devices in operation.

2.2.3.2 Spectrum Sensing

SU devices that are equipped with spectrum sensing technology can autonomously detect the presence of PU transmissions (i.e. TV signals in the case of TVWS) and would

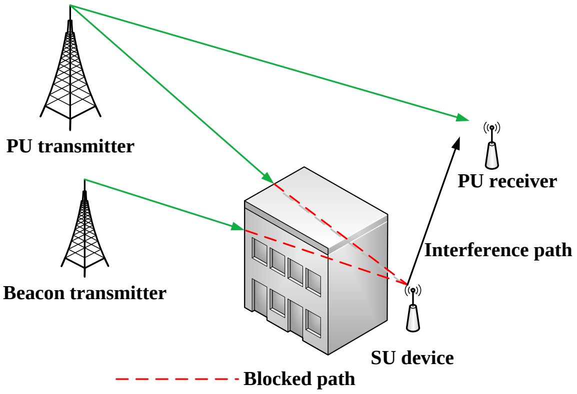


Figure 2.1: Illustration of blocked signals from beacon and TV transmitters.

only use the frequency bands or channels in which PU signals have not been detected. Like the beacon method, this method is also subject to the blocked signal problem as shown in Figure 2.1. This problem arises when there is a blockage between the PU transmitter and the SU device, but there is no blockage between the SU device and the PU receiver antenna. In such a case, the SU device may not detect the signal from the PU transmitter and may cause harmful interference to the PU receiver should it start transmitting on the same channel as the PU transmitter. Furthermore, some primary services, such as Programme Making and Special Events (PMSE) in TVWS, use wireless microphones that transmit at low power, which makes detecting the presence of these licensed signals challenging.

2.2.3.3 Geo-location combined with Spectrum Database

In this method, the SU device is aware of its geo-location coordinates and can access a geo-location spectrum database to acquire a list of frequency bands or channels that are vacant at its location. This method requires additional capabilities on the SU device. It needs to be able to report its location, which may require it to be equipped with a built-in GPS receiver, for example. However, for indoor operation, GPS reception may be poor. It also needs an additional IP connectivity, wired or wireless in another band, to access the geo-location spectrum database. This method requires development and maintenance of a geo-location database which can be implemented by a third party but needs to be certified by the regulator. Currently, the geo-location combined with spectrum database method offers the best short-term solution for interference protection of primary users [8] [9]. It provides audit information for use in the event of interference complaints by licensed primary users.

2.3 TVWS DSA System

In 1990, the FCC asked for High Definition Television (HDTV) service using the same 6 MHz channel that was used by standard definition analogue TV in the USA. This requirement was achieved through data compression techniques for spectral efficiency and through migration to digital electronics. The first standard for Digital Terrestrial Television (DTT) was approved in the US in 1995. By the late 1990s, Europe and Japan had produced their first DTT standards and the first transmissions began in 1998 and 2003, respectively, and coexisted with analogue transmissions. By 2006, European Union (EU) countries started switching off analogue transmissions and this was completed in most of the EU region by 2012. The digital switch-over has led to a significant amount of digital dividend due to the higher spectrum utilisation of digital TV over analogue TV [58].

In addition to this cleared spectrum, there will be typically a number of TV channels in a given geographical area that cannot be used by DTT channels as a result of interference planning for physical separation of co-channel or adjacent channel TV stations. According to modelling studies commissioned by Ofcom in 2009, more than 150 MHz of TVWS spectrum is expected to be available in over 50% of locations and over 90% locations are likely to have around 100 MHz [58]. Developing countries are likely to have plenty of white space spectrum because penetration of TV services is generally low, especially in rural areas. TVWS spectrum availability measurements conducted in 2013 in Malawi and Zambia suggest that up to 75% of the Ultra High Frequency (UHF) TV channels are available in both urban and rural areas [59].

TVWS is considered as a key resource for bridging the digital divide that still exists in rural areas. Due to the favourable propagation characteristics of the Very

High Frequency (VHF) and UHF bands, connectivity solutions that leverage TVWS spectrum have been proven to be a cost-effective means of connecting rural locations that are often characterised by sparsely-populated areas, dense vegetation and rugged terrain [60–64]. In countries where the spectrum costs are high, use of TVWS spectrum would be cost-efficient for both existing operators and new operators [65].

2.3.1 TVWS Regulatory Frameworks

To enforce the requirement that secondary users access TVWS spectrum on the condition that they cause no harmful interference to DTT services and that they vacate the channel when a licensed user occupies the channel, regulatory frameworks stipulate rules for dynamic spectrum sharing as well as radio equipment requirements for secondary devices. An overview of rules for implementation of TVWS ecosystems that have been published by FCC, European Telecommunications Standards Institute (ETSI) and Ofcom is presented in Appendix A. Malawi Communications Regulatory Authority (MACRA) released its first draft TVWS regulations in 2016. A comparative analysis of FCC's, Ofcom's and MACRA's TVWS regulations was carried out and the findings are published in [16].

National regulators in the United States of America (USA), Singapore, United Kingdom (UK), Canada and South Africa have passed TVWS regulations and they have adopted licence-exemption or GAA licence policy in their TVWS regulations [10–14]. However, unlike the Industrial, Scientific, Medical (ISM) band, it is a managed approach since secondary user devices are registered. The main motivation for licence exemption is to stimulate innovation and business start-ups by excluding such entry barriers as expensive licence fees and licence application delays. A compelling case in favour of licence-exempt access in delivering broadband internet and machine-to-machine connections was made in [66]. The study showed that the economic benefits which emerge as a result of enabling licence-exempt access far outweigh the revenue from spectrum licence fees.

Licensed models have been proposed to allow lease of temporary exclusive spectrum usage rights to secondary users in the form of a secondary market for spectrum leasing and auction. The spectrum broker regime may be the most suitable scheme, especially for commercial internet service providers and LTE networks which are obliged by regulation to meet an agreed level of service quality. In 2011, an EU-funded study called "COGnitive radio systems for efficient sharing of TV white space in EUropean context (COGEU)" proved the feasibility of a spectrum broker prototype for real-time radio resource management and spectrum trading of TVWS spectrum [67–71]. The framework was called *"Real-Time Secondary Spectrum Market (RTSSM)"*. A mixed licensed model that serves to achieve the best of both licensed and licence-exempt policies has also been proposed by (COGEU) [72].

2.3.2 Geo-location White Space Spectrum Database

The use of databases to coordinate dynamic spectrum sharing between primary and secondary users in the TV band has been made possible by improvements in computational power to enable rapid processing of propagation analysis and determination of operating parameters of secondary devices. Advanced wireless radio equipment can interact autonomously with the database to submit device parameters and to obtain operating parameters.

An illustration of Ofcom's TVWS database architecture is given in Figure 2.2. The geo-location spectrum database performs the following core functions: protection of primary users and other licensed users from harmful interference caused by secondary users, registration of secondary user devices, enforcement of use of authorised devices by secondary users, real-time provision of operating parameters and instructions to stop transmission.

The Ofcom framework does not require the Geo-location Spectrum Database (GLSD) to use actual spectrum usage data of secondary devices when determining available spectrum. Instead, the database determines the maximum allowable power based on an estimate of worst-case density of White Space Devices (WSDs), thus limiting WSDs unnecessarily. While this approach reduces the complexity of the white space spectrum database, it results in transmit power limits which could otherwise be more generous, possibly unleashing a wave of new use cases for white space spectrum.

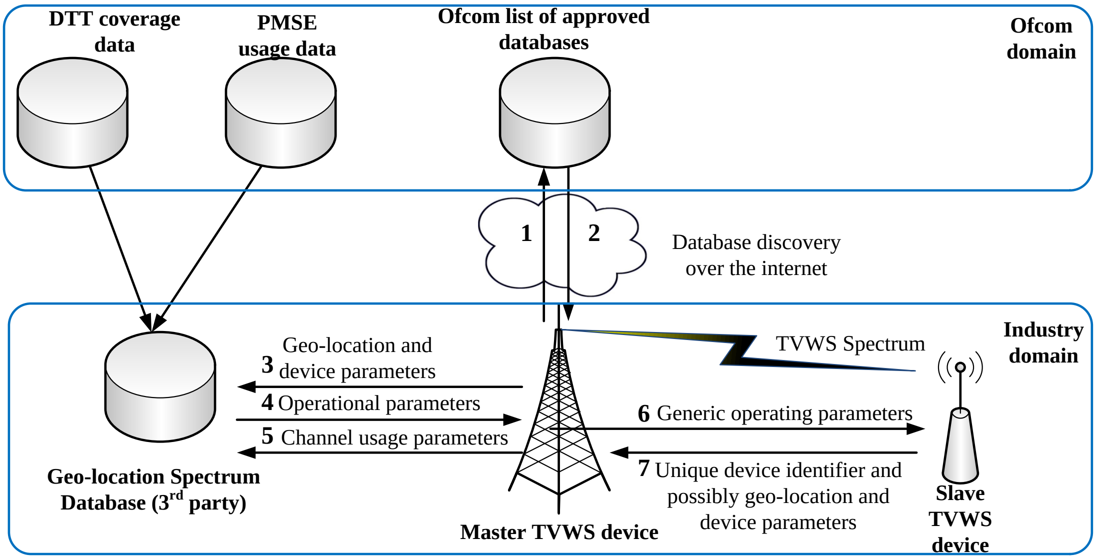


Figure 2.2: Overview of Ofcom's TVWS Framework.

In dynamic spectrum sharing within the TV band, there are two types of interference that need to be addressed: (a) between the primary user networks and secondary user networks, and (b) among the secondary user networks themselves. The current FCC and Ofcom regulatory frameworks for implementing white space databases only address interference protection of primary users from harmful interference that could be generated by secondary users. There is no guaranteed interference protection for secondary user networks from either primary user networks or other secondary user networks. The TVWS spectrum database does not assign exclusive rights to a particular channel when a WSD requests for available channels. Secondary networks are free to occupy any of the available channels. There is therefore the likelihood that more than one secondary network could occupy the same channel and interfere with each other, especially when the number of available channels is not enough to allow each network to occupy its own channel. Interference management at radio system level among the secondary users themselves is not covered in the regulations as this is not typically the focus of regulators.

Coordination of spectrum usage among secondary user devices could facilitate interference management among the WSDs. The ETSI TS 103 145 specifies three possible physical deployment scenarios for the spectrum coordination function: in the regulator-approved GLSD, by another third party database service provider, and in the WSD or network [73]. For a GLSD with spectrum coordination function, a subscribed network specifies the minimum QoS and usage protection requirements such as minimum bandwidth, minimum SINR or maximum allowable interference, and guaranteed minimum available time. The spectrum coordinator function in the GLSD in turn translates these requirements into protection criteria which are used by the GLSD to ensure that priority based channel assignment is maintained in the presence of other networks, including those that have not subscribed to the spectrum coordination service.

The authors in [74] propose implementation of a *"geo-location spectrum database with QoS guarantee"*. In this model, a portion of white space spectrum is reserved by the geo-location spectrum database for assignment of temporary exclusive rights to priority users. This essentially introduces a three-tier access system among the incumbent users, priority licensed users and licence-exempt users.

The authors in [75] propose a geo-location spectrum database that acts as an auctioneer for TVWS spectrum and reserves spectrum for exclusive use of successful bidders. The policies of this framework are aimed at maximising spectrum utilisation and revenue. A dynamic TVWS allocation algorithm was designed to determine the assigned bandwidth and power required to maintain the desired QoS and coexistence among the secondary users. This proposal rules out opportunistic licence-exempt access to white space spectrum.

2.4 CBRS DSA System

CBRS is designated in the FCC regulations under title 47, Chapter I, subchapter D, part 96 of the Electronic Code of Federal Regulations (e-CFR) [23]. The FCC rules that govern use of the 3.5 GHz band for CBRS have three objectives:

1. to protect incumbent users from interference. Incumbent users are federal radio location services, fixed satellite services and grandfathered wireless broadband licensed services (that is wireless broadband services that were were already op-

erating in the band before introduction of CBRS,

2. to make additional spectrum for flexible broadband, improved broadband access and performance,

3. to facilitate wireless broadband for industrial applications, innovation and economic growth.

The CBRS frequency band covers 150 MHz of bandwidth from 3550 MHz to 3700 MHz. The CBRS band has a three-tier access model. Incumbent users operate in the top tier and must be protected at a given location and time. Users that acquire Priority Access Licences (PALs) through auction operate in the middle tier and are protected from other PAL users and GAA users. PAL users shall operate in the 3550-3650 MHz band. GAA users operate on the bottom tier and are not guaranteed any interference protection. GAA users can occupy any vacant spectrum in the entire band.

2.4.1 CBRS Framework and Ecosystem

The CBRS rules designate two kinds of fixed CBRS devices (CBSDs). Category A CBSDs are low power devices that can transmit at a maximum effective isotropic radiated power (EIRP) of 30 dBm/10MHz channel, antenna height cannot exceed 6m Height Above Average Terrain (HAAT) for outdoor operation. Typical use cases include low power access points and femtocells. Category B CBSDs are high power devices that can operate at EIRP of up to 47dBm / 10 MHz channel. Typical use cases include point-to-point and point-to-multipoint links. An end-user device is a device that is controlled by an authorised CBSD and can operate at maximum power limit of 23 dBm/10 MHz. However, an end-user device is not considered as a CBSD.

The functional architecture of the CBRS system is illustrated in Figure 2.3 [76]. It consists of three main entities: the Environmental Sensing Capability (ESC), the SAS and the FCC Database. The ESC is a system that uses signal sensing to detect the presence of an incumbent federal user signal and communicates such alerts to the SAS. Typically, this would consist of a commercially operated network of sensing nodes that can be used to detect signals from federal fixed or shipborne radars in the vicinity of exclusion zones and in coastal areas. An ESC must be approved by the regulator. Access to spectrum is managed by the SAS. A SAS shall base its spectrum use authorisation on the information about incumbent users that is obtained from an FCC-approved ESC and from the FCC Database. The purposes and functionality of the SAS include:

1. implementation of interference protection of incumbent users and PAL users,
2. registration and authentication of CBSDs,
3. determination and assignment of operating frequency and maximum transmit power levels to CBSDs,
4. enforcement of exclusion zones and protection zones for incumbent and PAL users,
5. security of transmissions between the SAS and CBSDs,
6. interference complaint resolution,
7. coordination of operating parameters to minimise interference between GAA users operating Category B CBSDs as per sub-part 96.35 of the rules in [23].

2.5 Challenge of Heterogeneous Coexistence Management

In this thesis, a heterogeneous radio environment refers to radio systems that operate using different Physical (PHY)/Media Access Control (MAC) designs. Heterogeneous wireless environments can take two forms. First, when independently-operated networks, using different RAT standards, operate in the same spectrum band, they form a heterogeneous radio environment. Second, a composite radio system that is composed of radio subsystems that use different RAT standards is a heterogeneous radio system. For instance, a composite TVWS radio system could be made up of an IEEE 802.22 Wireless Regional Area Network (WRAN) radio for the back-haul connection and an IEEE 802.11 Television Very High Throughput (TVHT) radio for the access network.

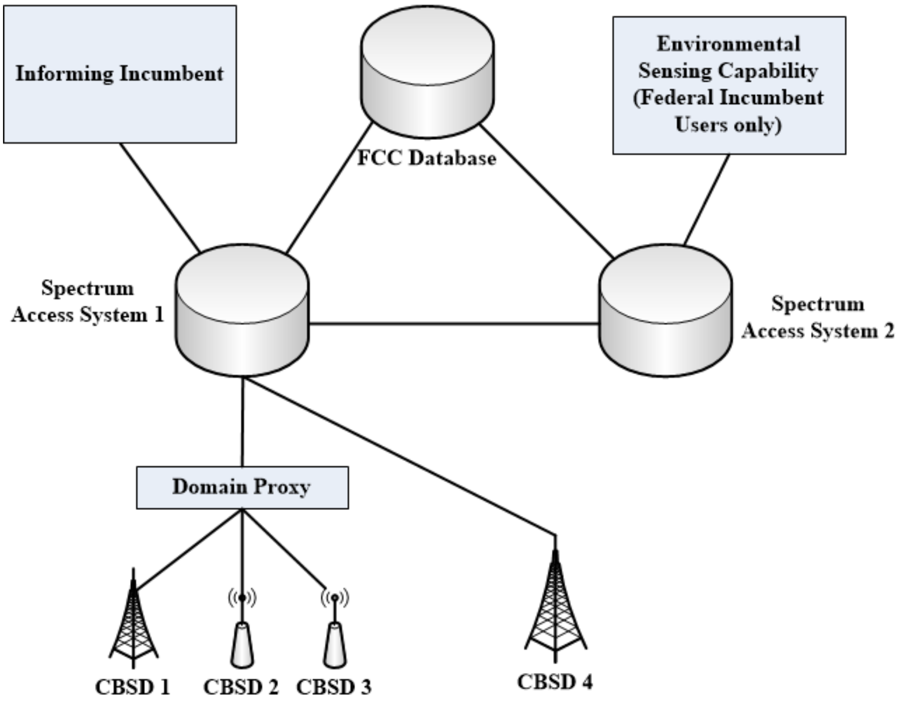


Figure 2.3: CBRS Functional Architecture.

One of the functions of the MAC sublayer is to control access to the shared physical transmission medium. Media access control methods can also incorporate coexistence methods for preventing or mitigating electromagnetic interference in order to coexist with different wireless devices and standards in the same frequency band. Such coexistence mechanisms can be classified into two: autonomous (non-collaborative) and collaborative methods, depending on whether the methods require different devices or networks to cooperate [77].

Autonomous coexistence protocols can be used independently by any device or network and do not require any communication or cooperation between interfering networks e.g. Channel Sense Multiple Access/Collision Avoidance (CSMA-CA), dynamic frequency selection, and transmission power control. Radio devices or networks make independent decisions about channel selection and interference mitigation based on context information that is gathered through individual observations. There is no information exchange between networks and there is therefore no need for a common control channel or central infrastructure. Each system aims at maximising its own performance based on knowledge of the local radio environment. With the exception of CSMA-CA, autonomous coexistence mechanisms do not enable channel sharing. Such mechanisms are generally sufficient when there are adequate spectral resources such that each network may operate in a separate channel. Coexistence becomes a challenge when the available spectrum is not sufficient to provide a separate channel for each network or MAC/PHY design.

When the environment consists of heterogeneous networks, different radio standards cannot coordinate channel access because they use different wireless protocols. Media access control mechanisms specified for the TVWS and CBRS radio standards can only enable effective spectrum sharing when the spectrum is shared by similar radio systems that use the same MAC/PHY standard [22]. For instance, co-channel IEEE 802.22 base stations share one or several super-frames and each base station uses only specific frames for transmission. Radio systems that are based on other standards, such as IEEE 802.11 TVHT, cannot join a frame schedule used by IEEE 802.22 base stations because their frame structures are different, among other factors. On the other hand, using the CSMA-CA algorithm, IEEE 802.11 TVHT devices can back-off when an IEEE 802.22 radio is transmitting, but the reverse is not true. The IEEE 802.22 radio would not back off because it is an “impolite radio”. Apart from incompatible media access control strategies, different PHY/MAC standards have other different operational characteristics and requirements such as transmission powers, channel bandwidths, packet size, which make media access coordination challenging [22].

2.5.1 Impact of Interference in a Heterogeneous Radio Environment

In [78], the authors performed stochastic geometry analysis to evaluate the percentage reduction in service area of cognitive TVWS wireless networks as a result of mild to severe interference from neighbouring networks. The objective of the study was to make a case for the future need for coexistence mechanisms in TVWS. The study used the metric fractional service area as a measure of quality of service. The fractional service area measured the fraction of the service area attained under mutual network interference conditions compared to that attained under no interference. The results showed that unless the number of available channels is sufficiently large, no reasonable service area can be achieved. As the number of available channels was increased, the fractional service area became increasingly sensitive to the density of Access Points (APs). When the number of available channels was held constant, equivalent service areas were obtained for path loss exponents of 2 to 6, with path loss exponents 3 and 4 representing rural areas and 6 representing urban areas. It was concluded that for the same number of available channels, rural and urban areas will obtain equivalent effective service coverage areas despite the significant difference in AP density between rural and urban areas. This was attributed to the favourable propagation characteristics in rural areas, which, though desirable from a communication point of view, also make signals susceptible to causing interference.

A controlled study was conducted in [79] to analyse performance and coexistence among IEEE 802.15.4, 802.11 and 802.22 radio systems operating in TVWS spectrum, and located in geographical proximity. The study concluded that generally, all of the systems would be significantly degraded if the interferer is located within 12m range. In [80], a simulation was conducted to evaluate the performance of an IEEE 802.22 system when co-channel IEEE 802.11af (now called 802.11 TVHT) systems are operating near an IEEE 802.22 Base Station (BS) and its Customer Premise Equipment (CPE). It was found that the upstream throughput of the IEEE 802.22 radio system was significantly degraded due to loss of control data.

Performance evaluation of LTE and Wi-Fi coexistence in TVWS spectrum was studied in [26] in the light of proposals for off-loading LTE traffic to unlicensed spectrum. The results showed that, while LTE systems were slightly affected by Wi-Fi, Wi-Fi was significantly impacted by LTE transmissions because the Wi-Fi nodes were blocked from accessing the channel and remained in “LISTEN” mode for more than 96% of the time. Results of another study on coexistence of LTE and Wi-Fi in a dense deployment scenario showed that Wi-Fi co-channel throughput decreases by up to 97% in the presence of LTE interference, whereas LTE co-channel throughput is reduced by up to 10% only [27].

The 3rd Generation Partnership Project (3GPP) requires that Long Term Evolution Unlicensed (LTE-U) should use Listen-Before-Talk (LBT) mechanisms to coexist fairly with other network technologies, such as Wi-Fi, in unlicensed spectrum [81]. The study in [82] assessed suitability of the LBT channel access mechanism for high- and low-power networks based on LTE technology operating in GAA CBRS spectrum. Throughput performance results showed that the mechanism is most effective when the GAA ecosystem is comprised of low-power CBSDs only. This is because, high-power CBSDs have a longer communication/interference range than low-power CBSDs and therefore a higher number of neighbour CBSDs would detect their transmissions and back off. This reduces opportunities for spectrum reuse, and hence degrades the overall throughput. The authors therefore conclude that, in scenarios of asymmetric operating power, interference mitigation could be more effective if LBT is combined with coordinated channel allocation in such a way that GAA CBSDs with highly asymmetric power are not allocated overlapping channels [82].

2.5.2 Significance of Coexistence Management

This thesis aims at addressing needs that are envisioned when deployment of large scale TVWS and CBRS networks operating under the control of a GLSD and a SAS, respectively, shall begin to roll out. Licence-exempt spectrum resources that are available to anyone may be used extensively, leading to spectrum congestion. Uncoordinated spectrum access is suitable for small scale deployments indoors or locally. However, for large scale or multiple co-located networks, spectrum coordination is necessary to minimise the likelihood of harmful interference.

Signals in the TV band travel further for the same transmission power than those in the upper frequency bands such as the ISM band. This propagation characteristic makes TVWS spectrum attractive for wide coverage applications. However, it also renders TVWS radios prone to causing or receiving interference because of larger cell sizes and capacity to serve more end user devices [78]. When commercial operators start deploying independent TVWS networks, there shall be the possibility of more than two operators operating in the same area without knowledge of the operating parameters of the other networks. Without proper coordination of operating channels, isolation of sources of interference and resolution of interference cases in such scenarios shall be almost impossible.

The OnGo Alliance specifications for LTE-Time Division Duplex (TDD) and NR-TDD in CBRS spectrum include multiple options for Uplink (UL)/Downlink (DL) configurations. LTE-TDD and NR-TDD cells require cell phase synchronisation and compatible UL/DL TDD configurations in order to effectively coexist in the same channel [39]. Although LTE-U and MultiFire specifications are initially focused on 5 GHz unlicensed spectrum, these technologies could also be potential candidate RATs for the CBRS and TVWS bands [81, 83, 84]. The 3GPP requires that the core technology should be as frequency-agnostic as possible and that these network technologies should use LBT mechanisms to coexist with Wi-Fi network technologies in unlicensed spectrum [81].

Radio resource allocation and coexistence management are not new issues in wireless communication. However, the challenge is distinctive in spectrum that is accessed using DSA techniques because of the dynamic nature of the availability of spectral resources. DSA systems require dynamic coordination of spectrum allocation and automated network management. Cognitive radio is capable of spectrum agility, which is the ability to change its operating frequency dynamically based on the spectrum conditions. But, in the presence of two or more independent heterogeneous networks, there is a challenge related to switching between available frequency bands to provide smooth spectrum access without interruption to service as a result of harmful interference among the networks. This dynamic spectral environment makes manual network planning and operation of large networks more challenging than in static spectrum assignment environments. To this end, the goal of this thesis is to develop a framework for coordinated dynamic radio resource allocation that ensures coexistence among heterogeneous DSA networks.

2.5.3 Approaches to Coexistence Solutions

A survey of state-of-the-art research proposals on heterogeneous coexistence solutions showed that there are three general approaches to solving this challenge. These approaches can be structured in a hierarchy as follows, from the bottom of the hierarchy to the top.

1. Technology-dependent coexistence mechanisms that can involve hardware and/or wireless protocol modifications to specific MAC/PHY designs in order to facilitate coordination of access to shared wireless media between radio systems that operate using those specific MAC/PHY designs.
2. Technology-agnostic coexistence management methods for managing coexistence between two or more radio devices/networks, which may operate using different wireless protocols with different coexistence mechanisms. This function could be implemented within a radio device/network or by a logical entity that does not take part in the communication process.
3. Technology-agnostic high-level spectrum coordination that coordinates bandwidth allocation to groups of networks that are under the management of different coexistence managers. Interference mitigation is achieved by allocating non-overlapping bandwidth to coexistence groups whose member radio devices/networks have potential to interfere with radio devices/networks of the other coexistence group.

A survey of state-of-the-art research on heterogeneous coexistence mechanisms that are based on the first approach is presented in Chapter 3, whereas a survey of coexistence management solutions that are based on the second and third approaches is presented in Chapter 4. The surveys are focused on techniques for modelling the RF environment and algorithms for radio resource allocation.

2.6 Investigation of RF Environment Modelling Techniques

An RF environment herein refers to all secondary radio devices and networks that are operating in a given spectrum band in a given location at a given time. The RF environment model is defined as a representation of how the device/system parameters (i.e. transmit frequency, power, desired SINR) and the spectral factors (i.e. signal propagation characteristics and number of available channels) interact so as to affect each other's performance [78]. Modelling is the art of formulating an application in terms of precise, well-documented problems in order to apply well-known algorithmic design techniques [85]. Algorithms are designed to work on well-defined data structures. Proper modelling can therefore eliminate the need to design new algorithms by relating an application to what has been done before. In this framework, RF environment modelling involves representing the RF environment as a well-known data structure to which algorithms of radio resource allocation can be applied.

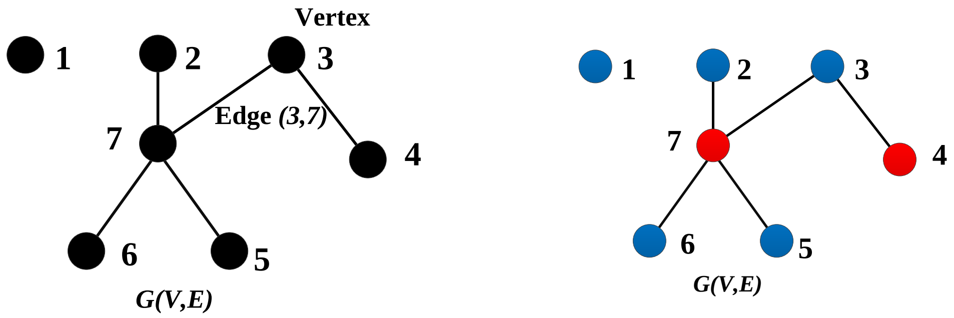
2.6.1 Basics of Graph Theory

A graph is a set of vertices and edges connecting some pairs of the vertices [86]. When graph theory is used in modelling, a vertex represents an entity and an edge represents a relationship between a pair of entities. Thus, in traditional graphs, only binary relationships can be represented by an edge since an edge is a two-element set comprising the two vertices that it connects.

A graph $G = (V, E)$ consists of a set of vertices V and a set of edges E. An illustration of a graph which has a set of 7 vertices and a set of 5 edges is given in Figure 2.4a. Two vertices are adjacent to each other if they are connected by an edge. For every i^{th} vertex $v_i \in V$, the total number of vertices that are adjacent to v_i is called the degree of vertex v_i, denoted by $\mathrm{d}(v_i)$. The maximum degree over all vertices in graph G is called the maximum degree of G, denoted by $\Delta(\mathrm{G})$. The graph in Figure 2.4a has $\Delta(\mathrm{G})$ of 4. A super-node is a vertex with a large number of edges that are incident on it.

Graph traversal refers to the process of visiting every edge and vertex in a graph in a systematic way. A graph $G = (V, E)$ is classified as an undirected graph if edge $(i, j) \in E$ implies that edge (j, i) is also in E. Thus, an undirected graph has edges that do not have a direction, and an edge can therefore be traversed in both directions. A connected set in a graph refers to a set of vertices in which any two vertices are connected to each other through at least one edge. In Figure 2.4a, vertices {2,3,4,5,6,7} form a connected set. Graph traversal is applied in solving graph problems, such as searching for connected sets in a graph. Examples of graph traversal algorithms include Breadth-First Search (BFS) and Depth-First-Search (DFS).

Vertex colouring of a graph $G = (V, E)$ seeks to colour the vertices of V using the minimum number of colours such that i and j have different colours for all $(i, j) \in E$. The chromatic number of a graph is the minimum number colors needed to produce a proper colouring of a graph. Computing the chromatic number of a graph is NP-complete, as such heuristic methods are used. Vertices are coloured sequentially and the choice of colour depends on the colours already assigned to the vertex's neighbours. These methods differ in how the next vertex is selected and how a colour is chosen. Selecting vertices in decreasing order of vertex degree is preferred because high-degree vertices have more colour constraints [87]. An illustration of vertex colouring is given in 2.4b. Vertex colouring algorithms are utilised in allocation, scheduling and clustering of resources, such as spectral resources in wireless communication systems.



(a) An example graph.

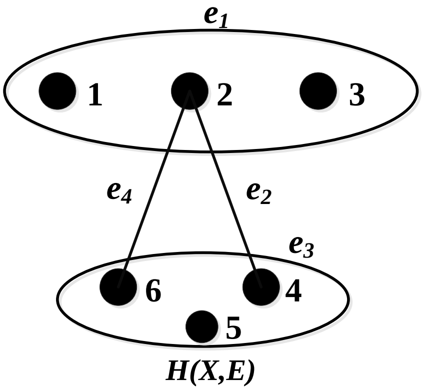
(b) Vertex colouring example.

Figure 2.4: An illustration of a graph and vertex colouring.

2.6.2 Basics of Hypergraph Theory

A hypergraph is a generalisation of an undirected graph in which a hyperedge is a subset of vertices of arbitrary cardinality rather than strictly a two-element subset, as is the case in a graph. While elements of a set are represented by vertices, properties of different subsets or general statements about arbitrary subsets are represented by the hyperedges [86, 88]. In a hypergraph, the relationships can be multifaceted, which allows modelling of multiple features at a time [89].

An example of a hypergraph is illustrated in Figure 2.5. Let H be a hypergraph $H = (X, E)$. $X = \{x_1, x_2, ..., x_n\}$ is a set of vertices of hypergraph H and $E = \{e_1, e_2, ..., e_m\}$ is a set of hyperedges of hypergraph H such that $e_j \neq \emptyset$ and $\bigcup_{j=1}^{m} e_j = X$. A hyperedge is therefore a subset of any number of vertices. In the hypergraph shown in Figure 2.5, hyperedges e_1 and e_3 contain 3 vertices each, whereas hyperedges e_2 and e_4 contain 2 vertices each.



	e_1	e_2	e_3	e_4
1	1	0	0	0
2	1	1	0	1
3	1	0	0	0
4	0	1	1	0
5	0	0	1	1
6	0	0	1	0

I(H)

Figure 2.5: An example of a hypergraph and its representation using an incidence matrix.

The cardinality of the j^{th} hyperedge, denoted by $|E_j|$ is called the degree of the hyperedge E_j. Any two hyperedges are said to be adjacent if the intersection of their sets is not an empty set. A hypergraph is represented in the form of an incidence matrix, $I(H)$, which has one row for each vertex and one column for each hyperedge. In Figure 2.5, the incidence matrix of the example hypergraph is shown. A vertex

$x_i \in X$ and a hyperedge $e_j \in E$ are said to be *incident* to each other if x_i belongs to hyperedge e_j, that is:

$$I_{ij} = \begin{cases} 1 & \text{if } x_i \ \in \ e_j, \\ 0 & \text{if } x_i \ \notin e_j. \end{cases} \tag{2.1}$$

2.6.2.1 Hypergraph Operations

Weak Deletion of a Hyperedge

Weak deletion of $e_j \in E$ from H is to remove e_j from E. This procedure is illustrated if Figure 2.6.

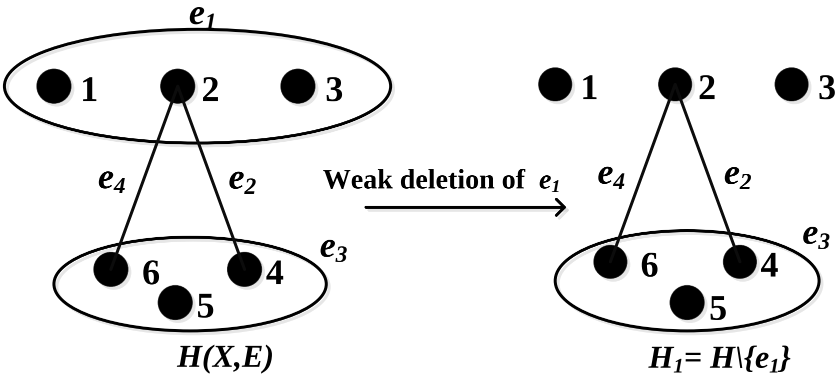


Figure 2.6: Weak deletion of hyperedge e_1.

Hyperedge Contraction

Contraction of hyperedges is used to decompose a hypergraph to a desired form [86]. Let e be a hyperedge in a hypergraph $H = (XE)$. A contraction of the hyperedge e involves the following two steps :

- weakly delete e from H.
- replace all vertices of e by one vertex belonging to each e' such that $e' \cap e \neq \emptyset$

This is illustrated in Fig. 2.7.

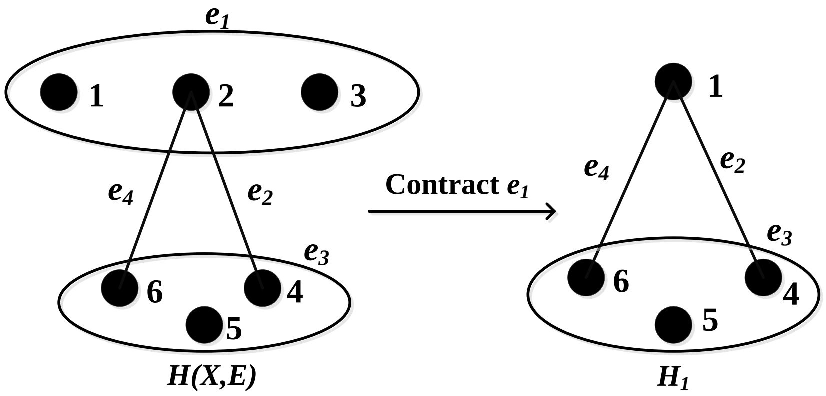


Figure 2.7: Contraction of hyperedge e_1.

2.6.2.2 Hypergraph Colouring

A proper λ-colouring of a hypergraph $H = (X, E)$ is a colouring of its vertices X with the colours from a set $\{1, 2, ..., \lambda\}$ in such a way that every hyperedge $e_i \in E$ has at least two vertices coloured with different colours [86]. Thus, in any proper colouring no edge e_i of size $|e_i| \geq 2$ is monochromatic. Proper colouring is sometimes referred to as weak colouring.

A strong λ-colouring of a hypergraph $H = (X, E)$ is a colouring of the vertices using at most λ colours in such a way that every hyperedge $e_i \in E$ is polychromatic, that is, all vertices in a hyperedge are coloured differently [86]. Strong hypergraph colouring algorithm has found application in radio resource allocation that aims at mitigating the impact of cumulative interference [40–45].

2.6.2.3 Hypergraph Clustering

A graph cut involves partitioning of the vertices of the graph into two disjoint subsets. Graph cuts have found application in optimisation problems. The hypergraph clustering problem is aimed at finding an optimal hypergraph cut solution for effective clustering. Hypergraph clustering has been used in several applications such as radio resource allocation [90, 91] and image processing [89]. In radio resource allocation, hypergraph clustering seeks to optimally partition the vertex set into K disjoint subsets, representing subsets of radios/networks which need to be assigned orthogonal channels [92].

2.6.3 Choice of RF Environment Data Modelling Technique

An RF environment data model is a representation of the RF environment characteristics, using a well-known data structure, in order to solve the radio resource allocation problem using well-known algorithms. The choice of the technique for modelling the RF environment data was based on two factors: 1) the parameters of the RF environment that would be taken into consideration to achieve maximisation of spectrum utilisation and 2) the nature of the data or information from these parameters.

2.6.3.1 Maximising Spectrum Utilisation

The goal of spectrum efficiency is to deliver greater transmission capacity for a given amount of spectrum. The solutions for achieving efficient utilisation of spectrum can be broadly categorised into two: 1) sending more information per transmission, and 2) sending more transmissions per unit of spectrum. The metric that is used to measure efficiency in the first category is called **spectral efficiency**, which is defined as the amount of data that can be transmitted using a specific radio access technology over a certain amount of spectrum. It is expressed in bits per second per hertz (b/s/Hz). It is therefore a measure of how efficiently a radio access technology can utilise a limited frequency spectrum based on the design of the PHY/MAC properties such as the type of modulation scheme. However, this measure does not address spectrum re-use across space and time. The second category is evaluated by how readily assigned spectrum can be reused across space and time by exploiting frequency-sharing, geographical spacing and time-sharing. The factors that affect how efficiently spectrum is used include reuse of frequencies across geography and the percentage of time that a unit of spectrum is in use. In this thesis, the focus is on this second approach.

The International Telecommunications Union - Radiocommunication Sector (ITU-R) recommendation SM.1046-3 defines how to evaluate utilisation efficiency of spectrum that is already assigned [93]. **Spectrum utilisation factor** is defined to be the product of the frequency bandwidth, the geometric (geographic) space, and the time that the frequency is occupied by a user and thus denied to other potential users. While this metric can be used to measure spectrum utilisation, it does not fully address the aspects that are being considered in this thesis.

The thesis is focused on spectrum use by multiple independent wireless networks that are competing for the spectrum to which they all have equal access rights, such as licence-exempt spectrum. In this case, the goal is to assign spectrum to as many independent networks as far as the interference and channel load constraints can allow. As such, unlike with the spectrum utilisation factor, which seeks to maximise the geographical space that is covered by the spectrum, in this thesis networks that have a larger coverage area are not deliberately prioritised over networks that have smaller coverage area. Rather, this thesis aims to provide spectrum to as many independent networks as far as possible with respect to interference, spectral coexistence and channel load constraints. To this end, spectrum utilisation is defined as a measure of how readily spectrum can be reused by multiple independent radio communication systems across space and time. Efficiency of spectrum utilisation will be measured by the number of networks that are assigned an operating channel out of the total number of networks that are competing for the same available channels and will be expressed as a percentage.

This thesis aims to maximise spectrum utilisation by optimising, most importantly, the percentage of time during which a unit of spectrum is put to use through effective time-sharing by coexistence networks, besides optimising the geographical space through frequency reuse. To implement this approach, the parameters of the RF environment that are necessary in decision making process for channel allocation are interference and spectral coexistence.

2.6.3.2 Shortcomings of Graph Theory

Graph theory is used to model radio resource allocation in the spatial domain. The RF environment is represented by an undirected graph such that a vertex represents a radio device or network, and an edge exists between a pair of nodes if the devices/networks that the vertices represent have potential for one-way or mutual interference. Radio resource allocation in space and frequency domain is modelled using a vertex colouring algorithm. Colours represent channels. A vertex colouring algorithm, which ensures that vertices that are connected by an edge between them are not assigned different colours, is used to model channel assignment in such a manner that networks that have potential to interfere if they operate on the same channel are assigned different colours. Thus, the vertex colouring algorithm is sufficient for modelling exclusive channel allocation, whereby a network is assigned an operating channel that is unique among its neighbour networks.

The authors in [27] pointed out their proposed joint graph multi-colouring channel assignment for inter-RAT coexistence management of LTE and Wi-Fi through frequency and spatial diversity fails to exploit Wi-Fi CSMA operation in the joint channel assignment algorithm to further improve spectrum utilization in the time domain through channel sharing among Wi-Fi neighbour networks. It can be intuited that this is due to the fact that the information about groups of Wi-Fi networks that can time-share the same spectrum was not represented in the graph-based data model of the RF environment model and could therefore not be included in the joint channel assignment algorithm.

A coexistence decision algorithm for spectrum sharing is proposed in [94] for use in IEEE 802.19.1 systems. The algorithm introduces shared spectrum allocation on top of exclusive channel allocation. The algorithm selects a network at each step and assigns spectrum to the network. The algorithm first tries to find an unoccupied channel for the network, and if no unoccupied channel is available, the algorithm searches for a channel occupied by a neighbour network of the same MAC/PHY type, subject to channel load constraints. While this approach ensures spectrum allocation stability in that previous allocations are not rearranged to accommodate new networks, channel sharing options are dependent on the previous channel allocations. There is therefore a trade-off between stable channel assignment and maximising bandwidth utilisation in terms of accommodating more nodes.

2.6.3.3 Proposed Approach to Efficient Channel Allocation

A more efficient channel allocation could be realised if the previous allocations could be re-arranged. Algorithms that minimise the need to change channel assignment frequently could be applied. Consider the illustration in Figure 2.8a. The RF environment is modelled using a graph, whereby a vertex represents a radio and an edge connects vertices of networks that have potential for interference if they operate on the same channel. There are 5 radios operating in TVWS spectrum. The 2 access points (AP_1 and AP_2) operate using the same MAC/PHY design, such as IEEE 802.11, and the 3 base stations (BS_1, BS_2 and BS_3) access the spectrum using the same MAC/PHY technology, such as IEEE 802.22. The two RATs cannot effectively coexist in the same channel because, while the 802.11 AP may back off when it detects ongoing transmissions, the 802.22 BS will not back off because it is an “impolite” radio.

Assume that there are 2 available channels. Assume also that an exclusive channel allocation scheme initially assigns channel 1 to BS_2 and channel 2 to AP_1 and BS_3, as illustrated in Figure 2.8a. Figure 2.8b is an illustration of the channel allocation when channel sharing is introduced on top of the exclusive channel allocations. AP_2 cannot be allocated channel 2 to share with AP_1 because it has potential to interfere with BS_3 which is already assigned the same channel. BS_1 is assigned channel 1 to share with BS_2. Figure 2.8c illustrates a more efficient channel allocation whereby, the radios are first organised into groups based on spectral coexistence, and the channels are assigned to groups of networks that can manage interference among them using their inherent MAC protocols, instead of to individual networks, resulting in all networks being accommodated. Thus, it can be intuited that representing spectral coexistence relationships in the RF environment model that serves as input to a radio resource manager may facilitate a more efficient channel allocation when the number of available channels is not sufficient for each network to be allocated an exclusive channel. This is so because channels can be assigned to groups of networks that are capable of spectral coexistence, instead of to individual networks.

The shortcomings of graph theory in modelling of the RF environment data for spectrum sharing in both the spatial and time domains can be summed up as follows. First, an edge in a graph can only connect two vertices, which means that, while an edge is sufficient to represent interference between two networks, it is not adequate to represent groups of coexisting networks that may comprise more than two networks depending on the channel load. Second, an edge in a graph can represent only one type of relationship, thus it cannot represent both interference and spectral coexistence at the same time.

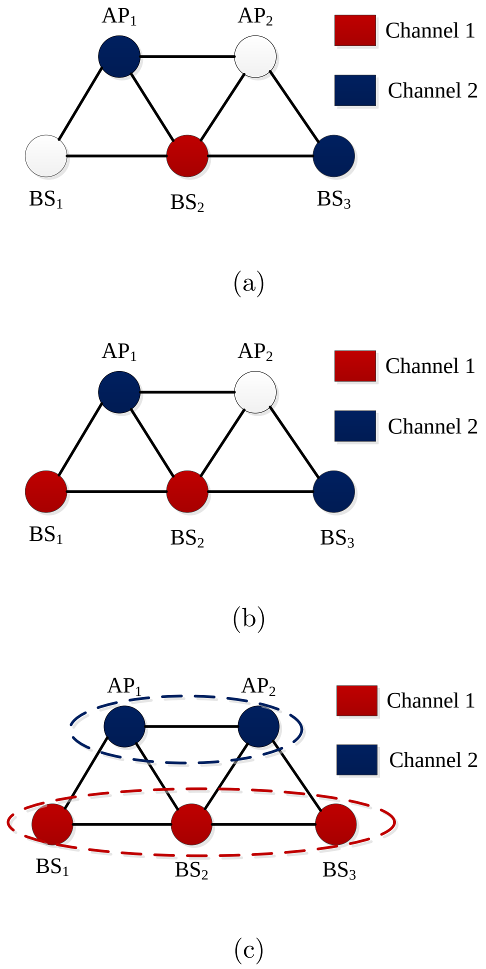


Figure 2.8: (a) exclusive channel allocation, (b) channel sharing on top of exclusive channel allocation, (c) more efficient channel sharing.

2.6.3.4 Choice of Hypergraph Theory

To maximise spectrum utilisation through implementation of an algorithm for spectrum allocation across space and time, requires information about interference and spectral coexistence, respectively, to be represented in the RF environment model so that it can be used in the decision-making process of the algorithm. Interference relationship is evaluated between two networks, whereas spectral coexistence relationship can involve two or more networks depending on channel load. Therefore, representing interference and spectral coexistence information of a given RF environment requires a data structure that meets two requirements. First, the data structure should be sufficient to represent multiple relationships, that is relationships involving more than two entities. Second, it should be possible to represent multi-faceted relationships, that is more than one type of relationships in the same data structure, e.g. representing interference and spectral coexistence information in the same data structure.

Hypergraph theory was therefore chosen over graph theory as the modelling technique because it meets the requirements. A hypergraph is a generalisation of a graph in which hyperedges can connect an arbitrary number of vertices and can represent multi-faceted relationships. In this model, interference relationship is represented by connections between two vertices, and for the purpose of clarity, these are called edges. Spectral coexistence relationships, which can involve more than two vertices, are represented by hyperedges. This is illustrated in Figure 2.9.

Directions of edges of a graph could be used to represent the direction of interference. This is useful in some cases, e.g. when transmit power adjustment is used to control interference, in which case identification of the interference source and victim networks is necessary to determine which networks need to have their transmit powers adjusted. According to the scope of the radio resource allocation algorithm design in thesis, there is no use for information of direction of interference since two neighbour networks cannot share the same network whether interference is one way or mutual. Furthermore, according to the definition of a hypergraph, it is a generalisation of an undirected graph. A hypergraph is represented by an incidence matrix (see Figure 2.5), which represents which vertices are incident on which hyperedges. Thus, the direction of edges cannot be represented in an incident matrix.

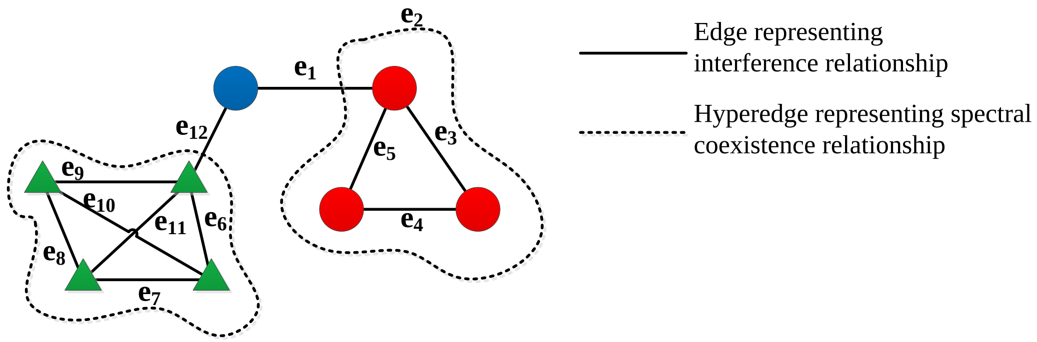


Figure 2.9: Illustration of representation of interference and spectral coexistence relationships using a hypergraph.

2.7 Literature Review on Hypergraph-based Radio Resource Allocation Models

A literature review on use of hypergraph theory in spectrum allocation schemes for dynamic spectrum sharing was conducted. The focus was on what type of relationships in the RF environment model were characterised using hyperedges and what hypergraph procedures or algorithms were used in spectrum allocation. A summary of the comparison between previous work and this study is presented in Table 2.1.

2.7.1 Review of Modelling Techniques

2.7.1.1 Cumulative Interference

Hypergraph theory has been proposed for modelling of potential cumulative interference between secondary user devices and primary user devices in opportunistic dynamic spectrum sharing systems. The hypergraph model is used to represent groups of cumulative interferers so that they are allocated different channels in order to alleviate the the impact of cumulative interference on licensed services. This is illustrated in

Table 2.1: Comparison with previous work.

Ref.	**Communication system type**	**Objective**	**Multiple relationship type**	**Channel allocation method**	**Year**
[46]	Heterogeneous wireless networks	Centralised, measurement-based, spectrum management for coexistence management of heterogeneous wireless networks.	Network dependency	Mixed-integer programming	2014
[91]	Femtocells in cellular systems	To alleviate cumulative intercell interfere in densely deployed femtocell base stations.	Cumulative interference	Hypergraph colouring of clusters	2015
[41–45, 95]	D2D underlaid cellular network	To protect primary user system (cellular network) from interference caused by co-channel D2D pairs.	Cumulative interference	Strong hypergraph colouring [40–42, 44, 45], hypergraph clustering [43]	2018, 2016, 2018, 2017, 2017, 2016
[90, 96]	Cross-cell D2D communications	To protect primary user system (cellular network) from interference caused by cross-cell D2D pairs.	Cumulative interference	Hypergraph clustering	2018
[92]	NOMA-HetNet	To alleviate cumulative interference among macro base stations (MBSs) and femtocell base stations (FBSs).	Cumulative interference	Strong hypergraph colouring	2019
[97, 98]	NOMA-Integrated, heterogeneous V2X Networks	To protect primary user systems (cellular UEs) from cumulative interference caused by a cluster of co-channel heterogeneous secondary user networks in D2D underlaid cellular network.	Cumulative interference	Strong hypergraph colouring	2019, 2018
[92]	NOMA HetNets in cellular networks	To mitigate cumulative interference from femtocells that are allocated the same subcarrier.	Cumulative interference	Hypergraph spectral clustering	2019
This thesis	TVWS and CBRS GAA systems	Centralised, location-aware coexistence management and spectrum coordination of heterogeneous TVWS and CBRS GAA systems.	Spectral coexistence	Hyperedge contraction	2021

Figure 2.10. For instance, hyperedge e_5 contains three vertices: PU_2 which represents a primary user, SU_2 and SU_4 which represent secondary users. Thus hyperedge e_5 is used to represent the information that SU_2 and SU_4 have potential to cause harmful interference to PU_2 in the event of concurrent transmissions from SU_2 and SU_4 in the same frequency band. To mitigate this, it can be seen that PU_2, SU_2 and SU_4 are allocated different colours: red, blue and green, respectively, and the colours represent different channel allocations.

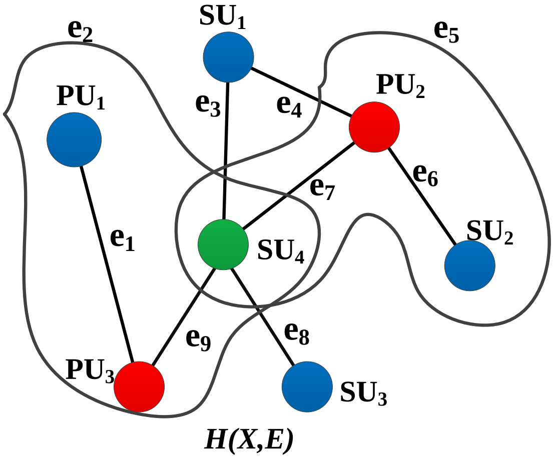


Figure 2.10: Illustration of modelling cumulative interference using a hypergraph.

In future 5G-enabled Vehicle-to-Everything (V2X) networks, various types of V2X communications are expected such as vehicle-to-vehicle (V2V), vehicle-to-person (V2P), vehicle-to-infrastructure (V2I). These heterogeneous networks may share the same wireless medium for data transmissions and hence the need for interference management. In [97, 98], the hypergraph model is used to model interference from clusters of nodes that belong to the same broadcast communication group. A vertex represents a communication group. An edge is used to model interference between a pair of vertices that represent communication groups that can interfere with each other. A hyperedge is used to model cumulative interference from multiple vertices that represent communication groups that belong to the same cluster. A strong hypergraph colouring algorithm is used to model resource block assignment such that vertices that are incident to the same edge and/or hyperedge cannot be coloured by the same colour.

When Device-to-Device (D2D) pairs share the same UL channels with cellular User Equipments (UEs), they can cause severe interference to UEs and to other D2D pairs. In [40, 41], a hypergraph is used to model interference relationships with the purpose of implementing channel allocation that alleviates the impact of cumulative interference. A vertex represents either a D2D pair or a UE. Two vertices are connected by an edge if the radios that they represent have potential to interfere when operating in the same channel. A hyperedge represents a set of neighbouring D2D pairs or UEs whose cumulative interference exceeds a set threshold. A strong hypergraph colouring algorithm is used to model channel allocation such that vertices in the same hyperedge are not coloured by the same colour to eliminate the cumulative interference. The proposed hypergraph-based radio resource allocation algorithm was compared with a graph-based radio resource allocation model in terms cell capacity. Results showed that the the hypergraph-based method effectively increases cell capacity better than the graph-based method. However the hyypergraph-based method has cubic time complexity compared to the graph-based radio resource allocation model which runs in quadratic time. In [45], an interference-aware hypergraph-based codebook allocation for D2D Underlaid Cellular Network Using sparse code multiple access (SCMA) is proposed.

While D2D communication underlaying cellular networks could improve spectrum efficiency, densely deployed D2D pairs could cause severe interference to cellular UEs without proper spectrum allocation, leading to failure by the cellular network to maintain guaranteed QoS. A spectrum allocation algorithm based on location-aware hypergraph colouring (LAHC) is proposed in [42]. The entire cell of the cellular network is divided into regions based on the outage probability of cellular UEs. To achieve protection of the QoS of cellular UEs with low complexity, spectrum sharing between a set of D2D pairs and UEs is limited according to the region in which the set of D2D pairs are located. Cumulative interference from densely populated D2D pairs is characterised using hypergraph theory and spectrum allocation is modelled using hypergraph colouring to eliminate cumulative interference and enhance the system capacity.

While the schemes proposed in [40–42] consider only spectrum resource, the study in [43] considers both spectrum and transmission power. To reduce the complexity, the radio resource allocation problem is decomposed into two sub-problems: subchannel allocation and power allocation. For subchannel allocation, a hypergraph clustering algorithm is proposed, and a bisection algorithm is used for power allocation.

While the studies in [41–43, 95] focus on D2D communication in the same cell, the studies in [90, 96] consider cross-cell D2D communication pairs. The papers propose a protocol to support D2D communications underlaid in cellular networks. Cumulative interference is modelled using a hypergraph, and hypergraph clustering is applied to solve the radio resource allocation problem such that clusters represent channels.

The radio resource allocation schemes in [41–43, 45, 90, 95] are implemented using a centralized architecture and require global coexistence-related information. However, due to the randomness of D2D pairs' activity and limited bandwidth backhaul, the paper in [44] proposes a distributed scheme for resource allocation. The distributed channel access problem is formulated as a local altruistic game and a distributed learning algorithm is proposed to quickly optimise the resource allocation.

Femtocells are very low-range, low-power base stations in cellular systems. As the density of femtocells increases, interference can become a challenge when the coverage areas of femtocells overlap. In [91], a hypergraph model is used to model cumulative interference relationships between femtocells in order to realise an inter-cell interference coordination scheme based on QoS. A two-vertice edge is used to represent interference between a pair of Femtocell Base Stations (FBSs). On the other hand, a three-vertice hyperedge is used to represent three neighbour FBSs whose cumulative interference is less than a set threshold and any edges between vertices of the same hyperedge are eliminated. A greedy hypergraph colouring algorithm is used to allocate all the femtocells into different clusters, each of which has maximum total throughput. FBSs whose vertices belong to the same cluster share the same sub-channel and orthogonal sub-channels are assigned to FBSs that belong to different clusters.

Non-Orthogonal Multiple Access (NOMA) is regarded as a solution for improving spectrum utilisation by allocating a subcarrier to more than one user at the same time within one cell, and additional benefits can be realised by employing NOMA in HetNets. However, NOMA systems are prone to serious cumulative interference because they are sensitive to the weak interference streams, hence the need to allocate spectrum resources intelligently to mitigate cumulative interference. A hypergraph based colouring algorithm that is proposed in [40, 41] to solve the cumulative interference problem requires high computation complexity. Hence, the paper in [92] proposes hypergraph spectral clustering (HGSC)-based algorithm which aims at improving the throughput, guaranteeing the fairness among user pairs associated to the same BS, while alleviating the strong interference and severe cumulative interference in dense NOMA-HetNets.

2.7.1.2 Network Dependency

Spectrum management could provide a solution to coexistence challenges among heterogeneous wireless networks that cannot effectively coordinate access to a shared medium by frequency-isolating incompatible networks. A centralised, measurement-based, spectrum management of heterogeneous wireless networks is proposed in [46]. A hypergraph is used to represent the structure of the RF environment in the 2.4 GHz ISM band such that the hypergraph can be searched for specific relationships among the radios and conflict subgraphs can be derived to realise spectrum assignment that ensures coexistence of heterogeneous wireless networks. This is illustrated in Figure 2.11. A vertex represents a radio device, a hyperedge represents radios that belong to the same network and require the same channel, and an edge between a pair of vertices represents either a transmission link if the vertices belong to the same hyperedge, or an interference relationship.

It should be noted that although Figure 2.11 shows the directions of the link and spatial edges for illustration purposes, the information about directions of the edges cannot be represented in a hypergraph, which is a generalisation of an undirected graph. A hypergraph is represented by an incidence matrix, which is a representation of the information about which vertices are incident on which hyperedges (see Figure 2.5). Thus, the direction of edges cannot be represented in an incident matrix. Instead, the authors use subgraphs to represent the information about the directions of

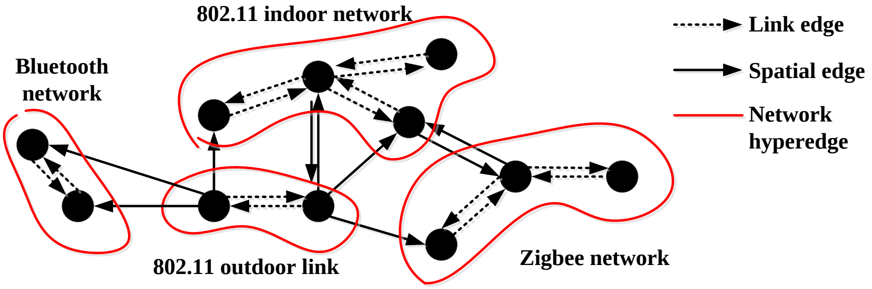


Figure 2.11: Illustration of modelling network dependency using a hypergraph.

the link and spatial edges. A mixed integer program (MIP) algorithm is applied to optimise the channel assignment and to realise spectrum assignment that ensures coexistence of heterogeneous wireless networks based on the constraints that are derived from relationships in the hypergraph and from the conflict subgraphs and based on radio measurements that are reported by the networks [46].

2.7.2 Comparison with Previous Work

As per the review that is presented in Subsection 2.7.1, hypergraph theory has found application in modelling of these two types of multiple relationships in radio resource allocation: (a) cumulative interference, and (b) network dependency. Cumulative interference is modelled using hypergraph theory in [41–45,91,92,92,95,97,98] and hypergraph colouring or clustering algorithms have been used to solve the channel allocation problem based on the constraints represented in the hypergraph data model. In [46], hypergraph theory is used to model network dependency, conflict subgraphs are extracted from the hypergraph and the channel assignment problem is solved using multiple integer programming. This thesis is distinct from previous work in that the type of multiple relationship that is represented using hyperedges is spectral coexistence. The RF environment is structured using a hypergraph such that pairwise interference and spectral coexistence are represented by edges and hyperedges, respectively, for the purpose of modelling coexistence management.

Applications of hypergraphs can be grouped in two: hypergraph representation, and the use of hypergraph procedures. The drawback of most of these applications is the computational complexity depending on how a hypergraph representation is computed and how the hypergraph procedures are exploited. Complexity increases when hypergraph properties are exploited without reducing the size of the hypergraph first [89]. In this thesis, reduction of computational complexity is considered in three ways:

1. since spectral coexistence relationships are derived either through spectral coexistence analysis in TVWS radio system or through CBSD grouping information that is provided by CBSDs in CBRS GAA radio systems, computing hypergraph representation is not complex, and no hypergraph clustering is required,

2. hyperedge contraction is used to reduce the size of the hypergraph by decomposing the hypergraph into the form of a traditional graph, without losing the coexistence information which provides the constraints for radio resource allocation, and

3. in this form, the decomposed hypergraph is amenable to a graph colouring algorithm for spectrum allocation, which has quadratic time complexity, compared to strong hypergraph colouring which could have cubic time complexity [85, 95].

2.8 Chapter Summary

This chapter has outlined the context of the research that is presented in this thesis. DSA policies are aimed at maximising spectrum utilisation by enabling dynamic access to vacant spectrum when and where spectrum is not being used by licensed users. In TVWS, the GLSD rules do not coordinate spectrum allocation among licence-exempt secondary user networks. In CBRS, while the regulations do not guarantee interference protection for GAA users, the regulations mandate that SAS administrators facilitate spectrum coordination of GAA users. A review of previous studies confirmed performance degradation when heterogeneous radio systems were co-located.

Techniques for modelling the RF environment are crucial in solving coexistence management problems. While graph theory is sufficient to model spectrum assignment in the space and frequency domains, it is not sufficient to model spectrum sharing in the time domain as well. Hypergraph theory has therefore been introduced as the modelling technique that will be investigated in this thesis. Coexistence management starts with the design of the radio system. The next chapter therefore reviews MAC/PHY-based coexistence mechanisms and investigates how hypergraph-based modelling could be employed.

Chapter 3

Heterogeneous Coexistence Mechanisms

3.1 Introduction

Multiple wireless technologies are being targeted for dynamic sharing of the same spectrum band, given that a single wireless access procedure cannot meet the specific needs and constraints of all wireless applications and given that efficient spectrum usage is necessary to support the exponential growth of wireless traffic. This chapter presents an overview of RAT standards for TVWS and CBRS. Consequently, coexistence mechanisms between heterogeneous wireless RAT standards operating in shared spectrum continues to be a growing research problem.

The contribution of this chapter is a survey of state-of-the-art solutions for MAC/PHY-based coexistence mechanisms between heterogeneous secondary user networks that operate in shared spectrum bands with equal spectrum access rights. While previous surveys are either outdated or are focused on the 5 GHz unlicensed band, this survey is focused on TVWS and CBRS spectrum bands which are governed by DSA regulatory frameworks. More importantly, this survey discusses the potential of using hypergraph theory in modelling data structures that are used in coexistence mechanisms.

3.2 Comparison of Surveys on Heterogeneous Coexistence Mechanisms

The challenge of coexistence mechanisms in shared spectrum has been studied in various spectrum bands and between various technologies. Table 3.1 presents a comparative summary of existing surveys. Authors in [99] review coexistence mechanisms for Heterogeneous Cognitive Radio Networks (H-CRNs) operating in TVWS, focusing on classification of the coexistence mechanisms that are either specified in TVWS radio technology standards or are proposed in literature. Although this survey [99] includes both technology-dependent mechanisms and technology-independent centralized coexistence frameworks in the taxonomy, the latter is not reviewed in detail. On the other hand, the surveys in [28, 100–102] focus on technology-dependent coexistence mechanisms only. A short survey on coexistence between radar and LTE-U in the 5 GHz unlicensed spectrum is presented in [100], whereas in [28], a comprehensive survey of coexistence between Long Term Evolution Licence Assisted Access (LTE-LAA) and Wi-Fi is presented, including corresponding deployment scenarios. Moreover, in [101], the authors focus on coexistence in the 5 GHz band between Wi-Fi and multiple technologies: LTE-U, LTE-LAA, Dedicated Short Range Communications (DSRC) and radar. The survey in [102] provides a comprehensive review of inter-technology wireless coexistence mechanisms in general, from a unified, system-level perspective.

In comparison, the survey that is presented in this thesis includes research that has been published after the publication date of [99]. While the surveys in [28, 100–102] focus on the 5 GHz unlicensed band, this survey, according to the scope of this thesis, is focused on TVWS and CBRS bands, which has different regulatory requirements than the 5 GHz unlicensed band. Furthermore, besides discussing the weaknesses and strengths of the coexistence mechanisms, this survey investigates the potential of using hypergraph-based modelling in coexistence mechanisms.

Table 3.1: Comparison of Existing Surveys on Heterogeneous Coexistence Mechanisms.

Ref	**Band**	**RAT Types**	**Description**	**Year**
[99]	TVWS	IEEE 802.22, 802.11, 802.15.2 and 802.16, ECMA-392, LTE	A taxonomy according to coexistence mechanism architecture, control channel, coordination technique, cycle state, placement in the cycle state, synchronicity and memory usage. Includes self-coexistence mechanism and technology-standard-independent centralised coexistence frameworks.	2012
[100]	5 GHz	Radar and LTE-U	A short survey of FCC regulations for 5 GHz subbands, radar types, spectrum sharing techniques and spectrum sensing techniques.	2016
[28]	5 GHz	Wi-Fi and LTE-LAA	A comprehensive survey of state-of-the-art research, including an analysis of algorithm implementation, coexistence-related features and considerations, deployment scenarios, challenges and further research directions.	2017
[101]	5 GHz	Wi-Fi and LTE-LAA, LTE-U, DSRC, Radar	A comprehensive survey of coexistence issues between the network technology pairs and coexistence scenarios, current coexistence techniques and open research challenges.	2018
[102]	Generic	Various technologies	A unified, comprehensive survey of inter-technology spectrum sharing, in hierarchical access regulatory frameworks and spectrum commons. Spectrum sharing constraints are discussed at system-level, including regulatory and business aspects.	2019
This thesis	TVWS and CBRS	IEEE 802.11, 802.22, 802.15.4, LTE-U.	A comprehensive survey of state-of-the-art heterogeneous coexistence mechanisms including a taxonomy according to architecture, coexistence coordination media, and coexistence discovery method. Application of hypergraph modelling in coexistence mechanisms is discussed.	2021

3.3 Radio Access Technologies

3.3.1 TVWS

Wireless communication standards have been developed for operation in the TV band in accordance with the applicable national and international TVWS regulatory frameworks. These have been developed by IEEE, ETSI, and ECMA. The Internet Engineering Task Force (IETF) also published a protocol to achieve interoperability between WSDs and white space spectrum databases in Request for Comments (RFC) 745. The protocol is called Protocol to Access White Space databases (PAWS). A summary of the categorisation of the standards is presented in Table 3.2. However, only standards for radio access interfaces are reviewed in this section.

Table 3.2: A Summary of TVWS Technology Standards.

Focus Area	**IEEE 1900**	**IEEE 802**	**ECMA**	IETF
Terminology	1900.1			
Coexistence	1900.2	802.19.1		
Spectrum Usage	1900.4			
Policy Language	1900.5			
Spectrum Sensing	1900.6			
WRAN		802.22		
WLAN	1900.7	802.11TVHT		
WPAN/IoT		802.15.4TVWS	ECMA-392	
Database Access				PAWS

Other use cases for TVWS spectrum have been proposed in the literature. TVWS is considered potential spectrum for traffic off-load to licence-exempt spectrum such as LTE-U and DSRC such as V2X [26, 103, 104]. Feasibility of TVWS spectrum for implementing middle-mile networks using LTE-Advanced technology to connect rural wireless access points to the internet Point of Presence (PoP) was studied in [105].

3.3.1.1 IEEE 1900.7-2015 Standard: White Space DSA Radio Systems

This standard specifies a radio interface, including MAC sublayer and PHY layer, of white space DSA radio systems for fixed and mobile operation in white space frequency bands, while avoiding causing harmful interference to licensed users. The goal is to facilitate development of cost-effective radio systems that support interoperability [17]. This standard is applicable to any white space spectrum and shall follow national and international regulations. This wide variety of use cases created a very wide range of general requirements which could not all be supported in one standard. As such, the developed standard is mainly focused on the wireless local area access network category of use cases [106].

The standard specifies 2 MHz sub-channels and 8 MHz channels. The 1900.7 PHY shall use 8 modulation and coding schemes: Binary Phase Shift Keying (BPSK) (1/2), Quadrature Phase Shift Keying (QPSK) (1/2,3/4), 16-Quadrature Amplitude Modulation (QAM) (1/2, 3/4) and 64-QAM (2/3, 3/4 and 5/6). The standard specifies Filter Bank Multi-Carrier (FBMC) for multi-carrier modulation. FBMC was selected because it has shown better simulated Adjacent Channel Leakage Ratio (ACLR) performance than Orthogonal Frequency-Division Multiplexing (OFDM). ACLR performance of white space radios is regulated in order to prevent interference to licensed primary users. A white space radio that has better ACLR performance is permitted to operate in more TV channels and with higher permitted transmit power than one with poor ACLR performance.

The 1900.7 network shall operate in a master-slave mode, with the designated master node being responsible for network coordination. The method of media access is based on CSMA-CA with a Request to Send/Clear to Send (RTS/CTS) mechanism.

3.3.1.2 IEEE 802.22 Standard: Cognitive Wireless RAN

This standard, which was first published in 2011, is for WRANs that operate in TVWS spectrum. It supports development of broadband wireless access systems that support multimedia services. It was initiated in 2004 to provide reliable and secure wireless broadband connectivity to under-served or unserved communities where wired infrastructure is economically not feasible to roll out because the areas are sparsely populated, among other factors. It is the first cognitive radio-based standard to allow dynamic spectrum sharing of the TV band with the licensed TV broadcasters and wireless microphones on a non-interfering basis according to regulatory requirements for protection of licensed services [107]. The standard specifies the following capabilities to aid spectral context awareness: geo-location, access to white space spectrum database, and spectrum sensing.

In 2012, the committee published the IEEE 802.22.2-2012 Installation and Deployment of IEEE 802.22 Systems, which specifies the recommended engineering practices that will ensure highest broadband rates, longest coverage radius, and the most efficient spectrum use [108]. An IEEE 802.22 network comprises a fixed BS that shall be able to provide broadband internet services for up to 512 fixed or portable CPE devices, serving a coverage radius of 10-30 km. In conditions of exceptional signal propagation conditions, a coverage radius of up to 100 km can be supported with intelligent scheduling of the traffic in the frame to absorb additional propagation delays. The architecture of an 802.22 network is given in Figure 3.1 [18]. More system parameter specifications of the IEEE 802.22 are given in Table 3.3.

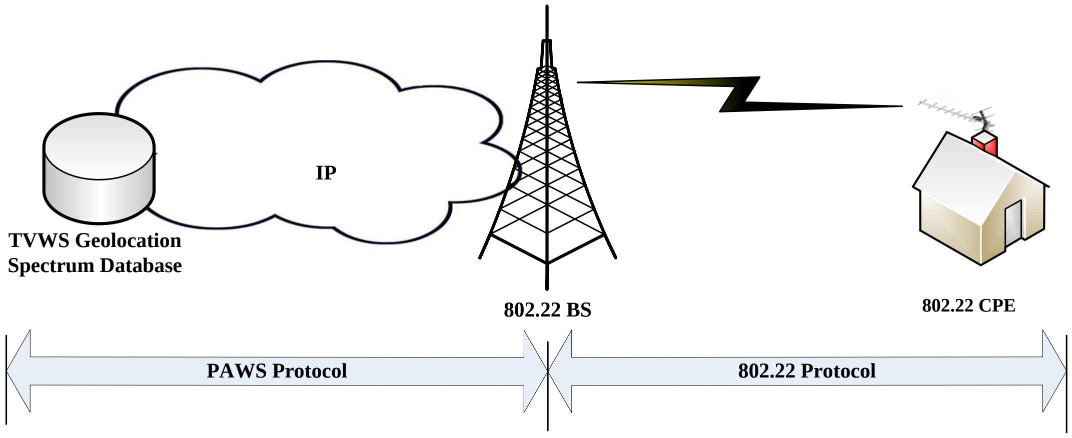


Figure 3.1: IEEE 802.22 Network Architecture.

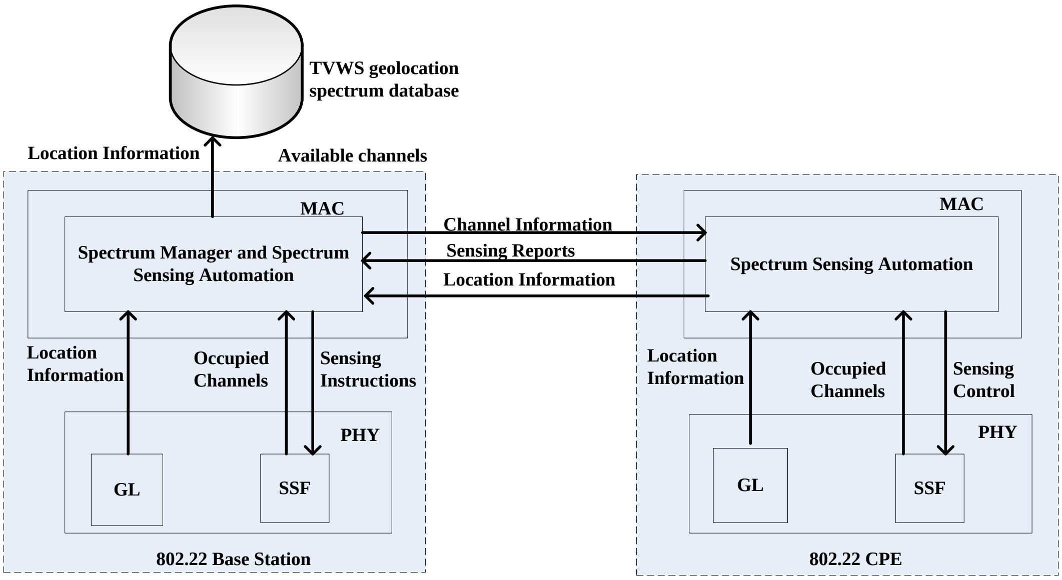
Table 3.3: System Parameters for IEEE 802.22 WRAN.

Parameter	**Specification**	**Additional information**
Supported Frequency Range	54-862 MHz	Subject to national TV Band Allocation
Channel bandwidth	6, 7, 8 MHz	According to regulatory region
Data rate	SISO and single channel operation: 4.54 to 22.67 Mbps (up to 31.78 Mbps optional)	Optional 4X4 MIMO and 4 channel operation: 72.59 o 362.96 Mbps (up to 513.91 Mbps)
Payload Modulation	QPSK, 16-QAM, 64-QAM	
Multiple Access	OFDMA	
Duplex	TDD	
Frame/Super frame size	10 ms / 160 ms	Super frame based on groups of 16 frames
Self-coexistence	spectrum etiquette and on-demand frame contention	

Two amendments to the standard have so far been made. Amendment 802.22a was published in 2014 to provide management and control plane interfaces and procedures as well as enhancements to the management information base (MIB) [109]. In 2015, amendment 802.22b was published to include PHY and MAC layer enhancements for broadband services and monitoring applications in Advanced WRANs (A-WRANs) through an additional PHY mode and additional functionalities of multi-hop relay, multiple channel operations and multiple-input-multiple-output (MIMO) operations and advanced security [110].

The IEEE 802.22 protocol reference model includes a cognitive plane in addition to the usual data plane and management/control plane. Figure 3.2 is an illustration of the cognitive plane. The cognitive PHY layer has three functions: data communications, spectrum sensing and geo-location. The MAC layer provides mechanisms for flexible and efficient data transmission and supports cognitive control mechanisms for reliable protection of licensed service and self-coexistence among IEEE 802.22 systems. The cognitive plane is comprised of the Spectrum Sensing Function (SSF) and Geo-location (GL) functions at the PHY layer and the Spectrum Manager (SM), Spectrum Sensing Automation (SSA) functions and a dedicated security sub-layer at the MAC Layer.

The SM entity shall reside at the MAC layer of the BS and shall maintain spectrum availability information, manage channel lists of backup and candidate channels, manage scheduling of quiet periods for CPEs to perform in-band spectrum sensing, and shall implement coexistence mechanisms. To fulfil these functions, the SM shall use input from SSF, GL and white space spectrum database as well as local regulations and any predefined SM policies. The SM shall make a decision on the the necessary configuration parameters to the MAC which shall in turn remotely reconfigure all the registered CPEs. The SSA entity shall reside at the BS and the CPE and shall implement procedures for out-of-band sensing of the RF environment. The security sub-layer at the cognitive plane enhances the security of the cognitive-based radio access besides the security sub-layer at the data plane.



Notes:
GL – Geo-location function
SSF – Spectrum Sensing Function

Figure 3.2: Reference Model for the IEEE 802.22 Cognitive Plane.

An IEEE 802.22 air interface is required to coexist with not only licensed services but also with other IEEE 802.22 radios such that multiple IEEE 802.22 BSs and CPEs that operate in the same vicinity do not interfere with one another. In IEEE 802.22 networks, interference is further aggravated by the fact that their coverage range can potentially go up to 100 km, and hence the interference range and impact on other co-located IEEE 802.22 cells is larger than in any other existing unlicensed technology.

The MAC layer uses the Coexistence Beacon Protocol (CBP) as transport mechanism for the following inter-WRAN self-coexistence elements: spectrum etiquette and on-demand frame contention. When a BS is powered on, it performs BS network discovery followed by spectrum etiquette process for channel acquisition. If an exclusive operating channel is available, the BS starts operation in the normal mode of data services. If no exclusive channel is available, the BS selects a channel occupied by one or more WRANs and checks if the potential interference is from BSs only or from both BSs and CPEs. The BS has the following options for self-coexistence mechanisms: downstream/upstream split adjustment mechanism if interference comes only from other BSs, otherwise if it comes from the CPEs, it performs on-demand-frame contention with neighbour WRANs on the selected channel by accessing a contention-based self-coexistence window.

3.3.1.3 IEEE 802.11 Standard: Wireless LAN

The 2016 revision of the 802.11 standard [19] is a compilation in one document of the 802.11 standard for wireless local area networks operating in 6 different bands and all the revisions that were released before 2016, including the 802.11af-2013: Television White Spaces (TVWS) operation (Amendment 5) [111]. In this review, the focus is on clause 22 of the 802.11-16 standard, which specifies the TVHT PHY entity based on Orthogonal Frequency-Division Multiplexing (OFDM), which in this thesis is referred to as *IEEE 802.11 TVHT*.

The Basic Channel Unit (BCU) is defined as a 6 MHz, 7 MHz, or 8 MHz TV channel, depending on the applicable regulatory domain. Multi-channel operation is optional for two contiguous or non-contiguous BCUs (TVHT 2W or TVHT W+W), or four contiguous BCUs (TVHT 4W) or two non-contiguous frequency elements, each of which comprises two contiguous BCUs (TVHT 2W+2W). The media access method that shall be implemented in a node (therein called Station (STA)), is a Distributed Coordination Function (DCF)-based CSMA-CA. The standard specifies additional coordination functions: Hybrid Coordination Function (HCF) which includes a QoS facility and Mesh Coordination Function (MCF) that is usable only in mesh Wireless Local Area Network (WLAN) networks.

The architecture of an 802.11 TVHT network operating in the TV white space band is given in Figure 3.3. The main architectural components that sets apart TV white space operation from other bands is the geo-location spectrum database which provides information about TV channels that are available for use by secondary devices, and which in this standard is referred to as Geo-location Database (GDB). The other distinctive architectural element is the Radio Location Secure Server (RLSS) which acts as a local database of the geo-location information and operating parameters for basic service sets (BSSs) that are under its management. It also has access to the GDB.

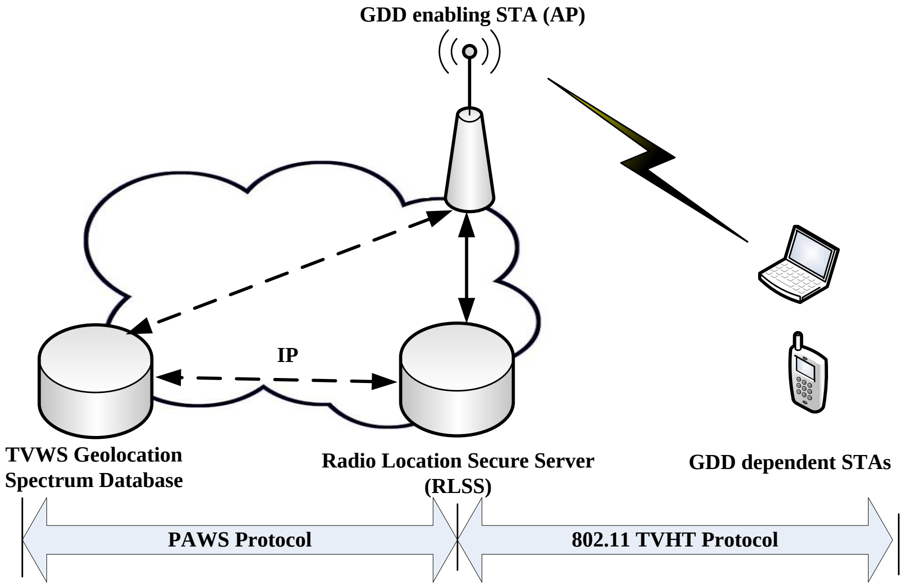


Figure 3.3: Architecture of 802.11 TVHT networks.

The standard defines an STA as any singly addressable MAC/PHY entity operating using the IEEE 802.11 radio system. STA operation that requires information from the GDB for regulatory compliance is termed as a Geo-location Database Dependent (GDD) operation. A *Geo-location Database Dependent (GDD) enabling STA* is required, according to the applicable local regulation, to access the GDB to obtain information about available TV channels and the permitted power limits after submitting its identification, geo-location, device parameters and other information specified in the regulations. A GDD enabling STA has authority to control the operation of one or more *GDD dependent STAs*.

3.3.1.4 IEEE 802.15.4 Standard: Low-Rate Wireless Networks

The 2015 revision of the 802.15.4 standard was created to consolidate all amendments that were made after the 2011 version; which includes the 2014 amendment (802.15.4m) that was published to define alternative PHY and MAC layers for low-rate, low-cost and low-power wireless networks that operate in TVWS spectrum.

The standard specifies a super-frame format that has a Contention Access Period (CAP) and Contention Free Period (CFP). During CAP, devices wishing to communicate shall use ether slotted CSMA-CA or ALOHA mechanism, as appropriate, to coordinate access to the shared medium. The CFP is formed by portions of the active super-frame that have been allocated as Guaranteed Time Slots (GTSs) to applications that are QoS-conscious such as low latency applications or those that require specific data bandwidth requirements.

Three types of PHY implementations are specified for TVWS operation: frequency shift keying (TVWS-FSK PHY), OFDM (TVWS-OFDM PHY) and narrow-band OFDM (TVWS-NB-OFDM PHY). The TVWS-FSK PHY shall use 2-level or 4-level FSK modulation. Six modes of BPSK, QPSK and 16-QAM modulation and coding schemes are specified for TVWS-OFDM PHY and their corresponding supported data rates. TVWS-NB-OFDM PHY has 9 modulation and coding scheme indices from BPSK 1/2 to 64-QAM 7/8.

3.3.1.5 ECMA-392

This standard specifies the PHY layer and MAC sub-layer for personal/portable cognitive wireless networks operating in the VHF/UHF TV broadcasting frequency bands, which, according to international regulations, the extremes of the range of the TV broadcast band is from 47 MHz to 910 MHz [21]. It also specifies a multiplexer (MUX) sublayer to enable the coexistence of concurrently active higher layer protocols within a single device. ECMA-392-compliant devices support at least one of the three device types (master, peer, or slave) and at least one of the bandwidths (6, 7 or 8 MHz). The PHY layer specifies OFDM implementation. Payload bits shall be mapped using any of the 10 allowed modulation and coding schemes ranging from QPSK 1/2 to 64-QAM 5/6.

The MAC service functionality includes mechanisms for detection and protection of licensed TV broadcast and wireless microphone services through access to a TV white space spectrum database and spectrum sensing. The standard also provides for seamless device operation using coordinated channel measurement, channel classification based on either channel measurement report or channel availability information from the white space spectrum database, or both, and transmission power control. Devices can access the medium during the Data Transfer Period (DTP) using Channel Reservation Protocol (CRP) or using Prioritised Contention Access (PCA). In PCA mode, which is a prioritised CSMA-CA access mechanism, devices contend for access to the shared medium based on traffic priority.

In master-slave network mode, the master device coordinates channel access. In peer-to-peer network mode, channel access is coordinated using distributed beaconing and channel reservation. Centralised and distributed self-coexistence protocol and mechanisms are included in the standard to enable neighbouring networks to coordinate sharing of the same channel. Distributed self-coexistence mechanisms include beacon period merging or promoting a slave device to a beaconing device if it observes interference from another network. Centralised coexistence mechanisms include merging two networks into a single master-beacon network.

3.3.2 CBRS

The CBRS ecosystem is expected to be characterised by radio access networks that operate using heterogeneous RATs. Fixed wireless access (FWA) is the default use case since licensed wireless broadband networks were already operating in this band before CBRS was approved. The OnGo alliance is leading efforts for development of 4G LTE and 5G NR solutions for the CBRS band. The OnGo alliance specifications for network architecture aim to allow both the traditional operator deployment model and private network operation, including neutral host network deployment models [112]. The Wireless Innovation Forum (WInnForum) is taking a leading role in standardisation of various aspects of the CBRS system, including software defined radios for operation in CBRS. A field trial for a CBRS ecosystem governed by a SAS was studied in [113]

Federated Wireless, an approved SAS administrator, reported in April 2021 that use of GAA spectrum has been growing exponentially: up to 120,000 CBSDs in just over a year. They concluded that the extensive CBRS ecosytem development using GAA spectrum led to the accelerated speed of Priority Access Licence (PAL) deployment [114]. The FCC announced winning bidders of the auction of PAL spectrum in the 3550-3650 MHz Band on 1st October 2020 [115]. SAS administrators would be able to offer a secondary spectrum market for CBRS PAL holders to lease their spectrum throughout the license area when they are not ready to deploy their network or to lease it for temporary use in a partial geography. The FCC has set up rules to facilitate a paperless secondary spectrum market, called “Light-Touch Leasing”, in order to conveniently establish a “use-it-or-share it” principle for PAL holders [116].

3.4 Taxonomy of Coexistence Mechanisms

A proposed taxonomy that classifies coexistence mechanisms using a diverse set of criteria as shown in Figure 3.4. The discussion of each category includes proposed implementations from literature or technical specifications and the associated features.

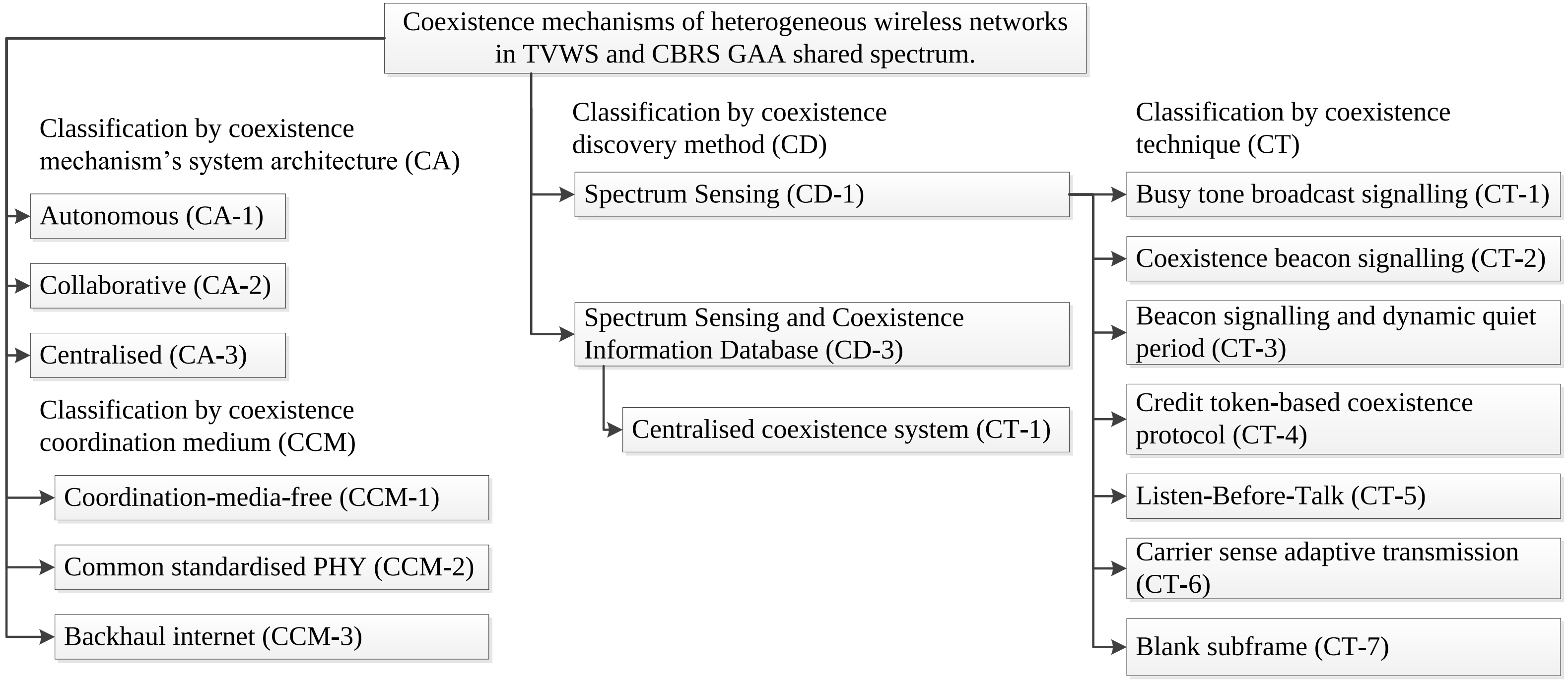


Figure 3.4: Taxonomy of heterogeneous coexistence mechanisms.

3.4.1 Classification by Coexistence Mechanism System Architecture (CA)

The coexistence mechanisn system architecture attribute classifies implementations depending on whether or not inter-network exchange of coexistence-related information is required, and whether coexistence-related information is distributed or centralised.

3.4.1.1 Autonomous (CA-1)

Each network makes its own decisions about operating parameters and manages inter-network interference mitigation based on local evaluation of channel quality. Thus, implementation of autonomous coexistence mechanisms is characterised by low complexity since inter-network coordination is not required. However, autonomous coexistence mechanisms by themselves do not result in overall optimal performance and fairness due to lack of global knowledge of the RF environment and each network aims at maximising its own performance without regard of the performance of other networks.

3.4.1.2 Collaborative (CA-2)

In collaborative protocols, each coexisting network can make autonomous radio resource allocation decisions, but makes use of coexistence information that is broadcast by other coexisting networks via an inter-network communication channel. Such collaborative coexistence protocols have also be referred to as *distributed* coexistence systems since autonomous radio systems are connected to communicate directly and to coordinate using a distribution medium.

Collaborative coexistence mechanisms are more likely to achieve more efficient coexistence decisions than non-collaborative mechanisms owing to broader knowledge of their radio environment through information sharing. Information exchange happens directly or indirectly between networks. Decision making capability is implemented in radio hardware that is responsible for initiating a network such as a base station or an access point.

The shared spectrum ecosystem is anticipated to be characterised by multiple operators, multiple RANs and multiple RATs. In such a radio environment, collaboration becomes complex. The following are the key challenges that would require expensive and complex modifications to the radios and wireless protocols [22]: (a) collaborative coexistence requires common control channel(s) for exchange of coexistence-related information between heterogeneous networks and they generate a lot of overheads as a result of the information exchange between networks, (b) implementation of collaborative coexistence strategies that enable sharing of a channel on frame reservation basis across heterogeneous networks would only be possible if time synchronisation can be achieved across all participating networks, which is a challenging problem [22].

Tight synchronisation is complex to implement among heterogeneous networks that use different wireless protocols. For instance, whereas it may be possible to keep tight synchronisation within an IEEE 802.22 network or across different IEEE 802.22 networks, it may not be possible to include IEEE 802.11 TVHT personal/portable networks unless all systems and protocols are based on a universal reference clock [22]. Thus, in both [117] and [118], the papers propose channel-based reservation for data communication channels, as opposed to frame-based reservation. In [117], frame-based communication is proposed for the control channel only because it is accessed using a common RAT. In [118], time synchronisation is avoided all together in the control channel by opting for a contention-based access method instead.

Other challenges regarding direct coordination between heterogeneous, independently-owned wireless networks are related to conflict of interest issues and customer privacy concerns.

3.4.1.3 Centralised (CA-3)

In centralised coexistence mechanism, exchange of coexistence-related information happens indirectly through a central database. Such schemes require infrastructure for centrally-collected information and each participating network requires access to the central database, e.g. through backhaul internet. The advantage of this approach is that a common standardised radio is not required since exchange of information happens using an Internet Protocol (IP) connection. However, this approach can only be effective if all networks in the environment subscribe to the coexistence information database. Hence, the centralised coexistence system that is proposed in [117] still requires a common RAT for the purpose of detecting networks that are not subscribed to the centralised coexistence information database. The drawback of this approach is the additional requirement for database infrastructure and a backhaul IP connection to access the database. Furthermore, in areas where internet infrastructure is either non-existent or slow, performance of the centralised coexistence mechanisms is likely to be affected. This can be mitigated by having the physical location of the database as close to the subscribed networks as possible and by using delay-tolerant networking techniques.

3.4.2 Classification by Coexistence Coordination Medium (CCM)

This attribute classifies solutions based on the type of interface that is used to exchange coexistence-related information, which determines the design of the solution.

3.4.2.1 Coordination-Media-Free (CCM-1)

In autonomous coexistence mechanisms (CA-1), there is no need for a coordination media since coexisting networks do not exchange any coexistence-related information.

3.4.2.2 Common Standardised PHY (CCM-2)

Coexistence-related information that is conveyed using the air interface can only be decoded by networks that use the same wireless protocol. The common control channel can be provided through a common PHY channel [119]. Heterogeneous networks that collaborate via a PHY channel therefore require additional radio hardware in terms of a common standardised RAT besides their native RATs. An in-band or out-of-band wireless channel may be dynamically designated as a common control channel for the purpose of information exchange [99]. However, reception of signals from the common control channel is subject to other features such as topology.

3.4.2.3 Backhaul Internet (CCM-3)

Indirect information exchange via internet access to a coexistence information database is one way of working around the challenge of inter-network communication between networks that operate using heterogeneous wireless technologies. This method is probably a natural means of information exchange in DSA systems, particularly TVWS and CBRS systems, because the regulatory frameworks already require a master device to have an IP backhaul connection and to have capability for database access [10, 15].

3.5 State-of-the-Art Heterogeneous Coexistence Mechanisms

The most common problems that affect performance of contention-based coexistence protocols when more than one transmitter-receiver pair share the same channel are hidden node collision and exposed node problems. Research on RAT-dependent coexistence mechanisms has focused on resolving these two problems.

The hidden node collision problem occurs when a transmitter is visible from its receiver node but hidden from another transmitter that is visible from the same receiver. When the two transmitters transmit simultaneously on the same channel, the transmissions would collide at the receiver. Consider the illustration in Figure 3.5. The 802.11 TVHT AP is close to the 802.22 CPE but far away from the the 802.22 BS. If the 802.11 TVHT AP cannot sense transmissions from the 802.22 BS, it may be a hidden terminal to the 802.22 CPE.

On the other hand, the exposed node problem happens where a transmitter that senses the activity of another transmitter cannot transmit even though their destined receivers are outside the transmission range of each other. Consider the illustration in Figure 3.5. If the 802.11 TVHT AP is able to detect the signal from the 802.22 BS, the 802.11 TVHT AP cannot transmit when the high-power 802.22 base station is transmitting, even when transmissions from the low-power 802.11 TVHT AP may not interfere with the 802.22 CPE which has a directional antenna. The 802.22 BS then becomes an exposed node to the 802.11 TVHT node.

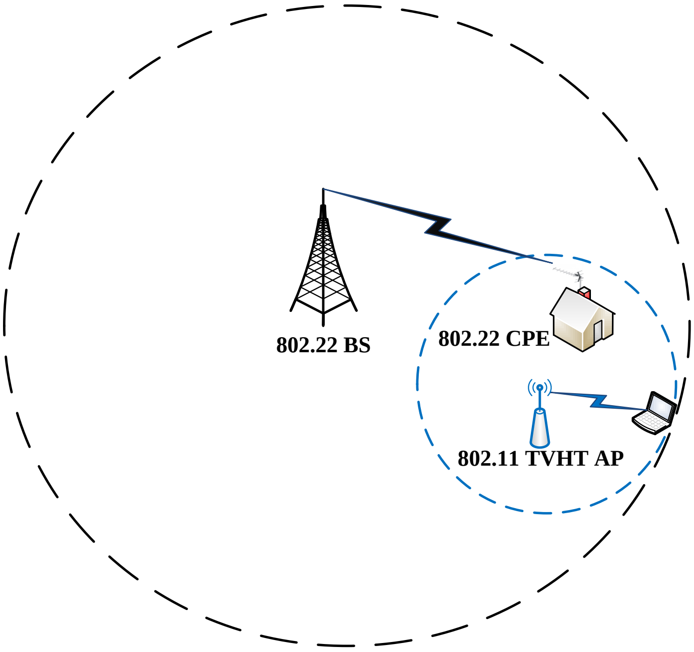


Figure 3.5: Illustration of hidden and exposed node.

Mechanisms have been adopted to address the hidden and exposed node problems in homogeneous networks, such as handshaking using RTS/CTS control packets. However, in heterogeneous environments, the handshaking procedures cannot work because the co-located networks use different air interfaces and therefore cannot understand each other's control messages.

Fair access to spectrum is another problem which is experienced when contention-based and frame-scheduling-based RATs operate in shared spectrum. For instance, the studies in [26, 31] showed that Wi-Fi networks experience spectrum starvation in the presence of LTE networks. Coexistence between contention-based network technologies and frame scheduling-based RATs has received attention, probably because these are the most common media access control techniques.

Mapping of the surveyed papers to the taxonomy is given in Table 3.4. The surveyed techniques are analysed by investigating the coexistence scenarios and constraints that are addressed, and the strengths and weaknesses of the approach. The surveyed papers are classified based on the coexistence discovery method, CD-1 or CD-2.

Table 3.4: Mapping of surveyed papers to the taxonomy.

Heterogeneous Coexistence Mechanism	CA-1	CA-2	CA-3	CCM-1	CCM-2	CCM-3	CD-1	CD-2	CD-1:CT-1	CD-1:CT-2	CD-1:CT-3	CD-1:CT-4	CD-1:CT-5	CD-1:CT-6	CD-1:CT-7	CD-1:CT8	CD-2:CT1
Allocation of channel time [120, 121]	Y			Y			Y								Y		
Beacon signalling and dynamic quiet period [122]	Y			Y			Y				Y						
Blank subframes [31, 123]		Y			Y		Y									Y	
Busy tone broadcast signalling [29, 30, 32]	Y			Y			Y		Y								
Carrier sense adaptive transmission [124–126]	Y			Y			Y							Y			
Centralised coexistence information database and spectrum sensing [117]			Y		Y	Y	Y	Y									Y
Coexistence beacon signalling [117]		Y			Y		Y			Y							
Credit token-based coexistence protocol [118]		Y			Y		Y					Y					
Listen-Before-Talk [82, 127–135]	Y			Y			Y						Y				

3.5.1 Spectrum Sensing (CD-1)

Note that the discussion on spectrum sensing mechanisms is restricted to detection of coexisting secondary user networks, and not primary users, since in the spectrum bands that this survey is targeting, primary users are protected by the regulator-approved spectrum database. In autonomous coexistence mechanisms, a network scans the spectrum to detect transmissions from coexisting networks [82], whereas in collaborative coexistence mechanisms networks facilitate cooperative sensing and exchange of coexistence-related information, in the form of coexistence beacons, in-band or out-of-band [117]. The surveyed papers are classified according to the coexistence technique (CT).

3.5.1.1 Busy Tone Broadcast Signalling (CD-1:CT-1)

A busy tone-based coexistence method has been suggested as a simple but effective method for ensuring coexistence between IEEE 802.22 WRAN and 802.11 TVHT networks. In this method, when the 802.22 network is transmitting, its receiver nodes can broadcast low-power busy tone signals using the sensing antenna to announce to neighbour networks that the frequency is occupied. The assumption in this approach is that, since IEEE 802.22 WRAN radio systems have simultaneous transmit and receive capability, the inherent self-cancellation technology can suppress the self-interference from the busy-tone.

This method was first studied in [32]. The authors propose that, when an IEEE 802.22 CPE is receiving packets from the 802.22 BS using its directional TX/RX antenna, it simultaneously transmits a low-power (100 mW) busy-tone signal using the omni-directional sensing antenna. The IEEE 802.22 CPE would no longer be a hidden node to the nearby 802.11 TVHT nodes since they can detect the busy-tone signal using CSMA-CA and would not transmit. Additionally, the IEEE 802.11 TVHT nodes would be able to differentiate between the much stronger signal from the IEEE 802.22 BS and the weak busy-tone signal and thus detect the exposed IEEE 802.22 BS node using an algorithm. The study simulated feasibility of the framework and results showed increased spectrum utilisation as a result of the coexistence scheme. There are two limitations of this research. In the IEEE 802.11 TVHT network, only the AP had the capability to detect the busy tone signal. As such, client nodes could still interfere with the IEEE 802.22 network transmissions. Moreover, an indoor path loss model was used for an outdoor environment resulting in unrealistic values for interference power.

The study in [30] addressed the limitations of the study in [32]. An extended busy tone coexistence protocol between IEEE 802.22 WRAN and 802.11 WLAN TVWS networks was analysed and simulated for different transmission ranges and under realistic conditions. The HATA path loss model for rural outdoor environments was used. Instead of only the IEEE 802.22 TVHT APs detecting the busy tone signal, their clients also had capability to listen for the busy tone signal and to convey their assessments to the AP. The results of the coexistence algorithm showed that the protocol can enable considerable reduction of interference without significant reduction in throughput.

In another study, the authors went further to analyse an extended busy tone coexistence algorithm for scenarios of different IEEE 802.11 TVHT client distributions experiencing log-normal shadowing [29]. The results showed that IEEE 802.11 TVHT WLAN node could reliably detect the busy signal and would move to a different channel to avoid interfering with the IEEE 802.22 WRAN nodes.

3.5.1.2 Coexistence Beacon Signalling (CD-1:CT-2)

A distributed coexistence system was proposed in [117]. This architecture implements inter-network coordination using coexistence beacons that are broadcast in a broadcast channel by each neighbouring network during the coexistence window. In this framework, when a BS or AP wants to initiate a network, it must identify which of the available channels has already been selected as a broadcast channel by already operating neighbour networks. The initiating network switches to the common RAT to listen for beacons of the available networks during the coexistence window. The coexistence beacon contains specific coexistence information such as geo-location, spectrum utilisation, transmit power, interference range. The initiating network selects the broadcast channel which is being used by neighbours that are geographically closer using the geo-location information in the beacon. Based on the information collected from the beacons during the coexistence window, the initiating network makes an autonomous coexistence decision about which of the available TV channels to use during the communication window. Unlike the broadcast channel, the selected communication channel should not be shared by neighbour networks to avoid interference. The framework implemented time-synchronisation based on absolute GPS time for timing of coexistence and communication windows among all associated nodes.

3.5.1.3 Beacon Signalling and Dynamic Quiet Period (DQP) (CD-1:CT-3)

The studies in [29, 30, 32] addressed the hidden node collision at the receivers of the IEEE 802.22 network only. However, packet collision can also occur at the receiver of the IEEE 802.11 TVHT network when the IEEE 802.22 transmitter, which is an “impolite” radio, starts to transmit before the IEEE802.11 TVHT transmitter has finished transmitting its packets.

The study in [122] was aimed at resolving the collision problem at both the IEEE 802.22 and 802.11 TVHT receivers. Collision at the IEEE 802.22 receivers was mitigated by transmitting beacon signals during a small time fraction at the beginning of every time slot. During the beaconing fraction of the time slot, the IEEE 802.22 transmitter would stop transmitting to allow the IEEE 802.22 receiver to to emit beacon signals which can be detected by IEEE 802.11 TVHT transmitters. The study also addressed collision at the 802.11 TVHT receivers that could happen when an IEEE 802.22 transmitter starts transmitting at the end of a scheduled quiet period while the IEEE 802.11 TVHT receiver is still receiving packets from a transmission that started during the quiet period. They proposed a collision avoidance algorithm for Time Division Multiple Access (TDMA) networks to prevent ongoing IEEE 802.11 TVHT transmissions from continuing beyond the scheduled quiet period by dynamically initiating an early termination of the quiet period immediately after detecting CSMA-CA Acknowledgement (ACK) packets. The IEEE 802.22 network initiates the early termination of quiet period by transmitting beacons and the IEEE 802.11 TVHT receiver would stop accessing the channel once it detects the beacons. The study assumed that the IEEE

802.22 network is registered with an IEEE 802.19.1-based coexistence system that is responsible for synchronisation of their clocks and scheduling of transmissions via the IEEE 802.19.1 interface, but there is no direct communication between the IEEE 802.22 and 802.11 networks.

3.5.1.4 Credit Token-Based Coexistence Protocol (CD-1:CT-4)

A distributed system architecture is proposed in [118]. It proposes implementation of a common RAT and common control channel for exchange of control messages among the coexisting networks. This system avoids the need for time-synchronisation for access control to the common control channel. Instead it proposes a contention-based MAC such as CSMA-CA for access control to the common control channel and to deal with control message collisions. This framework proposes a coexistence framework based on channel reservation of white space channels for data communication channels, rather than frame reservation because it is challenging to implement tight synchronisation between heterogeneous networks. The channel reservation process is coordinated via the back-haul internet connection of the master device. When a network has unused spectrum among its reserved channels, it can offer the fallow spectrum to networks that require extra spectrum through a non-monetary auction based on the credit-token-based coexistence protocol (CT-CXP), which is specified in IEEE 802.16h (this standard has now been superseded).

3.5.1.5 Listen-Before-Talk (CD-1:CT-5)

Cognitive radios typically adopt sense-before-talk strategy to detect the presence of incumbents. When incumbent protection is handled by the geo-location database, the cognitive radio would only have to handle interference from coexisting heterogeneous secondary networks. In [127], an optimal coexistence strategy for ad hoc cognitive networks operating in TVWS spectrum is proposed. The channel selection process models the achievable data rate on a channel as the reward and the time spent in sensing the available channels to assess interference as the cost. An autonomous self-coexistence decision making algorithm based on game theory is proposed in [128]. The problem of self-coexistence is modelled as a non-cooperative congestion-averse game between secondary cognitive networks.

The 3GPP requires that LTE-U should use LBT mechanisms to coexist fairly with other network technologies, such as Wi-Fi, in unlicensed spectrum [81]. Suitability of LBT channel access mechanism for networks based on LTE technology operating in GAA CBRS spectrum was assessed in [82]. The test scenario considered an outdoor deployment of low-power Category A and high-power Category B CBSDs in order to study the impact of asymmetric operating power situations on LBT-based coexistence. As per FCC specifications, the difference in maximum EIRP between the two categories of CBSDs is 17 dB [23]. Thus, if Category A CBSDs transmit using an EIRP level that is lower than the maximum, the difference in power could be greater than this. Performance was measured in terms of mean DL object data rate per user and total served traffic per operator per AP. Performance evaluation results showed that the mechanism is most effective when the GAA ecosystem is comprised of low-power CBSDs only, all operating at 24 dBm. When the deployment scenario comprises low-power CBSDs operating at 24 dBm and high-power CBSDs operating at 34 dBm, representing 10 dB power asymmetry on both UL and DL, a drop in performance is observed. This is because, high-power CBSDs have a longer communication/interference range than low-power CBSDs and therefore a higher number of neighbour CBSDs would detect their transmissions and backoff. This reduces opportunities for spatial-reuse of the channels, hence degrades the overall throughput. The authors therefore conclude that, in scenarios of asymmetric operating power, interference mitigation could be more effective if LBT is combined with coordinated channel allocation in such a way that GAA CBSDs with highly asymmetric power are not allocated overlapping channels [82].

Studies on coexistence of LTE and Wi-Fi have therefore concentrated on design of LBT features to achieve the objective of fair access to spectrum for Wi-Fi networks in the presence of LTE networks. Some of the features proposed include: (a) LBT with random backoff in a contention of variable size [130–132], (b) frame-based LBT [133], (c) synchronous LBT, in which frame boundary of licensed and unlicensed carrier is synchronized to enable modified use of existing co-ordination methods such as enhanced

Inter-Cell Interference Coordination (eICIC) [134], (d) LBT with RTS/CTS [135].

An LBT scheme that employs machine learning to allow opportunistic access to licensed CBRS spectrum and maximise spatial reuse of spectrum while minimising harmful interference to higher-tiers is proposed in [129]. The authors propose a reinforcement Q-learning technique to adapt an energy-detection threshold (EDT) for carrier sensing based on the spectrum observations of GAA secondary user radios.

3.5.1.6 Carrier Sense Adaptive Transmission (CD-1:CT-6)

The patent in [124] describes systems and methods for Carrier Sense Adaptive Transmission (CSAT) and related operations, which are aimed at mitigating interference between coexisting RAT standards. This is achieved through dynamic adaptation of certain parameters of a given CSAT communication scheme based on received signals and spectrum utilisation of the radio devices that are transmitting in shared spectrum using the RAT that requires interference protection.

CSAT is earmarked for LTE-U to facilitate its coexistence with Wi-Fi in the same licence-exempt band. This technique employs a duty cycling approach combined with CSAT to determine the duty cycle of LTE-U based on Wi-Fi occupancy. The study in [126] showed that, when optimally configured, CSAT is capable of providing the same level of throughput fairness to Wi-Fi as LBT would do. The impact of CSAT on AP-client association fairness was studied in [125]. The study concluded that energy-based CSAT will take a much longer time to scale back the duty cycle when Wi-Fi APs want to switch to the same channel due to beacon drops and delays in the reception. Hence, in order to maintain association fairness with Wi-Fi, the authors propose that the maximum duty cycle of LTE-U BS should be reduced from 95% to not more than 80% even if the channel is sensed to be vacant.

3.5.1.7 Allocation of Channel Time (CD-1:CT-7)

The study in [121] proposes allocation of only a fraction of time for the LTE to access the bandwidth, as a form of LTE-U duty cycling, in order to give WLAN networks a chance to transmit. However, this method is not efficient because, since it is based on static transmission time intervals, the LTE network would be muted even when the bandwidth is idle, including the times when WLAN networks backoff after a collision since transmitting during the backoff period would not impact WLAN performance.

A proportional fair allocation scheme is proposed in [120]. All the nodes that are competing for the same bandwidth are assigned equal channel times, including idle times. The scheme can be implemented without inter-RAT coordination and no changes are required to the WiFi standard. The LTE network obtains the parameter values that are required for computing optimal probability to access the channel and transmission duration through channel monitoring.

3.5.1.8 Blank Subframes (CD-1:CT-8)

Almost Blank Subframes (ABSs) are LTE subframes during which a macro BS transmits only control channels and cell-specific reference signals with reduced power, but no user data. ABSs are an important part of enhanced Inter-Cell Interference Coordination (eICIC) in the 3GPP standard because pico BSs can have no interference from macro BSs during these periods [136]. ABSs offer a practical way of implementing LTE-U duty cycling.

The authors in [31, 123] propose a modified version of ABS, called Blank Subframe or null subframe, in which no LTE control channels and cell-specific reference signals are transmitted to enable coexistence with Wi-Fi. LTE throughput is expected to decrease almost proportionally to the number of blank subframes and a trade-off must be established. However, if Wi-Fi transmissions are not completely aligned with the duration of the LTE silent periods, LTE performance degradation may be observed when Wi-Fi transmissions carry on beyond the duration of the blank subframe and interfere with LTE transmissions, especially when blank subframes are not adjacent. Hence, there is need for collaboration between the two wireless protocols. One possible solution is for the LTE node to report the duration and occurrence of its blank subframes to the Wi-Fi nodes as part of a negotiation process, so that Wi-Fi nodes might be able to effectively confine their transmissions within the LTE silent period [31].

3.5.2 Spectrum Sensing and Coexistence Information Database (CD-2)

3.5.2.1 Centralised Coexistence System (CD-2:CT1)

A centralised coexistence framework was proposed in [117], whereby information exchange between subscribed networks was implemented through the internet, by way of access to a coexistence information database. Additionally, the BS or AP was a multi-radio equipment which enabled it to detect un-subscribed networks by switching to a standardised RAT and searching for user signature in their packets. The BS or AP also had decision-making capability to identify coexistence opportunities and to make autonomous coexistence decisions. The BS or AP would initially access the secondary spectrum utilisation database to acquire operational information of other subscribed networks. Based on this information, it makes a preliminary autonomous coexistence decision regarding which TV channel to use. It then switches to that channel and uses the common RAT to detect the presence of any un-subscribed networks, after which it makes the final coexistence decision and uploads its decision to the coexistence information database.

3.6 Challenges of Heterogeneous Coexistence Mechanisms

Autonomous coexistence mechanisms by themselves may not achieve adequate heterogeneous interference mitigation and efficient spectrum utilisation due to their knowledge being only local, rather than, global and due to their best-effort nature. Such mechanisms are sufficient when the channel load is not excessive. For instance, in LBT, as the number of contending nodes increases, a significant fraction of the time is spent in the collision state which reduces the time spent on actual data transmission, which effectively decreases the throughput.

Although collaborative coexistence mechanisms may result in better interference mitigation and spectrum utilisation than autonomous coexistence protocols due to global knowledge of the RF environment, they are often limited to certain coexistence scenarios, such as when all networks in the system support the same coexistence protocol and when the network density is not excessive for the available channels [27].

Sustainability of MAC/PHY-based coexistence mechanisms is probably the main drawback since it is a radio-technology-dependent approach and technology evolves from time to time. Surveyed papers have focused on coexistence between IEEE 802.22 and 802.11 networks in TVWS [29, 30, 32, 117, 118, 122], and between LTE-U and Wi-Fi in TVWS, 5 GHz or CBRS GAA spectrum [31, 82, 123–126], because these are expected to be the most prevalent technologies. However, this approach generally requires N^2 solutions between all the radio technology pairs, where N is the number of radio technologies [46]. Technology is changing rapidly such that such solutions can be short-lived. Furthermore, new technologies could be introduced to meet specific use cases.

Nonetheless, autonomous and collaborative heterogeneous coexistence mechanisms could be exploited in centralised frequency coordination or coexistence mediators, which utilise intelligent coexistence decision-making to optimise interference mitigation and spectrum utilisation, rather than leaving the networks to fight for spectrum among themselves.

3.7 Potential Application of Hypergraph Theory in Heterogeneous Coexistence Mechanisms

Two potential areas of application of hypergraph theory in coexistence mechanism are envisioned: at the data storage layer, where coexistence-related information is stored, and at the application layer, where coexistence decisions and channel allocation are computed.

3.7.1 Database Model

As per the survey in Section 3.5, use of databases in the architecture of coexistence mechanisms has been proposed to overcome the challenge of inter-network communication. Databases can be used as a means of indirect exchange of coexistence information between networks that cannot communicate directly due to incompatible wireless protocols. Coexistence mechanisms, such as modified LBT and CSAT require dynamic adaptation of certain coexistence-related parameters in order to optimise performance of the coexistence mechanism. Machine learning techniques have been proposed to implement dynamic adjustment of certain features of the coexistence mechanisms. Such machine learning algorithms would make decisions using learning databases. It is envisioned that the data would involve complex multiple relationships that can be represented sufficiently using a hypergraph data model. A relational database management system, in which data structure is based on tables, may not be suitable for multiple relationships. On the other hand, the hypergraph data model has found application in modelling of complex relationships in knowledge databases and learning databases. For instance, TypeDB (previously known as Grakn) is a distributed, hyper-relational database solution which was launched in 2016 for managing complex data [137].

3.7.2 Coordinated Channel Allocation

The 3GPP specifies that LTE-U should use LBT mechanisms to coexist fairly with other network technologies, such as Wi-Fi, in unlicensed spectrum [81]. However, due to the difference in transmit power between the two network technologies, low-power Wi-Fi networks are likely to sense high-power LTE-U transmissions and back-off, thus reducing opportunities for spatial re-use of channels. Similarly, the authors in [82], who studied the suitability of LBT in scenarios of asymmetric operating power among GAA CBSDs, concluded that coexistence could be more effective if LBT is combined with coordinated channel allocation in such a way that GAA CBSDs with highly asymmetric power are not allocated overlapping channels [82]. Modelling of coordinated channel allocation would involve multiple relationships such as groups of coexistent networks that can effectively coordinate access to shared spectrum and therefore could be allocated overlapping channels. Such multiple relationships could be modelled using hypergraph theory. Application of hypergraph theory in modelling coordinated channel allocation is discussed further in Chapters 5 and 6.

3.8 Chapter Summary

This chapter has analysed state-of-the-art coexistence mechanisms as one of the solutions to minimise interference and maximise spectrum utilisation among heterogeneous wireless networks. Autonomous coexistence mechanisms are not sufficient due to their local knowledge and best effort nature. Collaborative mechanisms require modifications to the radio standard to meet the requirements for inter-RAT communication and time-synchronisation. Furthermore, both autonomous and collaborative mechanisms are specific to particular standards. However, technology is changing rapidly such that such solutions could be short-lived when new technologies would be introduced to meet specific use cases. Nonetheless, autonomous and collaborative coexistence mechanisms could be exploited in intelligent coexistence decision making functions.

The chapter has also discussed the potential use of hypergraph theory in modelling coexistence information in coexistence mechanisms. Two potential areas of application have been identified. First, hypergraph data models could be used to model coexistence information databases and learning databases in machine learning-enabled coexistence mechanisms. Second, hypergraph modelling could be used to model coordinated channel allocation in coexistence mechanisms that require assigning non-overlapping channels to networks that cannot effectively coexist. The next chapter reviews technology-independent solutions for spectrum coordination and coexistence management of heterogeneous wireless networks.

Chapter 4

Coexistence Management and Spectrum Coordination

4.1 Introduction

Coexistence management and spectrum coordination solutions have the potential to provide a long-term and radio-technology-independent solution to heterogeneous coexistence through intelligent radio resource allocation that ensures mitigation of harmful interference and maximisation of spectrum utilisation, among other objectives. The contribution of this chapter is a survey of state-of-the-art solutions for coexistence management and spectrum coordination in TVWS and CBRS GAA spectrum bands, focusing on modelling techniques for solving the channel assignment problem. This is followed by a discussion of research gaps that focuses on the suitability of hypergraph theory in modelling multiple relationships for coexistence management and spectrum coordination. Finally, the chapter contributes a high-level framework for development of coexistence management applications that employ hypergraph modelling techniques.

4.2 Definition of Terms

This section provides the meanings of the key terms as used in this thesis. Coexistence management refers to the function that is responsible for managing coexistence between two or more radio devices/networks which may operate using different wireless protocols with incompatible coexistence mechanisms. PHY/MAC-based autonomous and collaborative coexistence mechanisms may be exploited in coexistence management to further improve spectrum utilisation by allowing networks that operate using compatible PHY/MAC designs to share the same spectrum in the time domain. This function could be implemented within a radio device or network, such as a base station, or in a logical entity that does not take part in the communication process, such as a database-assisted application system.

A group of radio devices/networks that are subscribed to the same coexistence management entity form a coexistence group. Spectrum coordination is a high-level solution that ensures that coexistence groups that have potential to interfere with each other are allocated non-overlapping bandwidth. This function could be implemented through a geo-location database system.

4.3 Comparison of Surveys

While coexistence management is not a new issue in wireless communication, the problem is more challenging in dynamic spectrum access due to a dynamic radio environment and fragmentation of available spectrum. Radio resource allocation research has focused on finding solutions to accommodate as many spectrum requests as possible when the available spectrum is not adequate to serve the aggregated demand for channels. Optimisation techniques have been used to formulate optimisation problems from the the perspective of radio resource allocation.

Detailed surveys on radio resource allocation algorithms and optimisation techniques for cognitive radio systems can be found in [138–141]. Unlike these surveys which include techniques for interference protection of primary users in hierarchical spectrum access systems as well as coexistence between secondary users which have equal access rights, this survey is focused on the latter only because in TVWS, and CBRS GAA spectrum bands, interference protection of primary and priority users is covered by the geo-location spectrum database.

4.4 Taxonomy of Coexistence Management and Spectrum Coordination Solutions

The taxonomy used in this survey classifies the surveyed papers according to four different criteria as illustrated in Figure 4.1. The solutions are classified according to the following characteristics: (a) objectives, (b) coexistence discovery methods, (c) spectrum re-use methods, and (d) problem solving approaches regarding radio resource allocation.

4.4.1 Objectives (OBJ)

This attribute identifies the objectives of the spectrum coordination and coexistence management scheme. The main objectives in assignment of the available spectrum to secondary user networks are (a) spectrum utilisation maximisation (OBJ-1), and (b) interference minimisation among secondary user networks (OBJ-2). Other objectives include: (a) fairness optimisation (OBJ-3), (b) throughput maximisation (OBJ-4), (c) stability of spectrum assignment (OBJ-5), (d) channel contiguity (OBJ-6), (e) energy minimisation (OBJ-7), and (f) monetary or non-monetary revenue maximisation (OBJ-8).

4.4.2 Coexistence Discovery Methods (CD)

This characteristic classifies the coexistence management solutions based on the method used to collect information about other coexisting networks. The coexistence discovery methods are classified into three categories: (a) RF spectrum measurements (CD-1), (b) coexistence discovery database (CD-2) and (c)coexistence discovery database plus RF spectrum measurements (CD-3).

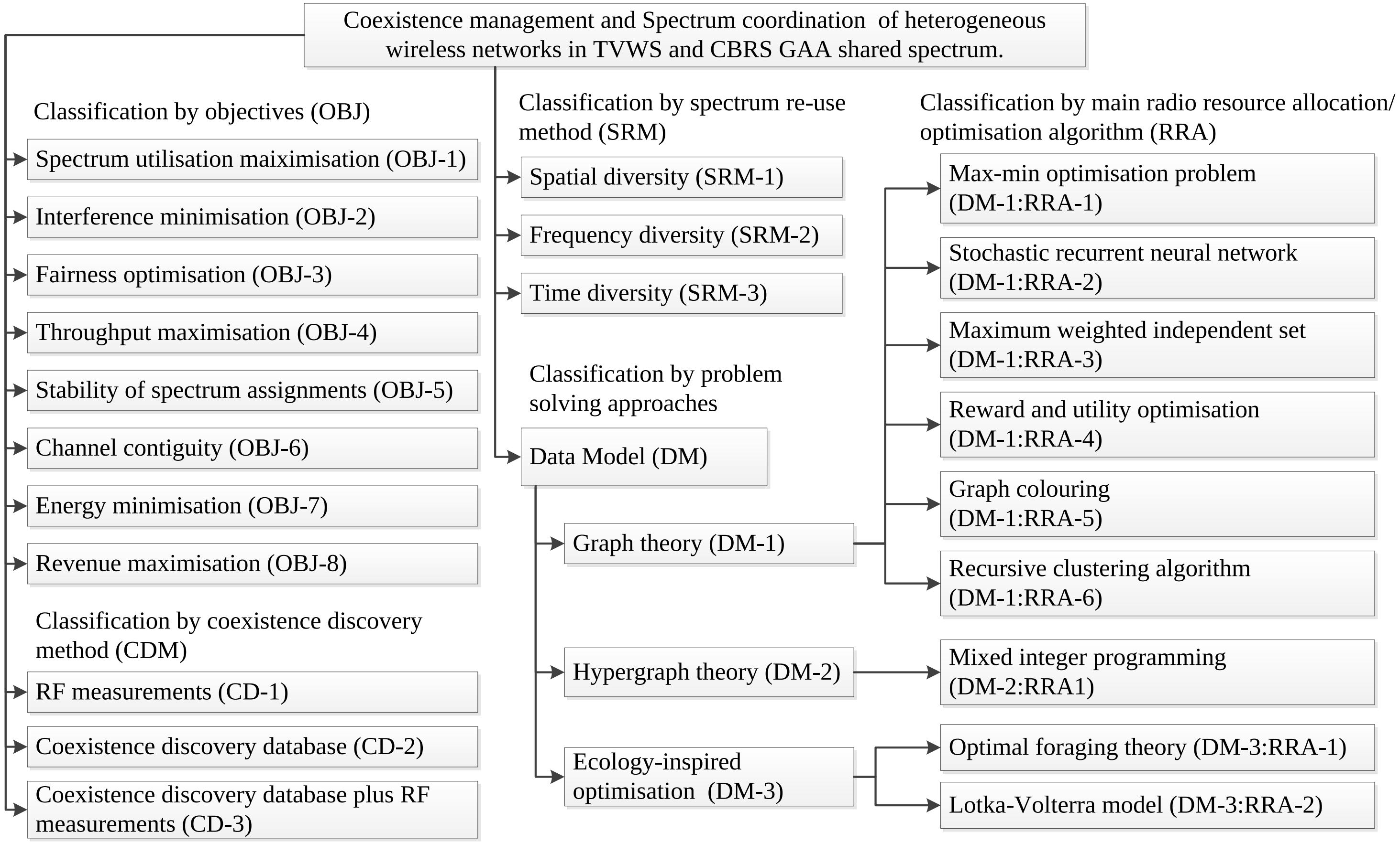


Figure 4.1: Taxonomy of spectrum coordination and coexistence management solutions for heterogeneous radio networks in TVWS and CBRS bands.

Coexistence management schemes that use spectrum monitoring measurements only to gain knowledge required for coexistence management do not require communication between coexisting networks. This approach is attractive for spectrum that is shared between different operators and different wireless technologies because inter-network communication presents technology compatibility, security and trust issues. Alternatively, a coexistence discovery database can serve as the main source of coexistence information, while measurement reports from networks may serve as a secondary source. The main disadvantage of this approach is the requirement for additional database infrastructure for exchange of coexistence-related information between networks and for coexistence decision-making.

In shared spectrum, the RF environment may be composed of radio devices or networks that belong to to different operators, which raises security and privacy concerns. However, the coexistence information database service can be provided by approved spectrum database administrators as a value-added service on top of the obligated service of providing lists of available channels. For instance, the characteristics of the regulatory frameworks that make it easier to deploy centralised spectrum coordination function include:

- Master devices are required to register their device parameters and channel usage parameters with the database. This information provides input for the coexistence information database,
- Master devices are IP-addressable and have a direct IP connection or an indirect connection via a proxy, which is likely to be a robust connection and can be wireline infrastructure. This IP connection can be used for most of the messaging between networks in order to reduce the overhead that is transmitted over the air interface,
- A radio resource management database operated by a regulator-approved spectrum database operator may serve as a trusted means of sharing coexistence-related information among different subscribing network operators. Since network operators are required by regulation to register contact information and radio de-

vice parameters with a regulator-approved spectrum database, indirect exchange of coexistence-related information via the infrastructure of a regulator-approved database operator stands a higher chance of being trusted by network operators than direct exchange between different operators that may be unknown to each other.

However, such independent spectrum managers can only be effective if all secondary networks subscribe to the spectrum management service. Secondary networks need to *subscribe* to the service and service fees may apply. It could be envisioned that the benefits of spectrum coordination would attract most network operators to subscribe to the service.

4.4.3 Spectrum Re-use Methods (SRM)

This attribute identifies the approach used to maximise spectrum utilisation. Spectrum utilisation can be re-used in spatial (SRM-1), frequency (SRM-2) and time (SRM-3) domains. Spectrum sharing using codes was not covered in the surveyed papers. Spectrum sharing in the time domain on a frame basis, using frame scheduling, frame reservation, or based on on-demand frame contention, requires time-synchronisation and inter-network coordination, which is a challenge to implement across heterogeneous network technologies. On the other hand, LBT mechanisms such as CSMA-CA allow spectrum sharing in the time domain without direct coordination among the networks.

4.4.4 Problem Solving Approaches

The problem solving approach attribute identifies the method used to solve the radio resource allocation problem in order to meet the objectives of the spectrum coordination scheme. This attribute is further classified into two: (a) data model (DM), and (b) radio resource allocation method (RRA).

The data model identifies the main method used to represent the RF-related attributes of the coexisting networks such as radios, networks, and interference. It represents the data structure of the input to the radio resource allocation algorithm, e.g.

interference constraints. The data models adopted by the state-of-the-art coexistence solutions use graph theory (DM-1), hypergraph theory (DM-2) and ecology-inspired optimisation (DM-3). A graph is a structure made of vertices and edges. Edges connect pairs of vertices. When graphs are used to model spectrum allocation, a vertex represents a radio device or network and an edge represents an interference relationship. A hypergraph is a generalization of an undirected graph in which a hyperedge is a subset of vertices of arbitrary cardinality rather than two-element subsets [86,88]. A hyperedge is used to represent a group of radio devices that belong to the same network. In ecology-inspired optimisation, behavioural ecology models that help predict how an animal behaves when searching for food, are used to model how networks select spectrum [142–144].

The radio resource allocation method represents the approach used to solve the problem of determining an optimal assignment of the available spectrum to the coexistent networks such that spectrum utilisation is maximised, the coexistent networks generate and receive minimum interference, among other objectives. Methods adopted in the surveyed state-of-the-art coexistent management solutions include optimisation problems, graph algorithms and machine learning techniques.

4.5 Coexistence Management Standards in TVWS and CBRS GAA Spectrum

Spectrum coordination has the potential to provide a long-term and radio-technology-independent solution to heterogeneous coexistence management since there is no requirement for major modifications to the radio standard. There are published standards for coexistence management in DSA systems that are based on the centralised dynamic radio resource management approach. A separate spectrum management entity, although not provided for in the current Ofcom and FCC TVWS regulatory frameworks, has not been disallowed either. The IEEE released the 802.19.1 standard in 2014 to guide development of wireless coexistence management of geo-location-capable devices operating in TVWS, CBRS and 5 GHz bands. The database for coexistence-related information and coexistence decision-making is centralised, but decision-making about which of the recommended channels to use can be autonomous, distributed or centralised.

As per sub-part 96.35 of the FCC rules in [23], GAA users operating Category B CBSDs, which are high power devices, must cooperate in the selection and usage of the available spectrum to minimise the potential for interference and maximise spectrum utilisation. The Wireless Innovation Forum (WInnForum) published technical reports for three RAT-agnostic approaches to GAA spectrum coordination in 2019 [36–38]. The OnGo Alliance published the CBRSA-TS-2001 CBRS Coexistence Technical Specifications in 2020, focusing on Band 48 LTE-TDD using Frame Structure 2 (FS2) and limited support for n48 NR-TDD deployment [39].

In the following sections, an overview of each of these technical standards and specifications is presented. This is followed by a survey of RAT-independent coexistence management implementations based on the standards.

4.5.1 IEEE 802.19.1 Wireless Network Coexistence Methods

In 2014, the IEEE released the 802.19.1 standard for network-based coexistence methods for dissimilar, independently operated networks to make the most effective use of TVWS spectrum. The standard was revised in 2017 and in 2018 to make it applicable to any WSD or geo-location capable radio device operating under general authorisation in TVWS, in 5 GHz licence-exempt spectrum and in 3.5 GHz GAA spectrum [33–35].

The standard specifies a system architecture for the coexistence system as illustrated in Figure 4.2. There are two entities that are external to the coexistence system. The Spectrum Management Database (SMDB) refers to any regulator-approved database, if required by the regulations for operation in the frequency band. White Space Object (WSO) refers to a WSD or a network of WSDs. Geo-location Capable Object (GCO) refers to a communication device or a network of communication devices that has/have inbuilt capability to determine its/their geo-location. The Radio Location Secure Server (RLSS) is a local database for IEEE 802.11 TVHT white space networks and is described in Section 3.3.1.3.

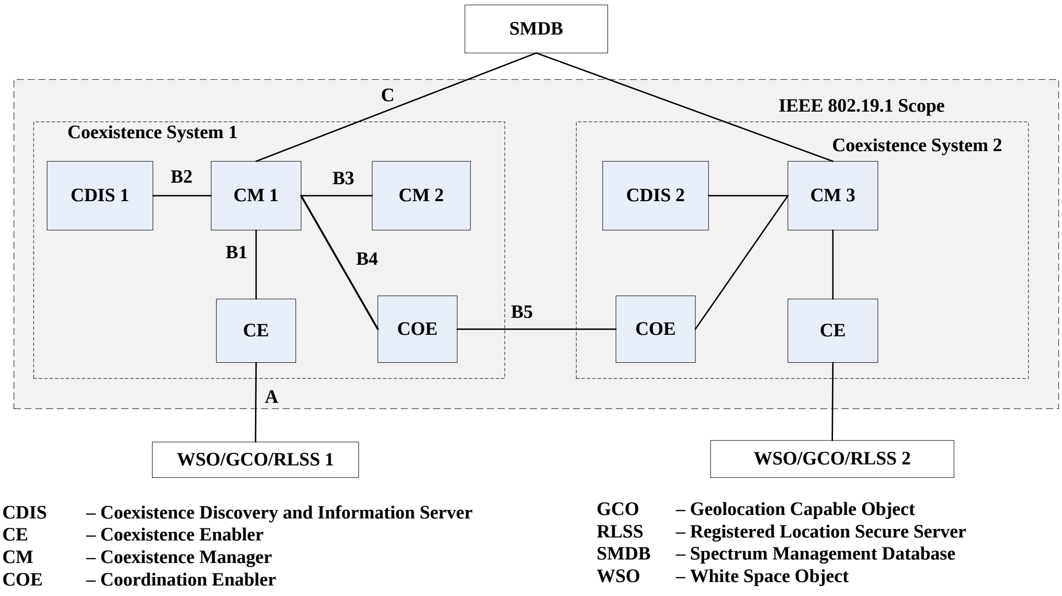


Figure 4.2: IEEE 802.19.1 System Architecture.

The scope of the coexistence system comprises four logical entities and seven logical interfaces. SMDBs and WSOs are accessed via interfaces C and A respectively. The Coexistence Manager (CM) uses the services of the Coexistence Discovery and Information Server (CDIS) to discover and to get information about potential neighbour nodes/networks via interface B2. The CM provides two kinds of services: information or management service. A WSO or GCO that subscribes to information service is only provided with available channels and expected interference levels from potential neighbours. The WSO or GCO itself must decide which parameters to use for the best performance. If a subscriber desires that the CM should make coexistence decisions and should also reconfigure their WSOs or GCOs, then they have to subscribe to the management service.

Coexistence Enabler (CE) is an interface element that represents one or multiple similar WSOs or GCOs or RLSSs and facilitates communication between the CM and the WSOs or GCOs or RLSSs via interfaces B1 and A, respectively. The standard also provides mechanisms for information exchange between CMs within the same coexistence system via interface B3. The Coordination Enabler (COE) is an interface element that represents one or several CMs via interface B4 and facilitates communication between CMs that belong to independently operated networks via interface B5.

The standard specifies two types of coexistence algorithm: coexistence discovery and coexistence decision. The CDIS uses coexistence discovery algorithms to discover WSOs or GCOs that can interfere with each other and thus affect each other's performance. Coexistence decision algorithms are used by the CM to produce a coexistence report or to arrive at a decision to reconfigure WSOs or GCOs in such a way that they cause minimum harmful interference to each other. The standard also specifies three decision making topologies among master and slave CMs: autonomous, distributed and centralised. A CM may change its decision-making topology at any time.

The standard specifies that the all communication between the logical entities of the coexistence system shall use Transmission Control Protocol/Internet Protocol (TCP/IP). Implementations of all entities shall support both Secure Shell (SSH) and Transport Layer Security (TLS) protocols. It also specifies several procedures for interactions between the logical entities that are required to fulfil the task of coexistence management.

There has been a number of studies in the literature to demonstrate proof of the concept of IEEE 802.19.1 standard [77, 117, 119, 145–149]. The standard leaves actual implementation of the system to the industry [106]. To the best of the author's knowledge, there are no 802.19.1-compliant TVWS radio systems on the market to date.

The study in [117] showed that in the absence of coexistence systems, up to 92% of the available spectrum is overlapped by neighbouring networks. It was shown in [145] that performance improved when a coexistence system was introduced to reconfigure heterogeneous networks that were interfering with each other. A simulation that was conducted as verification of a TVWS coexistence system based on the P802.19.1[1] showed that the coexistence system increased the throughput of the 802.11 networks by 30% when 30 network pairs were sharing three available TV channels [147]. The study in [148] involved comparing network performance between a scenario that employed

---

[1] Draft version of the IEEE 802.19.1 standard

an IEEE 802.19.1 coexistence system and another scenario that did not use any coexistence system, but relied on spectrum sensing only. Performance evaluation results showed that the gain of the coexistence system over the non-coexistence system was significant, ranging from 20% to 100%.

The study in [150] proposed an implementation of a channel allocation algorithm that is based on operating channel selection, which is specified in the 802.19.1 standard for coexistence management. In this method, the CM updates channel availability information as and when radios select operating channels from the list of available channels. This information is used to determine which is the most suitable channel for a particular radio. The test bed was implemented in such a manner that the 802.22 BSs were hidden nodes to the 802.11af APs (now called 802.11 TVHT). As such, the 802.11af APs would not back off when an 802.22 BSs was transmitting, which resulted in degradation of upstream throughput of the 802.22 network due to a significant loss of upstream allocation map data. The performance of the proposed channel allocation algorithm was measured in terms of interference mitigation between IEEE 802.11af APs and 802.22 BSs, which was evaluated by comparing throughput at the 802.22 CPEs with and without the proposed 802.19.1 coexistence management service scheme. The results demonstrated a significant throughput enhancement on the CPE of 802.22 BS that was subscribed to the proposed 802.19.1 coexistence management service scheme.

4.5.2 WInnForum GAA Spectrum Coordination (GSC)

The WInnForum has published technical specifications for GAA Spectrum Coordination (GSC) among CBSDs operating in GAA spectrum in order to implement coexistence management between the CBSDs [36–38]. The GSC function can be implemented by SAS administrators to coordinate use of GAA spectrum. While Approach 1 [36] considers bandwidth as the only resource to be allocated, Approach 2 [37] considers lowering of transmit power to reduce the number of CBSDs that would interfere with each other and then allocate non-overlapping spectrum to them. Approach 3 [38] is aimed at maximising contiguous GAA spectrum assignment.

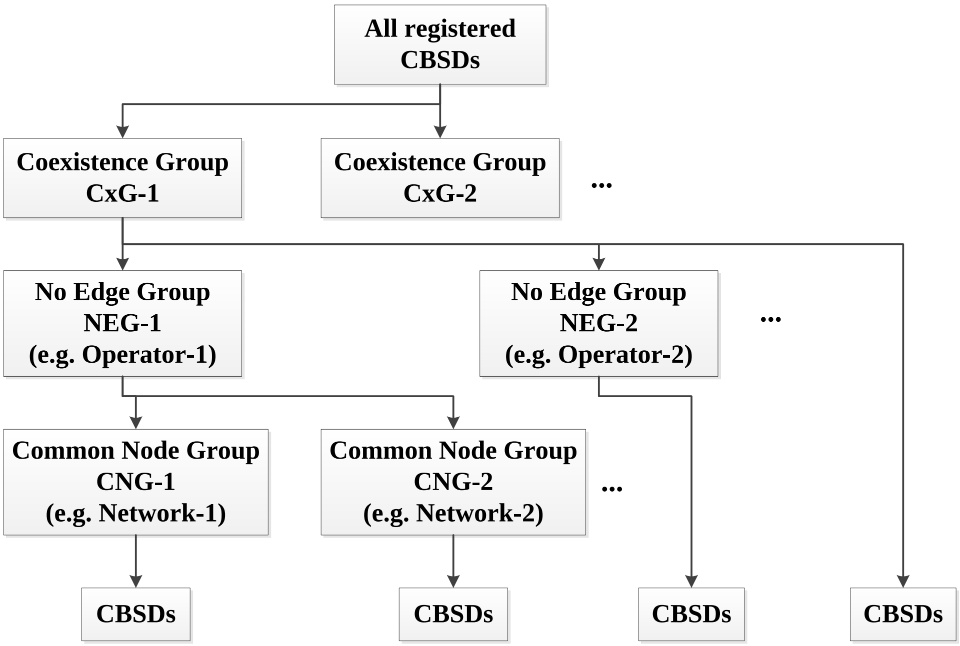


Figure 4.3: Illustration of specification of coexistence relationships in WInnForum GAA Spectrum Coordination Function.

The technical specification specifies the following coexistence-related relationships between CBSDs. A Coexistence Group (CxG) is a group of CBSDs that abide by a common interference management policy which is used to coordinate their interference within the group. CBSDs in a CxG could be managed by its own spectrum coordination entity, such as a CxM. An NEG is a group of CBSDs, belonging to the same CxG, which can manage their own interference within the group, and therefore do not require channel orthogonalisation. A Common Node Group (CNG) is a group of CBSDs that belong to the same NEG and all members of the CNG require the same channel assignment. These relationships are illustrated in Figure 4.3.

Two types of spectrum coordination are specified: (a) inter-CxG coordination function, which makes decisions about coordination of spectrum use among CxGs, (b) intra-CxG coordination function which manages spectrum use within a specific CxG [37]. Inter-CxG coordination function is managed by the SAS. If a CxG does not have its own CxM for intra-CxG coordination function, it could relegate the function to the

SAS. The GSC function creates a CBSD interference graph based on registration information of the CBSDs, service criteria, terrain and clutter data, and measurement reports. Inter-CxG coordination function is aimed at allocating non-overlapping spectrum to CxGs whose CBSDs have potential to interfere. A connected set refers to a set of CBSDs in which any two vertices are connected to each other through a path in the interference graph. Vertex colouring algorithm is used to find the number of colours required for each CxG in a connected set. A vertex colouring of a connected set comprising 3 CxGs is illustrated in Figure 4.4.

Bandwidth allocation to a CxG is based on the ratio of its chromatic number to the total chromatic number of the connected set. In the example given in Figure 4.4, the chromatic numbers of CxG 1, CxG 2 and CxG 3 are 3, 3, and 2, respectively. The total chromatic number is therefore equal to 8. Assuming a total available bandwidth

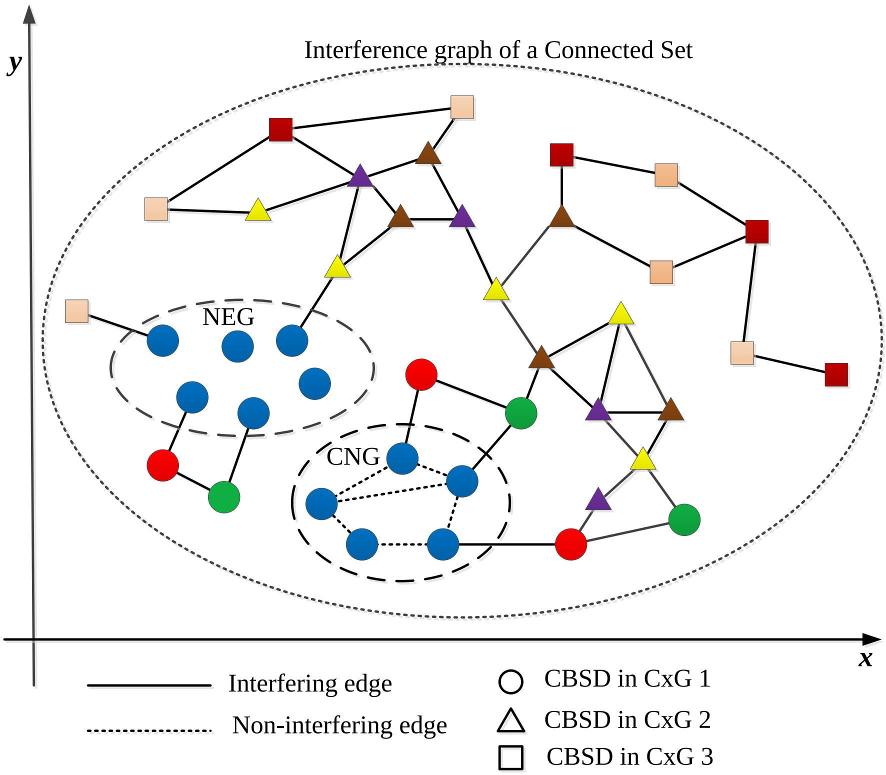


Figure 4.4: Illustration of vertex colouring of a connected set.

of 160 MHz, CxG 1 and CxG 2 would be allocated 60 Megahertz (MHz) each, whereas CxG 3 would be allocated 40 MHz.

4.5.3 CBRSA-TS-2001 CBRS Coexistence Technical Specifications

The CBRSA-TS-2001 CBRS coexistence technical specifications [39] specify implementation of a CxM to perform intra-CxG coordination function between and among CBRS Alliance LTE-TDD and NR networks operating on GAA basis. The standard relegates inter-CxG coexistence to the WInnForum GSC, which allocates bandwidth to the CxM.

This CxM is responsible for allocating the spectrum to all CBSD that have indicated membership in the CxG. The CxM obtains coexistence-related information about the CBSDs from the SAS to create a coverage overlap graph which represents interference relationships between the CBSDs. The CxM then determines the chromatic number of each connected set. The chromatic number is used to divide the spectrum that is available to the connected set into orthogonal and equal primary channels. Each vertex is assigned one of these channels corresponding to the colour of the vertex in the graph. The CxM may increase the bandwidth allocation to a CBSD by assigning it any spectrum or part thereof that does not overlap with the primary channel assignment of any of its neighbour CBSDs.

4.6 State-of-the-Art Coexistence Management Solutions

The survey of state-of-the-art coexistence management solutions is classified according to the problem solving approaches. Mapping of the surveyed papers to the classification is presented in Table 4.1.

4.6.1 Graph Theory-based Models (DM-1)

4.6.1.1 Max-Min Optimization Problem (DM-1:RRA-1)

A coexistence management solution for heterogeneous networks operating in white space spectrum is presented in [50]. An interference graph is used to model spectrum re-use. The bandwidth allocation problem is formulated as a max-min problem

Table 4.1: Mapping of surveyed technical standards and papers to the taxonomy.

Spectrum Coordination and Coexistence Management Solution	OBJ-1	OBJ-2	OBJ-3	OBJ-4	OBJ-5	OBJ-6	OBJ-7	OBJ-8	CD-1	CD-2	CD-3	SRM-1	SRM-2	SRM-3	DM-1:RRA-1	DM-1:RRA-2	DM-1:RRA-3	DM-1:RRA-4	DM-1:RRA-5	DM-1:RRA-6	DM-2:RRA-1	DM-3:RRA-1	DM-3:RRA-2
CBRSA-TS-2001 CBRS Coexistence Technical Specifications [39]	Y	Y	Y	Y	Y	Y	Y				Y	Y	Y	Y					Y				
Ecology-inspired optimisation - Lotka-Volterra [151–154]	Y	Y	Y							Y		Y	Y										Y
Ecology-inspired optimisation - Optimal Foraging Theory [151]	Y	Y	Y							Y		Y	Y									Y	
Graph colouring [47]	Y	Y									Y	Y	Y						Y				
Graph colouring [155, 156]	Y	Y								Y		Y	Y	Y					Y				
Graph colouring [27]	Y	Y		Y					Y			Y	Y						Y				
IEEE 802.19.1 [34, 35]	Y	Y	Y	Y	Y	Y	Y				Y	Y	Y	Y									
Max-min optimisation [50]	Y	Y	Y							Y		Y	Y		Y								
Maximum weighted independent set [157]	Y	Y				Y				Y		Y	Y				Y						
Mixed Integer Programming [46]	Y	Y							Y			Y	Y	Y							Y		
Recursive clustering algorithm [158]	Y	Y				Y				Y		Y	Y	Y						Y			
Reward and utility optimisation [159]	Y	Y								Y		Y	Y	Y				Y					
Stochastic recurrent neural network [160]	Y	Y	Y		Y	Y	Y			Y		Y	Y	Y		Y							
WInnForum GAA Spectrum Coordination (GSC) [36–38]	Y	Y	Y	Y	Y	Y	Y				Y	Y	Y	Y					Y	Y			

that seeks to maximise the minimum bandwidth allocated to all networks in order to achieve fairness while maximising spectrum re-use as much as possible. The available bandwidth is then divided into equal channels and each network is assigned a number of channels according to the amount of bandwidth allocated to it.

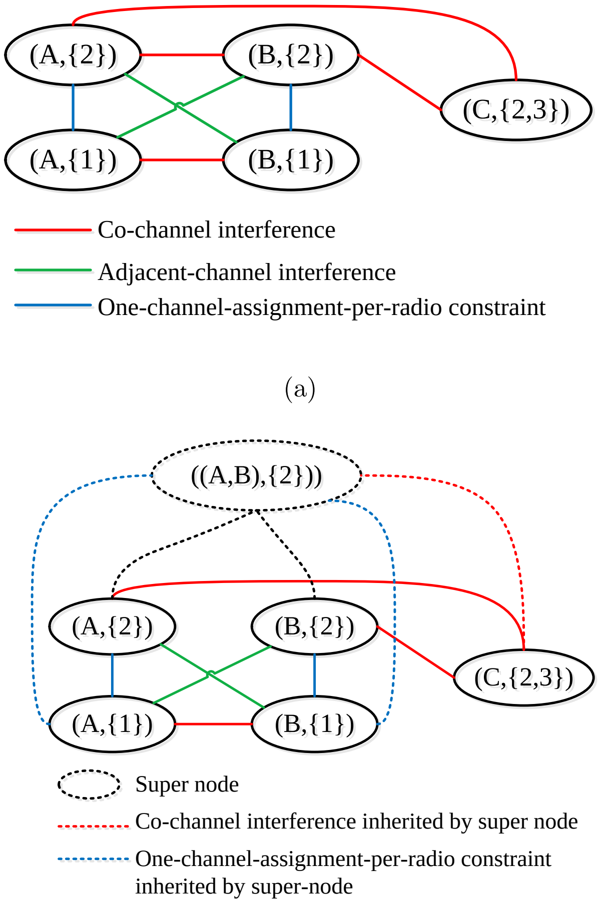
4.6.1.2 Stochastic Recurrent Neural Network (DM-1:RRA-2)

In [160], an algorithm called Fair Algorithm for Coexistence decision making in TV white space (FACT) is proposed. The inputs for coexistence decision making are: (1) each network's spectrum demand and (2) the weighted interference graph generated from the output of an IEEE 802.29.1 CDIS, whereby nodes represent the TV Band Device (TVBD) networks and edges connect networks that interfere with one another and the weight of an edge shows the minimum frequency separation required to achieve a threshold SINR at either of the networks connected by the edge. The following constraints are considered: (1) contiguity of channels, (2) interference, (3) fairness, (4) channel allocation invariability and (5) transmission scheduling constraints. This set of constraints is used to formulate the coexistence decision making problem as a multi-objective combinatorial optimization problem. The optimization problem is modelled as an energy minimization problem in a modified Boltzmann machine, which is a type of stochastic recurrent neural network [161]. An algorithm to find a Pareto optimal feasible solution is proposed [161]. A simulation scenario included 20 networks of 3 different types that are competing for different number of available channels. The number of available channels varies between 1 and 20. The results showed that performance of FACT is superior to the existing coexistence decision making algorithms which have been proposed for IEEE 802.19.1, in terms of fairness, and percentage of demand serviced [162, 163].

4.6.1.3 Maximum Weighted Independent Set (DM-1:RRA-3) and Reward and Utility Optimisation (DM-1:RRA-4)

In [157], a SAS-assisted, coexistence-aware, dynamic channel assignment for CBRS GAA radios is presented. A radio-channel-pair conflict graph is used to model spatial channel availability, co-channel interference, adjacent channel interference, and one-channel-assignment-per-radio constraint. A radio-channl-pair conflict graph is illustrated in Figure 4.5a. A radio-channel-pair is represented as a tuple (i, C_i) where i is the radio identity and C_i is a set of channels that are available at the location of radio i.

A pair of radios that are connected by an edge, which means that they are within each other carrier-sensing range, could be assigned the same channel when the channel is available at the location of both radios. In order to include coexistence awareness in



(a)

(b)

Figure 4.5: (a) radio-channel pair conflict graph, (b) coexistence-aware radio-channel pair conflict graph.

the graph, a super radio-channel pair is introduced to represent a pair of nodes that can coexist on the same channel(s) using CSMA-CA mechanism and is modelled using a super-node. In graph modelling, a super-node is a vertex with a large number of edges that are incident on it. A coexistence-aware conflict is illustrated in Figure 4.5b. The channel assignment problem is modelled as a conflict-free, max-demand channel assignment with a min-demand constraint and is solved using an algorithm based on maximum independent weighted set.

Further work from the authors of [157] using the same modelling technique of a coexistence-aware radio-channel pair conflict graph is presented in [159]. This work focused on optimisation of spectrum utilisation in a SAS-assisted, coexistence-aware, dynamic channel assignment for CBRS PAL and GAA users. Like in [157], the problem of GAA channel assignment is modelled as a radio-channel-pair conflict graph, but unlike in [157], only two binary constraints are considered: co-channel interference and one-channel-assignment-per-node constraint. Nodes that can coexist in the same channel using CSMA-CA are represented by a super-radio-channel pair, as illustrated in Figure 4.5. The channel assignment problem is formulated as maximum reward and maximum utility problems.

4.6.1.4 Graph Colouring (DM-1:RRA-5)

The problem of coordinated spectrum allocation and coexistence management in CBRS-SAS wireless networks is studied in [47]. Interference relationships are represented by a graph and spectrum allocation is modelled using a graph colouring algorithm. Aggregate interference is calculated for each node and if it violates the interference constraint, the aggregate interference is eliminated by adding an edge in the interference graph between the victim node and the most interfering node, or by reducing the transmit power of the interfering nodes. To decrease spectrum fragmentation, the paper proposes merging least-interfering colours in the graph to reduce the chromatic number, however, the scheme does not explicitly consider groups of networks that can coordinate interference management among themselves using compatible MAC/PHY designs and therefore do not need non-overlapping spectrum.

Performance studies of a GAA-GAA coexistence scheme in the CBRS band using Approach 1 [36] of the WInnForum GAA spectrum coordination technical report are presented in [155,156]. The purpose of the studies was to define performance metrics to be used by operators and SAS administrators to evaluate proposed GSC schemes since the WInnForum technical reports do not define any. The initial study in [155] did not have any CxGs, and the later study in [156] was done to study the performance of a GSC without CxGs as well as with different numbers of CxGs, in various configurations. Interference was modelled using an interference graph and graph colouring was used to find the chromatic number of each CxG. The chromatic number is used to partition the available bandwidth between the CxGs according to the ratio of their chromatic numbers to the total chromatic number.

A joint graph multi-colouring channel assignment for inter-RAT coexistence management of LTE and Wi-Fi through frequency and spatial diversity is proposed in [27]. Although frequency coordination improved the overall throughput of the networks, the algorithm fails to exploit Wi-Fi CSMA operation in the joint channel assignment to further improve spectrum utilization in the time domain through channel sharing among Wi-Fi neighbour networks.

4.6.1.5 Recursive Clustering Algorithm (DM-1:RRA-6)

A performance study of a GAA-GAA coexistence scheme in the CBRS band using Approach 3 [38] of the WInnForum GAA spectrum coordination technical report is represented in [158]. The purpose of the study was to define performance metrics to be used by operators and SAS administrators to evaluate proposed GSC schemes since such metrics are not covered in the WInnForum technical report. The GSC allocates bandwidth to each CxG. A recursive clustering algorithm is used to allocate bandwidth to CBSDs in a Connected Set according to their cluster size. A CBSD that is connected only to CBSDs belonging to the same CxG as itself belongs to cluster size 1 and is allocated 100% of the allocated bandwidth. A CBSD that has edges to CBSDs belonging to its own CxG and to one other CxG belongs to cluster size 2 and is allocated 50% of the allocated bandwidth. This procedure is repeated recursively until

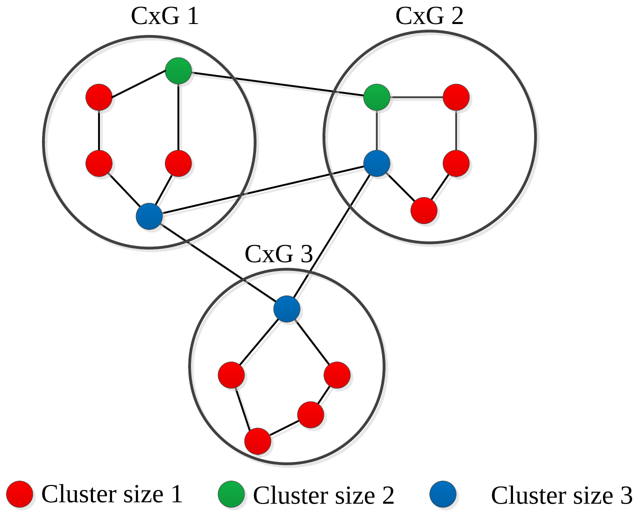


Figure 4.6: Illustration of clustering of CBSDs in a connected set.

bandwidth is allocated to all CBSDs.

Consider the illustration in Figure 4.6. Assuming there is 30 MHz of bandwidth available, all CBSDs of cluster size 1 would be allocated the full bandwidth (0-30 MHz). The two CBSDs of cluster size 2 would each be allocated half the bandwidth, that is 0-15 MHz and 15-30 MHz. Finally, the three glsplCBSD of cluster size 3 would each be allocated a third of the bandwidth, 0-10 MHz, 10-20 MHz and 20-30 MHz.

4.6.2 Hypergraph Theory-Based Models (DM-2)

4.6.2.1 Mixed Integer Program (DM-2:RRA1)

A centralised, measurement-based, spectrum management solution of heterogeneous wireless networks is proposed in [46] to provide a solution to coexistence challenges among heterogeneous wireless networks that cannot effectively coordinate access to a shared medium by frequency-isolating incompatible networks. A hypergraph is used to represent the structure of the RF environment such that the hypergraph can be searched for specific relationships among the radios and conflict subgraphs can be derived to realise spectrum assignment that ensures coexistence of heterogeneous wireless networks. As illustrated in Section 2.11, a vertex represents a radio device, a hyperedge represents radios that belong to the same network and require the same channel, and an edge between a pair of vertices represents either a transmission link if the vertices belong to the same hyperedge, otherwise it represents interference relationship. A mixed integer program (MIP)-algorithm that uses the relationships from the hypergraph model to derive constraints and the conflict subgraphs and measurement metrics to optimise the channel assignment.

4.6.3 Ecology-Inspired Optimisation Models (DM-3)

4.6.3.1 Optimal Foraging Theory (DM-3:RRA-1)

In [151], an architecture for enabling coexistence of H-CRNs, called SYMbiotic heterogeneous Coexistence ARchitecturE (SymCare), is proposed. Indirect communication between the networks is implemented via an 802.19.1-based mediator system. The channel selection algorithm is modelled using optimal foraging theory, which models competition between animals of different species. The animals compete for the same foraging resource in an ecosystem, without direct interactions between them, and in such a way as to maximise their net energy intake per unit time, that is the difference between the energy spent to access forage and the energy gained from the forage [143]. A TVWS channel is represented as a patch of forage resource, a network agent is represented by an animal and the selectivity of a channel in terms of least interference is represented by the suitability of a patch. The solution employs ideal free distribution [164] to model a sequential allocation process whereby more animals are distributed in patches with higher suitability. An equilibrium is reached when each animal maximises its own net energy intake by moving into the most suitable patch, which means, in terms of channel selection, when each network select the channel in which it will experience minimum interference.

4.6.3.2 Lotka-Volterra competition model (DM-3:RRA-2)

The Lotka–Volterra model is used to describe the dynamics of ecological systems in which two species interact as predator and prey [144]. This model can theoretically predict the outcome of inter-specific competition between the two species [142]. This model has been proposed for solving the problem of coexistence among H-CRNs in TVWS [152–154]. The H-CRNs are represented by a biological ecosystem, while each H-CRN represents a species. The population dynamics represent the dynamics of spectrum sharing. The design of the proposed solutions relies on an IEEE802.19.1 system for indirect coordination among coexisting H-CRNs. In [154], an ecology-inspired spectrum sharing algorithm to achieve a weighted-fair spectrum sharing allocation among H-CRNs is proposed. The work in [153] builds on the work in [154] by introducing a QoS parameter and different mutual interference factors in the spectrum competition model. Finally, the work in [152] introduces a Lotka–Volterra-based model discrete non-linear control system for state feedback control.

4.7 Discussion of Research Gaps in Centralised Coexistence Management Systems

The DSA ecosystem is characterised by multiple independent operators, multiple independent RANs, and heterogeneous RATs operating in the same spectrum band. To facilitate management of such a diverse ecosystem, radio devices are required by regulation to be registered with a spectrum database operator that is approved by the national regulator. During registration, operators are required to provide their contact details and parameters of their devices that have a bearing on the RF environment characteristics. The device parameters include network technology type, coverage area, and installation parameters such as antenna geo-location, gain and height, radio transmit power. The nodes are expected to operate under different transmission parameters and policies according to the RAT configuration, regulatory policies, licence conditions and operator policies.

Modelling of such an RF environment involves multiple relationships. In this thesis, multiple relationships refers to relationships among multiple radio devices or networks, as well as two or more connections between nodes. The discussion on research gaps is therefore focused on RF environment modelling techniques for data representation of multiple relationships in the light of coordinated radio resource allocation and spectrum sharing.

4.7.1 Representing Multiple Relationships in the RF Environment Model

The focus of the discussion is on four types of relationships. The first relationship identifies potential interference between nodes and provides constraints to the radio resource allocation algorithm. While one-way/mutual interference is a relationship between two nodes, cumulative interference is received from multiple nodes. The second relationship is network dependency among radios. This group is termed Common Node Group (CNG) or Common Channel Group (CCG), which represents radio devices that belong to the same network and provides constraints to the radio resource allocation algorithm, ensuring that nodes within the same network are allocated uniform channels. The third relationship is spectral coexistence, which identifies Interference Coordination Groups (ICGs), which are groups of radio devices/networks that can coordinate interference within their groups when sharing the same spectral resources by using inherent MAC mechanisms. The last relationship identifies radios that are subscribed to the same coexistence management entity such as radios in the same CxG. These four types of relationships are illustrated in Figure 4.7.

4.7.1.1 Interference Relationships

Graph theory is conventionally used to represent one-way/mutual interference in RF environment modelling. A vertex represents a node or a cell, and an edge exists between vertices if the nodes or cells that are represented by these vertices have potential to interfere when operating in the same channel. Cumulative interference from multiple networks can be harmful to a victim node, although some of the networks may not individually interfere with the victim network.

In [47], aggregate interference was represented by adding an edge between the victim node and the most distorting node from the list of interferers that are not connected to the victim node by an edge. Another potential approach to mitigating the impact of cumulative interference is to ensure that nodes that have been identified as cumulative interferers to a victim node are not all assigned the same frequency as the victim node [41, 90, 91, 95, 97, 98]. As illustrated in Figure 2.10 on page 44 in Chapter 2, this approach requires that groups of cumulative interferers are represented in the RF environment model in order to provide cumulative-interference-related constraints to the radio resource allocation algorithm. As such, the concept of an edge in a traditional graph, which is a two-element subset, is not sufficient to accurately represent cumulative interference from multiple networks [40]. Hence, hypergraph theory was used to represent cumulative interference in [41, 90, 91, 95, 97, 98].

4.7.1.2 Network Dependency

In [46], a hypergraph model is used to represent the structure of the radio ecosystem as illustrated in Figure 2.11 on page 48. Network dependency is modelled using a

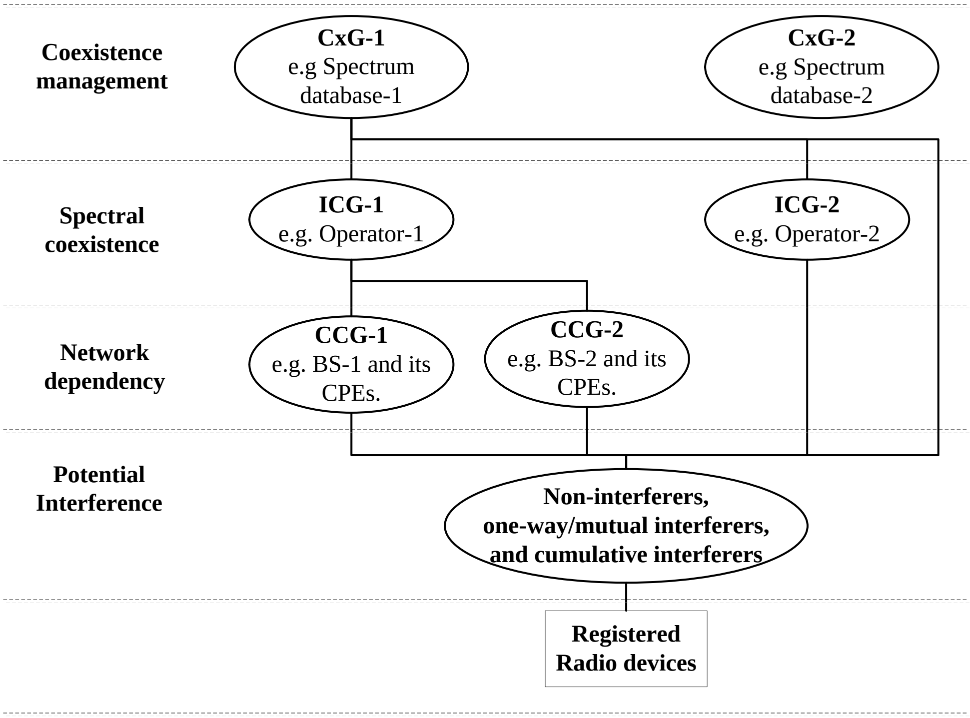


Figure 4.7: Illustration of multiple relationships between networks.

hyperedge which represents radios that belong to the same network and require the same channel. In the WInnForum GAA spectrum coordination framework, a group networks that belong to the same network, that is a CNG, is represented by a single node if CBSDs in a CNG are in multiple connected sets in order to merge those connected sets into one. While vertices can easily be merged in a graph, the information about the set of vertices that belong to the same CNG which need to be merged cannot be represented by an edge in a graph data structure when the CNG comprises more than two nodes because an edge is strictly a two-element subset. However, the CNG can be modelled by a hyperedge in a hypergraph model, and can be represented by one node through hyperedge contraction.

4.7.1.3 Spectral Coexistence

In [157,159], spectral coexistence relationship between a pair of networks is represented by a super node in a coexistence-aware conflict graph. As illustrated in Figure 4.5 on page 98, when a super node is added to a conflict graph, it inherits conflict relationships of its children nodes and the edge between its children pairs is removed. Thus, super nodes have a high number of incident edges, giving the radio resource allocation algorithm too many paths to consider. Furthermore, representing a relationship by a node or representing multiple entities by a single node violates consistency in the graph data structure since, conventionally, a node represent an entity and a relationship between two entities is represented by an edge. On the other hand, hyper relationships are consistent with hypergraph data structures.

4.7.1.4 Coexistence Management

In CBRS GAA spectrum coordination, bandwidth is allocated to the coexistence manager, according to its bandwidth requirements and based on spectrum availability. Non-overlapping bandwidth is allocated to coexistence managers when radio devices or networks associated with one coexistence manager have potential to interfere with radio devices or networks that are associated with the other coexistence manager. In a graph data structure, vertices that represent networks that belong to the same coexistence management entity cannot all be connected by a single edge because an edge is strictly a two-element subset whereas a coexistence group is likely to comprise more than two radio devices or networks. On the other hand, a hyperedge in a hypergraph model can sufficiently model the multiple relationships involving any number of vertices.

4.7.2 Multiple Relationships in Machine Learning

Construction of an interference graph can be derived based on modelling of the propagation environment, RF measurements, network performance, etc. A coexistence performance study of CBRS GAA use cases using LTE-TDD technologies that is presented in [112] concluded that while location-based propagation modelling is sufficient for coexistence management of outdoor micro networks, it leads to conservative frequency reuse when many indoor pico networks are deployed nearby. The authors then suggested that instead, interference prediction based on sophisticated long-term measurements can improve the performance of low-power private networks (using Category A CBSDs with maximum EIRP of 30 dBm) at some cost to the high-power micro network (using Category B CBSDs with maximum EIRP of 47 dBm).

Machine Learning (ML) is a suitable technique to enable coexistence management systems to learn and extract knowledge by interacting with huge volumes of data, such as long-term radio measurements [165]. ML-enabled coexistence systems could automatically extract features from complex measurement data. Furthermore, a neural network (NN), which is an ML technique, can be used to model the objective functions of non-linear problems that require optimisation [165]. For instance, in one of the surveyed papers [160], in which the optimisation problem had seven different types of constraints, a neural network was used to solve the optimisation problem. In [166], learning capability of a neural network predictor (NNP) is used to obtain the statistics of coexisting primary user systems from the RF traces collected by an ML-enabled secondary user cognitive radio network. Neural networks have also found application in modelling propagation loss and radio resource allocation [160, 165, 167–169].

Graph databases are gaining popularity over relational databases for representing relational information, because in graph databases, relationships are first-class constructs [170]. Relationships associate and structure the nodes. Like nodes, relationships can also have meta-data that could provide additional constraints in radio resource allocation algorithms. Graph-based neural networks have shown to be superior on representation learning than traditional neural networks due to use of graph data structures [171]. However, in coexistence management, data is complex, beyond the pairwise connections that are represented by a graph. While a simpler approach is to approximate complex relationships as pairwise relationships, it can lead to loss of information.

Hypergraphs are a natural way to describe complex relationships, without loss of information. Vertices represent elementary units of consideration for the problem, and hyperedges represent relationships among any arbitrary number of vertices. In a hypergraph, the relationships can be multifaceted, which allows modelling of multiple features at a time [89]. The hypergaph data model has found application in knowledge database platforms. For instance, TypeDB (previously known as Grakn) is a distributed, hyper-relational database solution which was launched in 2016 for managing complex data that serves as a knowledge base for cognitive/artificial intelligence (AI) systems [137].

Hypergraph data models have also recently found application in machine learning. Hypergraph learning has attracted increasing attention due to its flexibility and capability in modelling complex data [172]. Learning on a hypergraph structure has found application in neural networks for various research fields [173]. There is therefore the need to investigate application of hypergraph data structures for modelling multiple relationships of an RF environment, in order to facilitate data representation learning using ML tools and efficient coexistence-aware spectrum sharing. Furthermore, there is need to investigate ways of reducing processing time of machine learning applications since machine learning algorithms can be computation intensive.

4.8 High Level Solution Framework

A proposed high level application framework to guide development of applications for dynamic radio resource management in DSA networks is presented in Figure 4.8. The distinctive feature of the framework is that the output of the spectral coexistence analysis function is input to the hypergraph-based RF environment modelling function. The reason is that this thesis seeks to model spectral coexistence relationships, along with interference relationships, in the same hypergraph data structure to enable spectrum sharing among networks that have the capability to coordinate interference management among themselves. The functions of interference analysis, spectral coexistence analysis, and dynamic radio resource allocation could be enhanced by machine learning and artificial intelligence techniques.

4.8.1 Contextual Information

Input Contextual Information

This refers to raw information obtained from the secondary networks/devices. A secondary device, especially if it is a high power device or a master device, is typically required by regulation to have geo-location capability or to have it's geo-location set at the time of installation; in other words it must be *location-aware.* The secondary device sends a request for a list of channels that are available at its location to an authorised white space spectrum database. Once it gets the output from the database, the secondary device can be said to be *spectrum-aware.* It then chooses one of the available channels as its operating channel and informs the database about its intended operating channel and Effective Isotropic Radiated Power (EIRP); and this property is herein referred to as *frequency-aware.* Secondary networks are required to specify the network technology; and this property is herein referred to as *technology-aware.* Networks that provide service to QoS-sensitive applications can also provide their QoS requirements; and this property is herein referred to as *QoS-aware.* Networks can also submit their radio measurements reports, which can be used to adjust radio resource assignments in the event that radio performance is reported to be below guaranteed levels.

Derived Contextual Information

This information covers the entire RF environment of subscribed networks and is obtained from internal functions of the radio resource management system. Using the input contextual information, the interference and coexistence analysis functions generate the relevant knowledge for *interference-awareness* and *coexistence-awareness* respectively.

4.8.2 Interference Analysis

A radio resource manager is required to allocate resources intelligently so that networks generate or receive the least interference. Interference analysis is the process aimed at discovering which devices or networks can interfere with each other if they were to operate in the same channel. Networks that have potential to interfere when operating in a co-channel are called *neighbours*, hence this process has also been termed *"neighbour discovery"* [33].

4.8.3 Spectral Coexistence Analysis

In licence-exempt or GAA spectrum, when the available spectrum is not enough for each network to operate in its own channel(s), the spectral coexistence analysis function determines whether the networks that have potential for co-channel interference can effectively *share* a set of radio resources by coordinating access to the shared channel. This function could also be used in a case where several light-licensed users are granted scheduled access to the same spectrum on a guaranteed contention ratio basis.

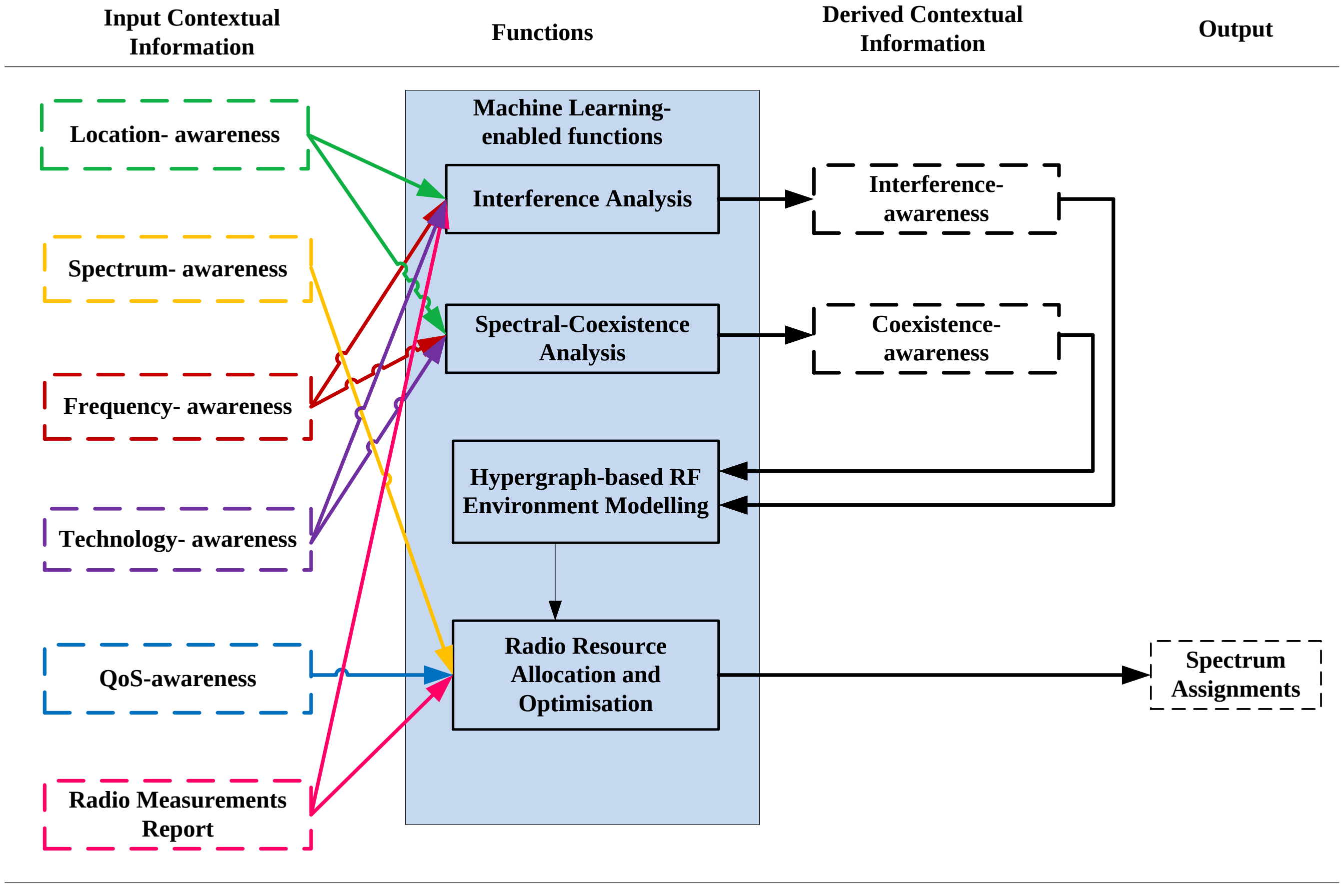


Figure 4.8: High-level framework for dynamic radio resource management.

4.8.4 RF Environment Modelling

An RF environment herein refers to all secondary radio devices and networks that are operating in a given spectrum band in a given location at a given time. The RF environment model is defined as a representation of how the device-system parameters (i.e. transmit frequency, power, desired Signal-to-Interference-plus-Noise-Ratio (SINR)) and the spectral factors (i.e. signal propagation characteristics and number of available channels) interact so as to affect each other's performance [78].

Modelling is the art of formulating an application in terms of precise, well-documented problems in order to apply well-known algorithmic design techniques [85]. Algorithms are designed to work on well-defined data structures. Proper modelling can therefore eliminate the need to design new algorithms by relating an application to what has been done before. In this framework, RF environment modelling involves representing the RF environment as a well-known data structure to which conventional algorithms can be applied to represent coexistence constraints among the networks and to solve the radio resource allocation problem.

4.8.5 Dynamic Radio Resource Allocation

Dynamic radio resource management refers to frameworks, strategies and algorithms for system-level dynamic allocation of radio resources, transmission power, transmission intervals and other radio transmission characteristics within the radio domain in wireless communication systems, with the objective of maximising spectrum utilisation and network performance [174]. In this thesis, the concept is different from the traditional radio resource management in LTE that involves link-based or node-based transmission scheduling. Here, radio resource management is defined as the process of intelligently allocating spectrum to coexistence groups, base stations or access points of subscribed networks in such a manner that the networks will receive and generate the least interference when operating on the same channels and that overall spectrum utilisation shall be maximised as far as possible.

4.9 Chapter Summary

This chapter has presented a comprehensive survey of state-of-the-art solutions for spectrum coordination and coexistence management of heterogeneous wireless networks operating in shared spectrum. It has been discussed that traditional graph theory is not sufficient to model relationships in spectrum coordination and coexistence management systems of heterogeneous wireless networks because such systems involve complex multiple relationships which are beyond the pairwise connections of a graph data structure. Finally, this chapter proposed a high-level framework to guide development of applications for machine learning-enabled, coexistence-aware RF environment modelling and radio resource allocation. In the next chapter, this framework is used to develop an application that investigates the use of hypergraph theory in modelling spectrum allocation among heterogeneous TVWS networks.

Chapter 5

Efficient Spectrum Sharing Using a Hypergraph Model

5.1 Introduction

The contribution of this chapter is an investigation into whether the hypergraph-based spectrum sharing technique is more efficient than traditional-graph-based spectrum sharing. This is investigated by comparing spectrum utilisation performance of hypergraph-based and graph-based radio resource allocation algorithms. In the first experiment, performance is measured by the number of networks that are assigned an operating channel, out of the total number of competing networks, when the the number of available channels is not sufficient for each network to be assigned an exclusive channel among its neighbour networks. In the second experiment, efficiency of the model is measured by the number of channels required to reach the point when 100% of the competing networks are assigned an operating channel. The coexistence decision algorithm that is used in the scheme is based on a method called "co-sharing based on network geometry classification" which is specified in the IEEE 802.19.1 standard for coexistence management mechanisms.

5.2 Analysis of Previous Work

Graph colouring is conventionally used to model channel assignment in space and frequency domains [27, 47, 155, 156]. Spatial re-usability of the available spectrum could be improved through transmission power control [47, 48]. When the available spectrum is not enough for each radio or network to be assigned an exclusive channel among its neighbour networks, spectral efficiency could also be improved through co-sharing in the time domain between networks that can coexist in the same spectrum using compatible media access control mechanisms [27, 94].

In [159], the spectral coexistence relationship between a pair of networks is represented by a super node in a coexistence-aware conflict subgraph. When a super node is added to a conflict graph, it inherits conflict relationships of its children nodes and the edge between its children pairs is removed. Thus, super nodes have a high number of incident edges, giving the channel assignment algorithm too many paths to consider.

A coexistence decision algorithm for spectrum sharing is proposed in [94] for use in IEEE 802.19.1 systems. The algorithm introduces shared spectrum allocation on top of exclusive channel allocation. The algorithm selects a network at each step and assigns spectrum to the network. If no unoccupied channel is available, the algorithm searches for a channel occupied by neighbour networks of the same MAC/PHY design, subject to channel load constraints. While this approach ensures spectrum allocation stability in that previous allocations are not rearranged to accommodate new networks, channel sharing options are dependent on the previous exclusive channel allocations. Thus, there is a trade off between spectrum utilisation efficiency and channel allocation invariability. A more efficient channel allocation could be realised if the previous allocations could be re-arranged. Algorithms that minimise the need and frequency to change channel assignment can also be applied.

The RF environment could be organised into coexistent groups so that channels are allocated to groups, instead of individual networks. This requires modelling spectral coexistence information in the RF environment model that is input to the radio resource allocation algorithm. But, the concept of an edge in a traditional graph, which is a two-element subset, is not sufficient to model subsets of potential co-sharing networks because such subsets may have cardinality of greater than 2.

A hypergraph is a generalization of an undirected graph in which a hyperedge is a subset of vertices of arbitrary cardinality rather than two-element subsets [86,88]. This thesis proposes hypergraph theory as an efficient mathematical tool for representing groups of networks that can coordinate interference management between them, so that the channel allocation algorithm is able to assign channels to groups of coexistent networks instead of only to individual networks.

Hypergraphs have found application in modelling of cumulative interference [40–45, 91, 92, 97, 98] and network dependency [46]. To the best of the author's knowledge, hyperedges have not been used before to model spectral coexistence among multiple independent networks for spectrum sharing.

5.3 System Design

5.3.1 System Model

As illustrated in Figure 5.1, a heterogeneous TV white space environment is considered. There are N wireless networks operating using the following RATs: IEEE 802.22 Wireless Regional Area Network (WRAN) and 802.11 Television Very High Throughput (TVHT) wireless local area network (WLAN). Each BS and AP radio is associated with a set of slave devices in the form of CPEs and UEs. In a cell, the master device and the slave devices communicate on the same channel and the master device coordinates access to the channel among its slave devices. The independent networks may not be able to communicate directly with each other by using their MAC/PHY protocols either because they use incompatible network technologies or they are outside each other's communication range. The geo-location, service area, receiver sensitivity and RAT of each master device is known. A service area or coverage area of a network is specified by its coverage radius, with reference to the geo-location of the master device. Slave devices are located within the service area of their master devices. Service areas of different master devices may overlap.

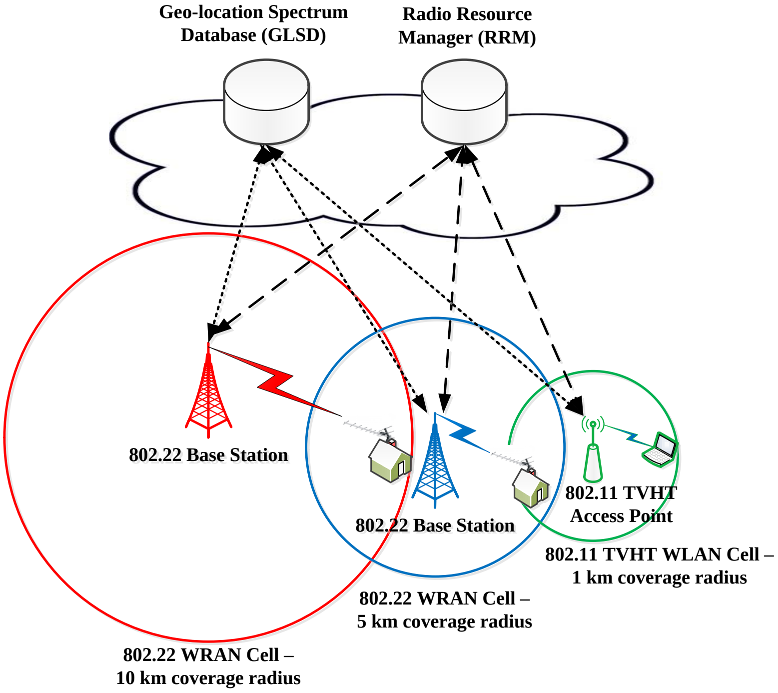


Figure 5.1: System model for heterogeneous networks operating in TVWS under the control of a GLSD and an RRM.

The scenario is based on the TVWS regulatory framework that has been approved by UK's Office of Communication (Ofcom) [15]. The master devices have access to a Geo-location Spectrum Database (GLSD) via IP backhaul connection. The GLSD provides the list of TV channels that are available at the location of a master device. Thus, primary user protection is not considered in this system design because primary users are protected by the GLSD. The procedure is shown in Fig. 5.2.

When a master device wants to initiate a network, it provides the GLSD with its parameters (2a). In response, the GLSD provides a list of TV channels that are available at its location and the permissible transmit power for each available channel (2b). The master device also has access to the centralised Radio Resource Manager (RRM), such as an IEEE 802.19.1-based coexistence management system, which is not part of Ofcom's TVWS framework, but the service can be provided by a third-party. If the master device uses its radio interface to access the RRM, then it is required to choose an operating channel from the list and to report its channel usage parameters to the GLSD before it can communicate with the RRM (2c); but if the master device uses its IP backhaul connection, this step is not required. The master device then provides the RRM with its operating channel and the list of available channels. The RRM runs the radio resource allocation algorithm and requests the master device to reconfigure its network (4b). The assigned frequency and transmission power must comply with the output of the GLSD. The master device confirms the reconfiguration parameters if the assigned frequency and transmission power complies with the output of the GLSD (4c). The master device reports its channel usage parameters to the GLSD before it starts operation (4d). From then on, the master device periodically contacts the GLSD

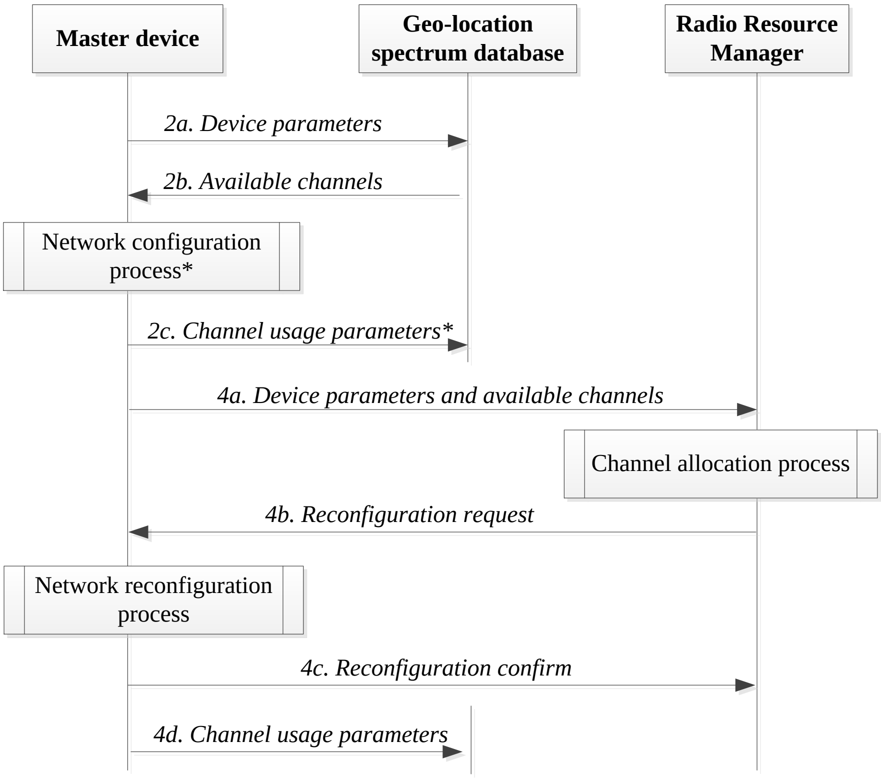


Figure 5.2: Communication protocol among system components. Note: *Only required if master device uses its radio interface to contact RRM, otherwise not required if it uses the IP backhaul connection.

to check the validity of its operating parameters. The GLSD can also instruct the master device to immediately stop transmission when its operating channel becomes unavailable, for example, when a primary user occupies the channel.

5.3.2 Interference Analysis

In this model, only co-channel interference among secondary user networks is considered. ACLR performance of TVWS radios is regulated in order to prevent interference to licensed primary users. It is assumed that all networks have overlap in their operating frequency range capabilities. The wavelength of a signal, which is the distance over which the shape of a wave repeats itself, is inversely proportional to the frequency of the wave. Thus, for the same transmit power, the distance covered by a signal that is operating in a lower frequency is greater than that of a signal that is transmitted using a higher frequency. Interference levels are calculated for the worst case scenario when the master device is transmitting at the maximum power permissible by regulation or attainable by the RAT standard, and at the lowest frequency where TVWS is permitted in the TV band. Ofcom's channelization for the TV band is used.

A SINR threshold is used to determine if a pair of networks can potentially interfere if operating on overlapping channels. Only interference caused or received by the BS/AP radio is considered for SINR constraint because it is likely to transmit at a higher power than the CPE/UE radio, using an omni-directional antenna and it is therefore more likely to cause or receive interference. Even though CPEs typically use directional antennas, CPEs that are within the line of sight of more than one BS will suffer or cause interference. It is assumed that this scenario will be avoided at the time of CPE installation since the IEEE 802.22.2 Standard for Installation and Deployment of IEEE 802.22 Systems [108] specifies that the CPE antenna should be oriented toward its serving BS and should be further adjusted to minimise the gain in the direction of an interfering BS while keeping the gain toward its serving BS within 2 dB of its maximum.

Consider two cells, i and j, with master devices W_i and W_j, and with coverage radii r_i and r_j. Let d_{ij} be the physical distance between the two master devices that is calculated from their geo-locations using the Haversine formula which is based on spherical trigonometry [175]. A pair of networks are neighbours if their coverage areas overlap, and this is evaluated by $d_{ij} < r_i + r_j$.

If the coverage areas of two networks do not overlap, as illustrated in Fig. 5.3, these two networks are considered as neighbours if the SINR of cell-edge users, which experience lowest SINR due to their distant locations, is less than a set threshold, δ. This condition is satisfied if at least one of the following equations, eq. (5.1) and eq. (5.2), holds true.

$$\frac{P_i}{P_j} < \delta_i \text{ ; at the edge of network } i \tag{5.1}$$

$$\frac{P_j}{P_i} < \delta_j \text{ ; at the edge of network } j \tag{5.2}$$

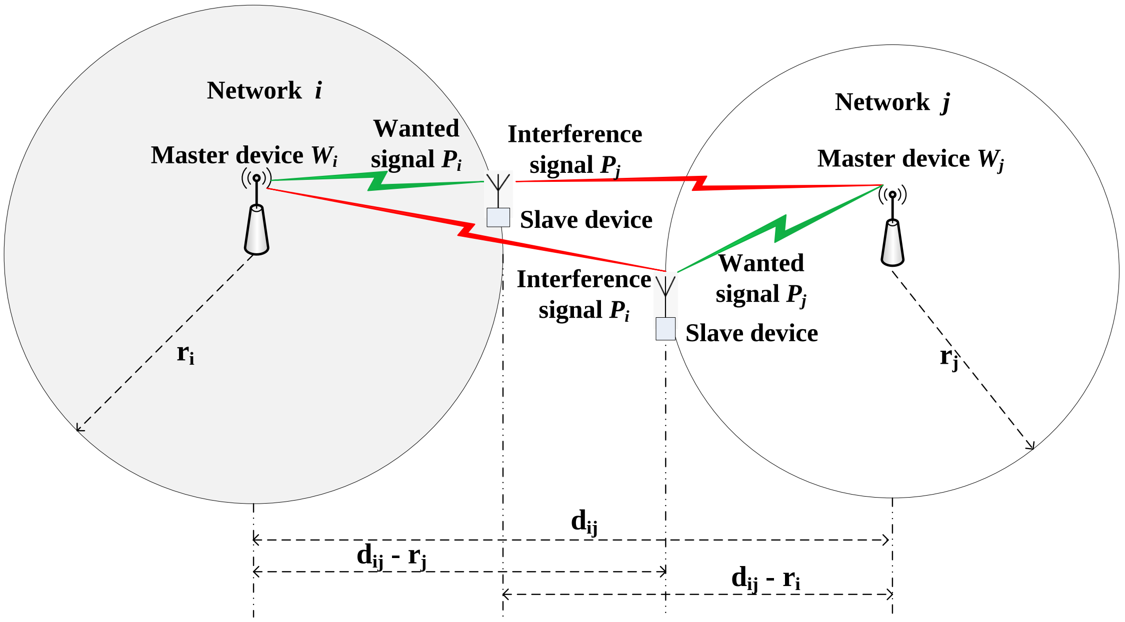


Figure 5.3: Interference analysis between a pair of networks with non-overlapping coverage areas.

Interference information is represented by an undirected graph $G = (V, E)$ using adjacency lists. Construction of the interference graph is described in Algorithm 1.

Algorithm 1: Interference graph construction.

```
Data: csv file of device parameters of master devices
Result: Adjacency lists of vertices
for each pair $(i, j)$ of master devices do
    if coverage areas of cells $i$ and $j$ overlap then
        cells $i$ and $j$ form an edge;
    end
    else
        if cells $i$ and $j$ satisfy eq. (5.1) AND/OR eq. (5.2) then
            cells $i$ and $j$ form an edge;
        end
    end
end
```

5.3.3 Spectral Coexistence Analysis

Multiple IEEE 802.22 WRAN BSs use on-demand frame contention to share a channel in the time domain. Time-synchronisation can happen over a wireless connection if the network controllers are within each other's communication range. In IEEE 802.11 TVHT WLANs, UEs use CSMA-CA with RTS/CTS to minimise collisions, as specified in the IEEE 1900.7 standard for white space DSA radio systems. While the IEEE 802.11 TVHT devices can back-off when an IEEE 802.22 radio is transmitting, the IEEE 802.22 would not back off because it is an "impolite" radio. Thus, the two standards cannot effectively coexist in the same channel.

The spectral coexistence criterion that was used in [94] only considers RAT compatibility. It is assumed that master devices of neighbour networks are within communication range to effectively coordinate access to shared channels, or an IP connection is used instead. The study in [159] assumes that all the heterogeneous networks use Listen-before-talk coexistence mechanisms, hence spectral coexistence analysis involves determining whether the networks are within each other's carrier sense/energy detection range. This was solved by using the Bron-Kerbosch algorithm to find a clique, which is a subgraph in which every two distinct nodes are connected to each other [176].

This thesis considers a heterogeneous environment in which networks share spectrum in the time domain using either frame scheduling or Listen-before-talk mechanisms. Co-channel operation among networks that use TDMA-based MAC mechanisms requires time-synchronised operation among the networks. Synchronisation can happen over the wireless connection if the network controllers are within each other's communication range and if they use compatible RATs. Similarly, networks that use contention-based MAC mechanisms, such as CSMA-CA, need to be within each other's wireless range to be able to detect each other's transmissions. Thus, these conditions can be evaluated to derive groups of networks that can manage interference among themselves using compatible RATs when they share a channel. In this thesis, the method for evaluation of spectral coexistence is based on the IEEE 802.19.1 mechanisms for *"co-sharing via network geometry classification"*, and two classes in which synchronisation happens over the wireless connection are considered [35].

5.3.3.1 Network Geometry Class 4

In network geometry class 4, the coverage area of a smaller network is completely overlaid by that of a wider network, as illustrated in Figure 5.4. In such cases, the two networks can share a channel if they communicate using compatible RATs and if the interference power from the wider network to the smaller network is not harmful. BS interference into neighbouring BSs can be prevented by avoiding line of sight and/or maximising the separation distances between BSs. It is assumed that line of sight would be avoided at the time of installation.

The absolute minimum separation between the antennae must be a horizontal distance of greater than 1/4 of its RF carrier's wavelength, but they should not be located at the exact multiples of the wavelength. The longest wavelength in the TV band is 0.63247m for the centre frequency of the lowest channel, 474 MHz. In [79], a controlled study was conducted to analyse performance and coexistence among IEEE 802.15.4, 802.11 and 802.22 radio systems. The study concluded that generally, all of the systems would significantly deteriorate if the interferer is located within 12m. Hence, a separation distance of 15m is used in this model. Thus, networks i and j are considered as coexisting networks of network geometry class 4 if the coverage of one the two networks is completely overlaid by the other network, that is when $d_{ij} < r_i$ or $d_{ij} < r_j$, and if the physical distance between the base stations of the two networks is greater than 15m, that is when $d_{ij} > 15$m.

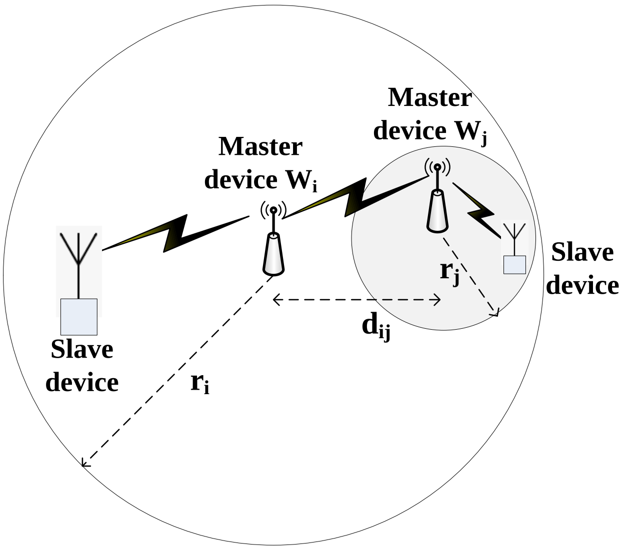


Figure 5.4: Illustration of network geometry class 4.

5.3.3.2 Network Geometry Class 1

In network geometry class 1, the coverage areas of master devices W_i and W_j overlap and the two master devices are within each other's communication range, as illustrated in Figure 5.5. Let P_i and P_j represent the transmit powers of the master devices W_i and W_j, respectively. The Signal-to-Noise-Ratio (SNR) is used to determine if the master devices are within each other's communication range it is calculated at the geo-location of the other master device. The noise floor, N, is based on the receiver sensitivity. The SNR must be greater than a set threshold, δ, for the master devices to be able to communicate. Thus, evaluation of whether networks i and j are coexistent networks of network geometry class 1 is done in two stages: 1) if their coverage areas overlap, that is when $d_{ij} < r_i$ or $d_{ij} < r_j$, and 2) if the SNR for the signal from master device W_i at the geo-location of master device W_i is greater than a set threshold, and vice versa, that is if $\frac{P_i}{N} > \delta_j$ at the geo-location of master device W_j and $\frac{P_j}{N} > \delta_i$ at the geo-location of master device W_i. The method for coexistence analysis is summarised in Algorithm 2.

Spectral coexistence information is stored in an $N \times N$ matrix C, where an entry of 1 for C_{ij} signifies that networks i and j can coexist.

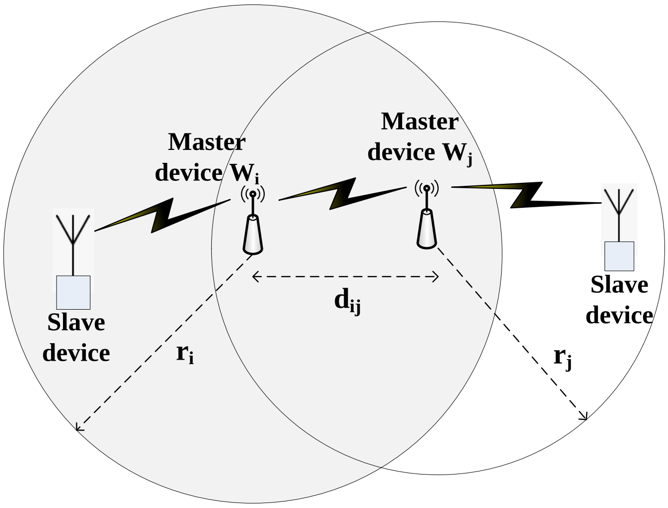


Figure 5.5: Illustration of network geometry class 1.

5.3.4 Problem Formulation and Performance Metric

Given a set of N networks that are competing for the same channels in a set of K available channels, assuming that all channels are available at the geo-locations of all the networks, channel allocation is represented by a matrix $R_{N\times K}$ with each entry in the matrix called $\beta_{n,k}$ for all $1 \leq n \leq N$ and $1 \leq k \leq K$, as expressed in Equation 5.3.

$$R_{N\times K} = [\beta_{n,k}] \tag{5.3}$$

$\beta_{n,k}$ takes the value of either 1 or 0, as defined in Equation 5.4.

$$\beta_{n,k} = \begin{cases} 1 & \text{when channel } k \text{ is allocated to network } n; \\ 0 & \text{otherwise.} \end{cases} \tag{5.4}$$

A network is considered as an operational network if it has been assigned an operating channel from a set of K available channels. The number of operational networks, α, is expressed in Equation 5.5.

Algorithm 2: Coexistence Analysis Algorithm.

```
Data: csv file of device parameters of master devices
Result: Coexistence matrix; $C_{N\times N}$
Apply Algorithm 1 to get adjacency lists ;
Initialise the coexistence matrix $C_{N\times N}$ to zeroes;
for i from 1 to N do
    for j in adjacency list of node i do
        if nodes i and j use the same RAT then
            Calculate distance $d_{ij}$ ;
            if condition for network geometry class 4 is satisfied then
                $C_{ij} = 1$ ;
            end
            else
                Calculate SNR in both directions ;
                if condition for network geometry class 1 is satisfied then
                    $C_{ij} = 1$ ;
                end
            end
        end
    end
end
```

$$\alpha = \sum_{k=1}^{K}\sum_{n=1}^{N}\beta_{n,k} \tag{5.5}$$

The performance metric, α_{avg} is the average number of operational networks from S different simulations, as given in Equation 5.6.

$$\alpha_{avg} = \frac{\sum_{s=1}^{S}\alpha_s}{S} \tag{5.6}$$

5.4 Graph-Based Spectrum Sharing

In the graph-based model considered in this thesis, the spectrum sharing technique that was proposed in [94] is reproduced, with a minor modification that, whereas the design in [94] assumes that either master devices of neighbour networks are within communication range to effectively coordinate access to shared channels or an IP connection is used instead, this design considers both RAT compatibility and communication range constraints in spectral coexistence analysis, as described in Section 5.3.3.

Exclusive radio resource allocation is solved using a vertex colouring algorithm whereby a vertex represents a cell and a colour assignment represents a channel allocation. The vertex colouring problem seeks to colour the vertices of the interference graph $G = (V, E)$ using the minimum number of colours such that all neighbour vertices are coloured using different colours, that is: v_i and v_j are assigned different colours for all $(v_i, v_j) \in E$. Thus, a cell is assigned an exclusive channel among its neighbour cells, that means a cell is assigned an operating that is unique from the operating channels of its neighbour cells, but the operating channel can be re-assigned to cells that are not its neighbours to achieve frequency re-use across space.

Nodes are coloured in descending order of vertex degree since high degree vertices represent the networks that interfere with more networks and therefore have more colour constraints. Where there is a tie, the vertices are coloured in ascending order of network identity number. Unlike colouring in descending order of vertex degree which is meant to prioritise high-degree vertices because they have more colour constraints, colouring in ascending order of network id is arbitrary, just to impose uniqueness. However, in real world deployments, other factors can be used to determine order of priority such as first-come-first-served basis. An example of a coloured interference graph is illustrated in Figure 5.6. Four out of seven radios are each assigned an operating channel that is exclusive from the operating channels of its neighbour radios. Thereafter, channel sharing is applied so that if a network could not be allocated an exclusive channel, it can share the same channel with networks of the same RAT that have already been allocated the channel, on the conditions that it can coexist with all other neighbour networks that have already been assigned that channel and that the total Channel Occupancy Rate (COR) would not exceed unity when the new network joins the channel. The entire procedure is summarised in Algorithm 3.

When this spectrum sharing technique is applied to the example network that is given in Figure 5.6, the result is illustrated in Figure 5.7. BS_1 is allocated channel 1 to share with BS_2. AP_2 cannot share channel 1 with AP_3 because it would interfere with BS_2 which uses a different RAT. Similarly, AP_2 cannot share channel 2 with AP_1

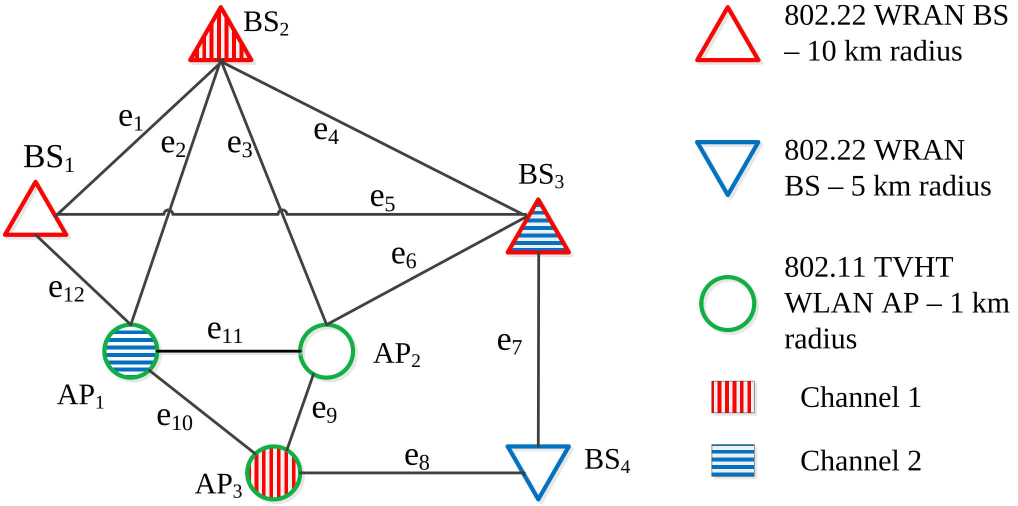


Figure 5.6: An example of exclusive channel allocation.

because it would interfere with BS_3 which uses a different RAT. Thus, channel sharing options for AP_2 are limited by previous allocations. Finally, BS_4 can share channel 2 with BS_3. In the end, six out of the seven networks are assigned an operating channel. This thesis therefore seeks to investigate a modelling technique for channel allocation that is more efficient than this traditional graph-based modelling technique.

5.5 Hypergraph-Based Spectrum Sharing

In hypergraphs, hyperedges represent subsets of any cardinality, not just 2 as in graphs, such that hyperedges can be used to represent *"arbitrary general statements about arbitrary subsets"* [86, 88]. The basics of hypergraph theory are presented in Section 2.6.2.

5.5.1 Hypergraph Construction

In a hypergraph, the relationships can be multifaceted, which allows modelling of multiple features at a time [89]. In this thesis, the hypergraph model is used to represent pairwise interference and spectral coexistence. An example of hypergraph modelling is given in Fig. 5.8. Edges e_1 to e_{12} represent pairwise interference and hyperedges e_{13} and e_{14} represent spectral coexistence capability. Notice that BS_4 cannot join hyperedge e_{14} because it is outside the communication range of BS_1 and BS_2.

Algorithm 3: Graph-based Spectrum Sharing.

```
Data: csv file of device parameters of master devices
Result: Coloured graph, number of coloured vertices ($\alpha$)
Apply Algorithm 1 to construct interference graph;
// exclusive channel allocation
Sort vertices $v_1$, $v_2$,..., $v_n$ in decreasing order of vertex degree;
Assign the first colour to the vertex of maximum degree $v_1$;
for i from $v_2$ to $v_n$ do
    Get neighbour colour list;
    for colour k from 1 to K do
        for each element in neighbour colour list do
            Check if colour k is in neighbour list;
        end
        if colour k not in neighbour colour list then
            Assign colour to vertex $v_i$;
            Break;
        end
    end
end
// spectrum sharing allocation
Generate the coexistence matrix;
for each node $v_i$ not coloured do
    for each colour k in list of colours assigned to adjacent nodes do
        for for each adjacent node $v_j$ already assigned colour k do
            Check if node $v_i$ can coexist with node $v_j$;
        end
        if node $v_i$ can coexist with all adjacent nodes already assigned colour k
         then
            Calculate the expected total COR;
            if $COR_{total} \leq 1$ then
                assign colour k to vertex $v_i$;
                break;
            end
        end
    end
end
Calculate $\alpha$ using eq.(5.5)
```

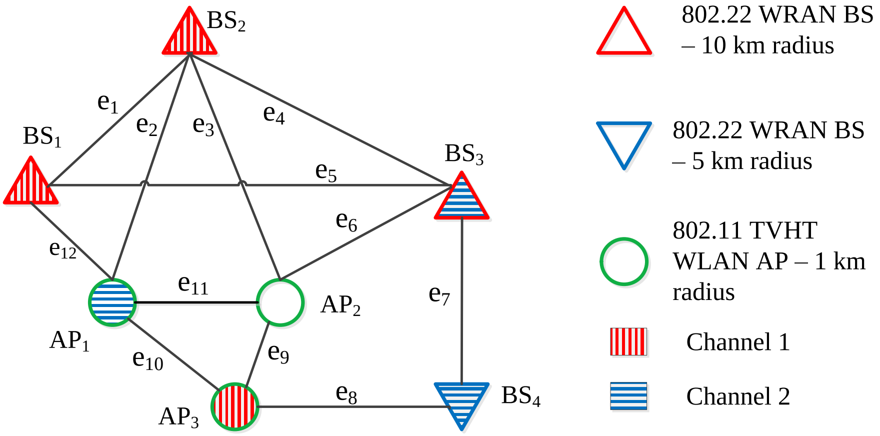


Figure 5.7: An example of graph-based spectrum sharing.

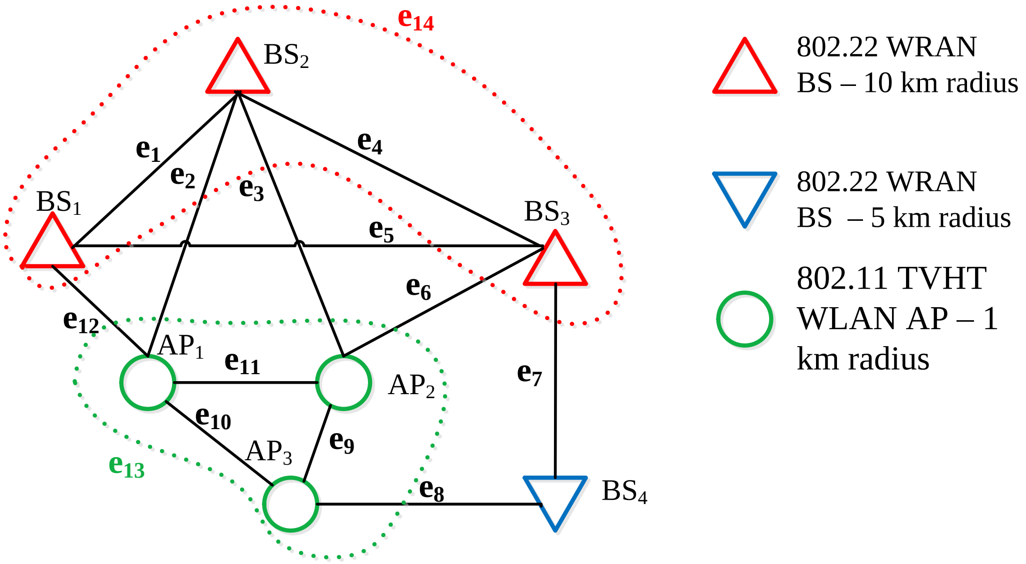


Figure 5.8: An example of hypergraph modelling.

The first step is to construct the edges that represent pair-wise interference. Next, spectral coexistence analysis is performed and the information from the coexistence matrix is then processed to generate *"interference coordination subsets"*, such that each node in the subset can coexist with every other node in the subset, and the total COR of the elements of the subset is less than or equal to unity. Interference coordination subsets form the hyperedges. To reduce complexity, a node can only be assigned to one interference coordination subset. The corresponding hyperedge construction is given in Algorithm 4.

Algorithm 4: Hypergraph Construction Algorithm.

```
Data: $v_1$, $v_2$, $v_3$,..., $v_n$; list of vertices
Data: csv file of device parameters of master devices
Data: Spectral coexistence matrix, $C_{N \times N}$
Result: Hyperedge incidence lists, $E$
Initialise dictionary of hyperedge incidence lists $E$;
for each node $v_i$ in list of vertices do
    Initialise $COR_{total}$ to 0;
    if node $v_i$ not already added to any hyperedge then
        Initialise hyperedge incidence list $e$;
        Append node $v_i$ to $e$;
        Increment $COR_{total}$ by the COR of node $i$;
        for each node $v_j$ adjacent to $v_i$ and not yet added to $E$ do
            if node $v_j$ can coexist with all nodes in $e$ then
                Increment $COR_{total}$ by $COR_j$;
                if $COR_{total} \leq 1$ then
                    Append node $v_j$ to $e$;
                end
            end
        end
    end
    if $e$ has more than one vertex then
        Append hyperedge incidence list $e$ to $E$;
    end
end
```

5.5.2 Hyperedge Contraction

Hyperedge contraction theory is then applied to decompose the hypergraph H into the form of a traditional graph and make it amenable to the vertex colouring algorithm, without losing coexistence information. As illustrated in Figure 2.7, contraction of a hyperedge involves sequentially contracting the vertices of the hyperedge into one new vertex and then weakly deleting the hyperedge. The new vertex is adjacent to the union of the vertices that were originally adjacent to the individual vertices before contraction. The output is a minor graph H_1 in which each hyperedge is contracted to a single vertex, such that colouring of that single vertex implies assigning a channel to a group of coexistent networks. This is illustrated in Figure 5.9. Pseudocode for the procedure is given in Algorithm 5.

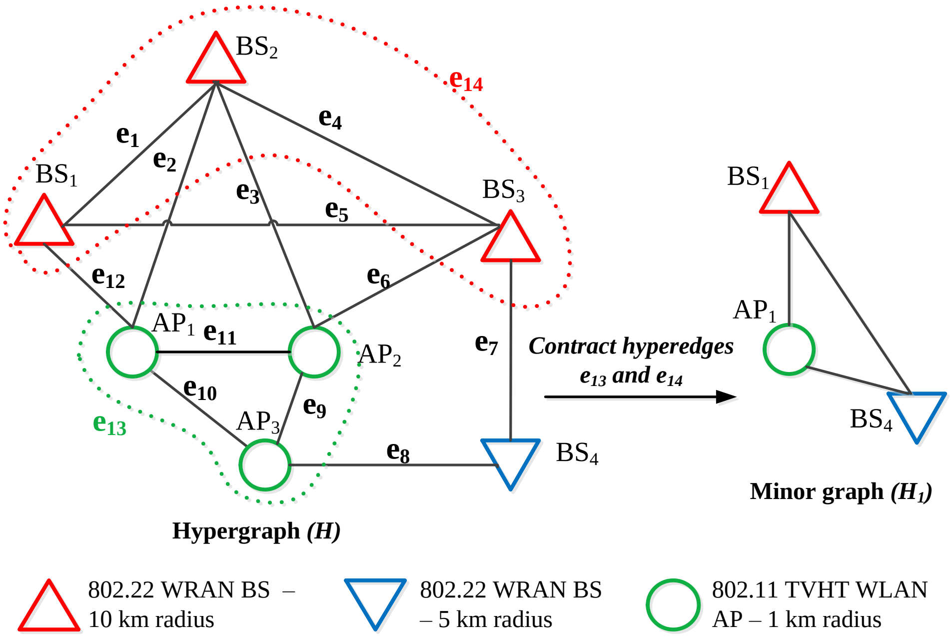


Figure 5.9: An example of hypergraph contraction.

5.5.3 Channel Allocation Algorithm

Channel allocation involves applying the vertex colouring algorithm to the minor graph and then applying the resultant colour map to the hypergraph, while ensuring that the vertices of a hyperedge get the colour that is assigned to the vertex of the minor graph that replaced all the vertices of that hyperedge. This procedure is illustrated in Fig. 5.10. However, during algorithm testing, it was found that applying the vertex colouring algorithm to the minor graph may in some cases not exhaust all possible channel allocations. In hyperedge contraction, all vertices in a hyperedge are replaced by a single vertex such that all edges that were incident on the individual vertices are now incident on the new vertex, hence information about some possible channel allocations could be masked. For instance, in Fig. 5.10, when hyperedge e_{14} is contracted, there will be an edge between the new vertex BS_1 and BS_4 in H'. However, it can be noted in H that BS_4 can share the same channel with BS_3 if they are able to coexist and calculation of total COR will only involve BS_3 and BS_4 because BS_4 is not visible to BS_1 and BS_2. To deal with this issue, the algorithm was augmented to check for additional possible allocations that do not violate interference, coexistence and COR constraints if there are still some uncoloured nodes after vertex colouring of the minor graph.

The entire procedure is summarised in Algorithm 6. Sample output of a preliminary test that was done on a heterogeneous radio environment comprising 12 networks to demonstrate the concept of this hypergraph-based model is given in Appendix B.

Algorithm 5: Hyperedge Contraction Algorithm.

```
Data: Hypergraph, $H$
Result: Minor graph, $H_1$
for each hyperedge $e$ in $H$ do
    Identify the first vertex $v_1$ in $e$ ;
    for every other vertex $v_i$ incident on $e$ do
        Contract $v_1$ and $v_i$ to one vertex $v_1$;
    end
end
```

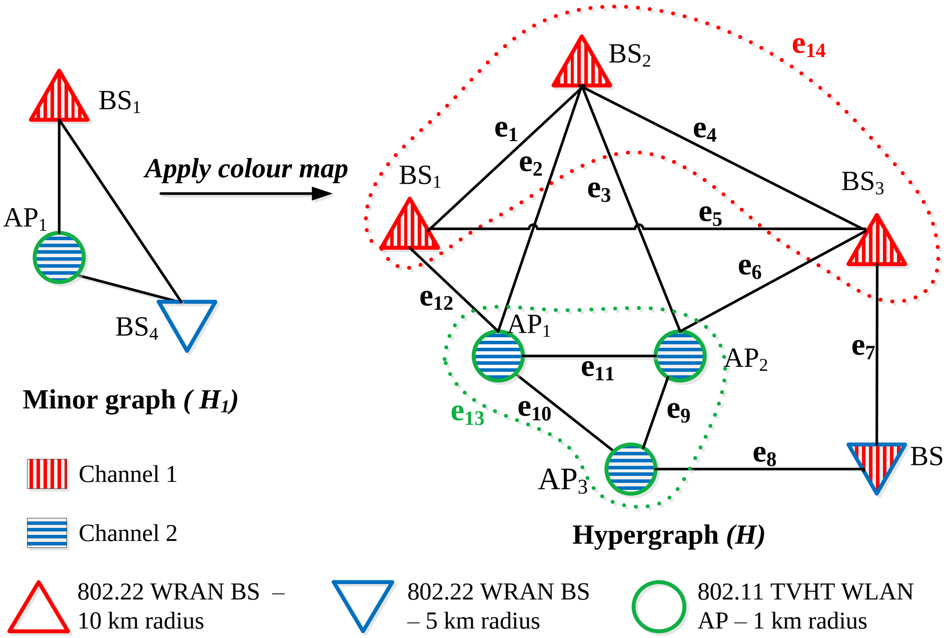


Figure 5.10: An example of hypergraph colouring.

5.5.3.1 Limitation of the Channel Allocation Algorithm

According to the specification of the vertex colouring algorithm, the vertices of the minor graph are coloured in descending order of vertex degree, and if there is a tie, the vertices are coloured in order of network ID. However, during algorithm testing it was found that prioritising nodes according to the cardinality of the contracted hyperedges that are represented by these nodes could in some cases result in a higher number of coloured vertices. Whereas modifying the vertex colouring algorithm to selectively colour nodes according to the cardinality of the contracted hyperedge would in some rare cases result in a slightly higher number of operational networks, it would introduce unnecessary complexity to the algorithm. Therefore, this was not pursued further because the cost of computational complexity would outweigh the benefits.

Algorithm 6: Hypergraph-based channel sharing algorithm.

```
Data: $v_1$, $v_2$, $v_3$,..., $v_n$; list of vertices
Data: 1, 2, 3,..., K; list of available colours
Result: Coloured hypergraph, number of coloured vertices ($\alpha$)
// Hypergraph construction
Apply Algorithm 1 to form edges between between independent interferers;
Generate the $C_{N \times N}$ coexistence matrix;
Apply Algorithm 4 to form hyperedges from interference coordination subsets;
// Hyperedge contraction
Apply Algorithm 5 to form a minor graph $H_1$;
// Colour assignment
Apply vertex colouring algorithm to colour the minor graph $H_1$ to get the
  colour map;
for each node v in hypergraph H do
    Apply the colour map;
end
// Check for possible additional channel allocations
for every uncoloured node $v_i$ do
    for every colour k do
        for every adjacent node $v_j$ that is assigned colour k do
            Check if $v_i$ can coexist with $v_j$;
        end
        if node $v_i$ can coexist with all adjacent nodes then
            Assign colour k to node $v_i$;
            break;
        end
    end
end
Calculate $\alpha$ using eq.(5.5);
```

5.6 Simulation Parameters and Results

The Python programming language was used to simulate the channel allocation algorithms in order to ascertain that the proposed hypergraph model enables more efficient spectrum usage than the traditional graph model. Simulations were carried out on a personal computer with the following specifications: 64-bit system, Processor:Intel Core i5-1035G1 CPU at 1.00GHz, 1190 Mhz, 4 Cores, 8 Logical Processors.

A 50 km by 50 km test area is considered, which is bounded by the geo-coordinates given in Table 5.1, and is centred around Lilongwe city in Malawi. A physical map of the area is given in Figure 5.11. It covers the Lilongwe Plain as well as some hilly areas, and includes both urban and rural areas. A path loss component of 4 is chosen since most of the area would be relatively lossy environments. The geo-locations of the test networks are randomly and independently generated within the test area.

Table 5.1: Geo-location coordinates of the 50 km by 50 km area.

Northern-most	-13.736010°
Southern-most	-14.193300°
Eastern-most	34.031800°
Western-most	33.567194°

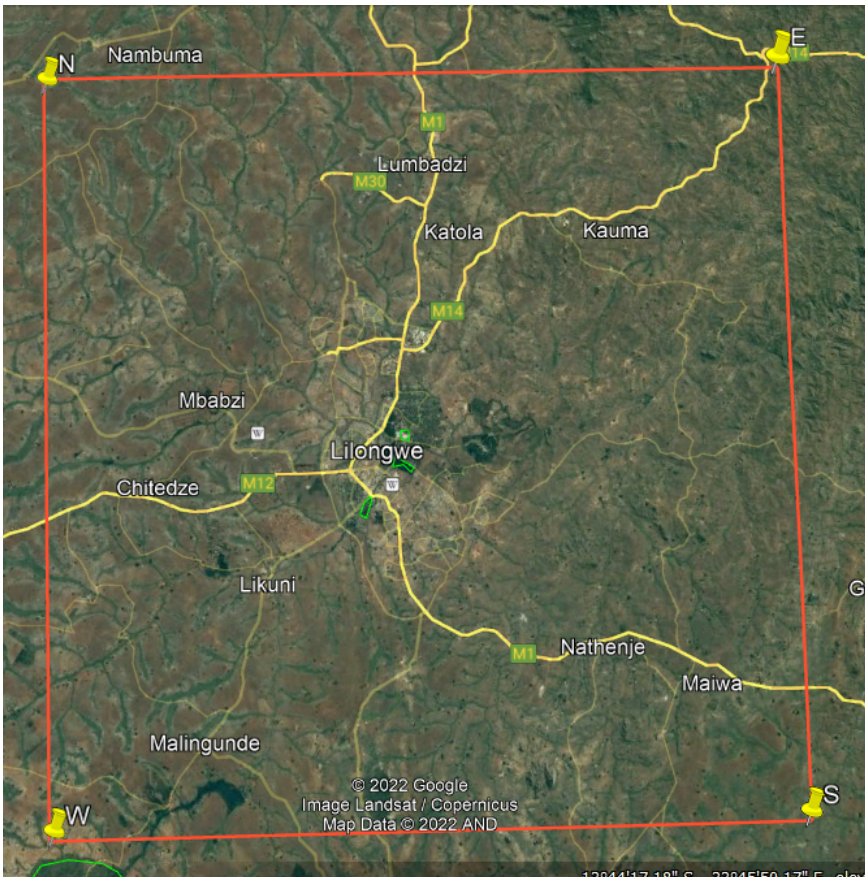


Figure 5.11: A physical map of the simulation area.

The propagation loss model given in Equation 5.6, which is suggested in the IEEE 802.19.1 standard [35, 177], is used to predict the path loss of the transmissions. The rest of the test parameters are given in Table 5.2.

$$L(d) = 10log\left(\frac{4\pi d}{\lambda}\right)\alpha - 20log(h_t * h_r) \tag{5.7}$$

Table 5.2: Parameters for Simulation.

Radio Access Technology (RAT)	802.11 TVHT WLAN	802.22 WRAN	802.22 WRAN
Cell coverage (m)	1,000	5,000	10,000
BS / AP conducted power (dBm)	15	20	31
BS/AP antenna gain (dB)	5	5	5
CPE/UE antenna gain (dB)	0	11	11
BS/AP antenna height (m)	10	12	15
CPE/UE antenna height (m)	1.5	6	10
Receiver sensitivity (dBm)	-88	-88	-88
Attenuation factor, α	4	4	4
Channel Occupancy Rate (COR)	0.3	0.25	0.25
SINR/SNR threshold (dB)	10	10	10
Centre frequency (MHz)	474	474	474

Three channel allocation schemes are simulated: (a) exclusive channel allocation, (b) graph-based channel sharing, and (c) hypergraph-based channel sharing. Exclusive channel allocation is included in order to appreciate the improvement in spectrum utilisation that is achieved through channel sharing when the number of available channels is insufficient. The results of performance comparison between hypergraph-based channel sharing and exclusive channel allocation were published in [51]. In this chapter, discussion of performance comparison is focused on graph-based and hypergraph-based channel sharing techniques. The performance metric used is spectrum utilisation which is herein measured either by the percentage of the available networks that are operational, having been assigned an operating channel, on a non-interfering basis or on a coordinated co-sharing basis, from a fixed set of available channels, or by the number of channels required to achieve a given percentage of operational networks.

The simulation involves varying two factors that have an impact on the output of the channel allocation algorithm: (a) level of interference, which is varied by increasing the density of competing networks (N) in a fixed test area, and is measured by the average number of neighbours per network, and (b) the given number of available channels (K). There are three test scenarios, with different numbers and ratios of the three types of networks. The test scenarios characterise three levels of interference, scenario 1 being the lowest, scenario 2 the middle and scenario 3 the highest.

The dataset is presented in the form of a box and whisker plot to show the spread and centres of the results from simulations. The spread is measured in terms of the interquartile range and the mean of the data set, whereas the measures of centre are the mean and median of a data set. Figure 5.12 shows how this information is represented in the box and whisker plot.

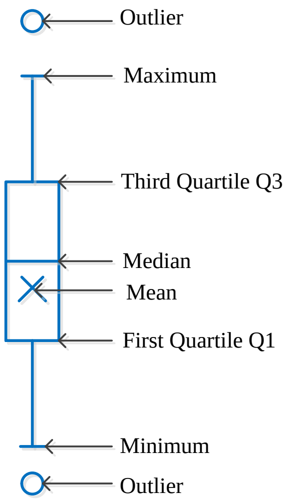


Figure 5.12: Description of box and whisker representation.

5.6.1 Number of Operational Networks as a Function of Number of Competing Networks

The objective of this test is to study the improvement in spectrum utilisation that is realised through channel sharing using the proposed hypergraph-based algorithm when the number of available channels (K) is not sufficient for exclusive channel allocation. The interference level in the RF environment is varied by increasing the number of competing networks (N) in the test area, while the number of available channels (K) is held constant at 2 and at 3 in the first and second experiments, respectively. First, the interference level is characterised by plotting the distribution of the average number of neighbours per network in the sets of networks used in the 100 simulations. Then the spectrum utilisation performance results are plotted showing the number of operational networks (α) as a function of the number of competing networks (N).

5.6.1.1 Test Scenario 1

The first test scenario consists of a set of 50 networks, in the ratio of 25:15:10 for 1 km-, 5 km- and 10 km-coverage radius networks, respectively, which are randomly and independently distributed in the 50 km by 50 km area. It is assumed that there are initially 25 networks of 1 km-radius in the test area. Then the 15 networks of 5 km radius are added, five at a time, followed by the 10 networks of 10 km-radius, also five at a time.

The distribution of interference level from the 100 simulations, in terms of the average number of neighbours per network, is presented in Figure 5.13. When there are 25 networks of 1 km-radius, the average number of neighbours per network is negligible at 0.2. When the 5 km-radius network start to join, interference level increases up to a mean number of neighbours per network of 2 at $N = 40$. Finally, the mean interference level increases to 5.7 average neighbours per network at $N = 50$ when all the 10 km-radius networks radius join the ecosystem. The simulation results for the number of operational networks when there are 2 and 3 available channels are given in Figures 5.14 and 5.15, respectively.

When K=2

When $N = 25$, 100% of the competing networks are operational because the interference is almost zero, such that the same channel can be shared by almost all networks in the spatial domain. When $30 \leq N \leq 40$, average performance of both channel sharing models drops from 100% operational networks due to the rising interference levels as the 5 km-radius networks start to join. Some networks cannot be allocated an operating

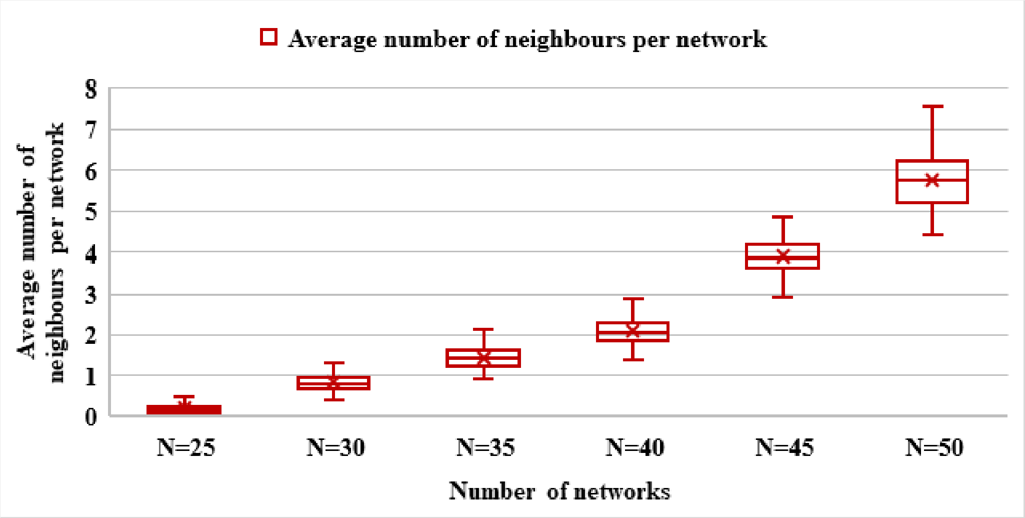


Figure 5.13: Interference characterisation of test scenario 1.

channel on either a non-interfering or a co-sharing basis. On average, when $N = 40$, the graph-based method assigns channels to 35.7 networks (about 89%) whereas the hypergraph-based method achieves 36.6 operational networks (about (92%). When the 10 km-radius start to join at $N = 45$, performance drops further as interference levels increase. However, the hypergraph-based method performs better, on average, than the graph-based method. At $N = 50$, the hypergraph-based model achieves an average number of operational networks of 34.96 (about 70%), whereas the graph-based method achieves 33.37 (about 67%).

When K=3

When the number of available channels is increased to 3, performance of both models improves compared to when $K = 2$. When all the 5 km-radius have joined the ecosystem (at $N = 40$), the number of available channels is nearly sufficient such that hypergraph-based and graph-based methods achieve average performance of 99.4% and 98% operational networks, respectively. At $N = 50$, the number of available channels is however insufficient. Nonetheless, the mean number of operational networks for the hypergraph-based model is 44.48, representing about 89% operational networks, whereas the graph-based method achieves an average of 42 operational networks, representing 84% operational networks.

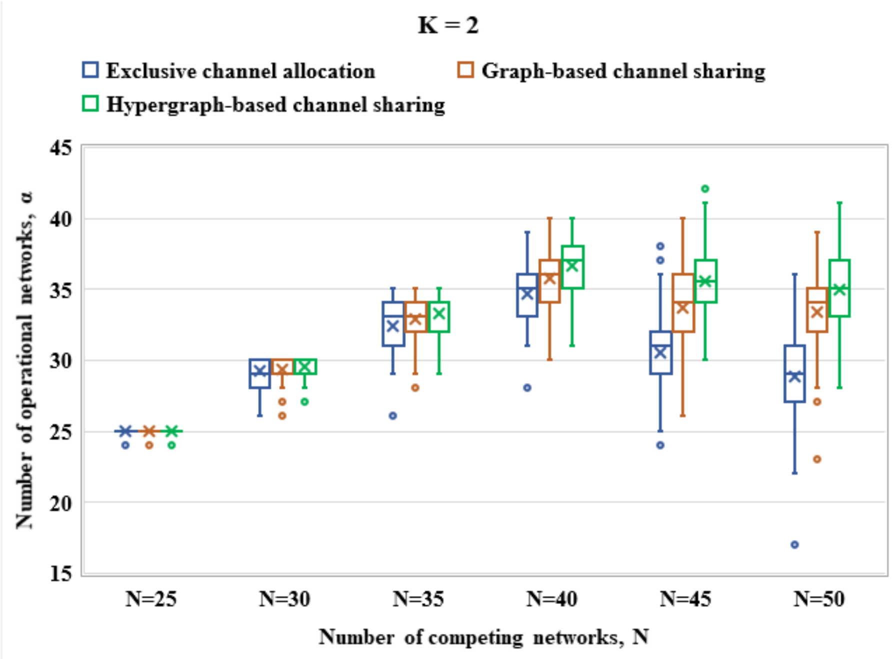


Figure 5.14: Number of operational networks for test scenario 1 when $K = 2$.

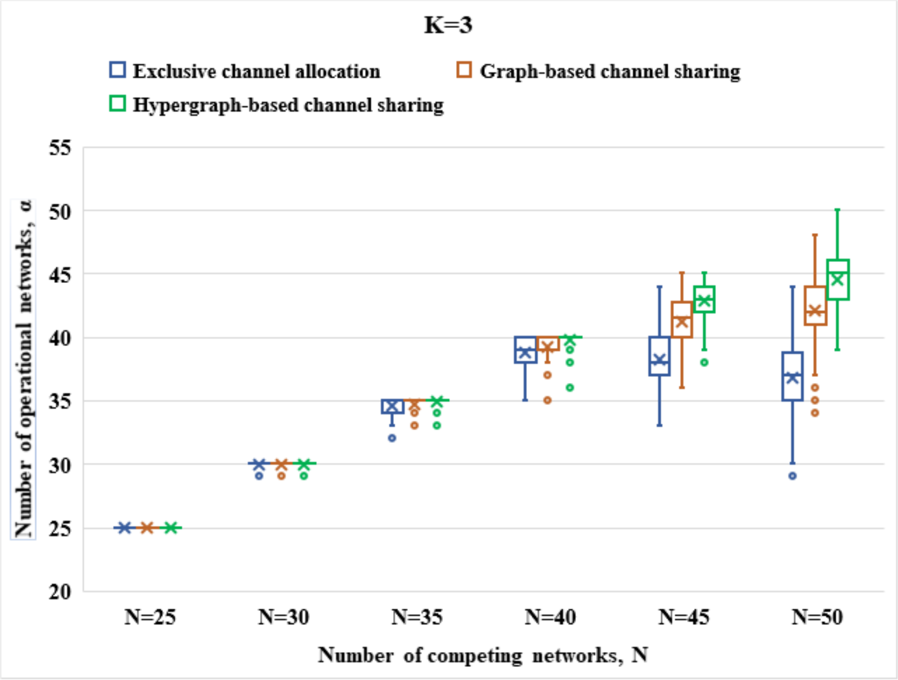


Figure 5.15: Number of operational networks for test scenario 1 when $K = 3$.

5.6.1.2 Test Scenario 2

The second test scenario comprises a set of 100 networks, in the ratio of 40:35:25 for 1 km-, 5 km- and 10 km-coverage radius networks, respectively. The distribution of interference level from the 100 simulations is given in Figure 5.16. It is assumed that there are initially 40 networks of 1 km-radius in the test area. At this level of network density, interference level is very low at a mean of 0.25 average neighbours per network from 100 simulations. Then the 35 networks of 5 km radius are added, five at a time, raising the interference level to a mean of 4.84 average neighbours per network at $N = 75$. This is followed by the addition of 25 networks of 10 km-radius, also five at a time, thus increasing the interference level to a mean of 14.22 average neighbours per network. The simulation results for the number of operational networks when there are 2 and 3 available channels are given in Figures 5.17 and 5.18, respectively.

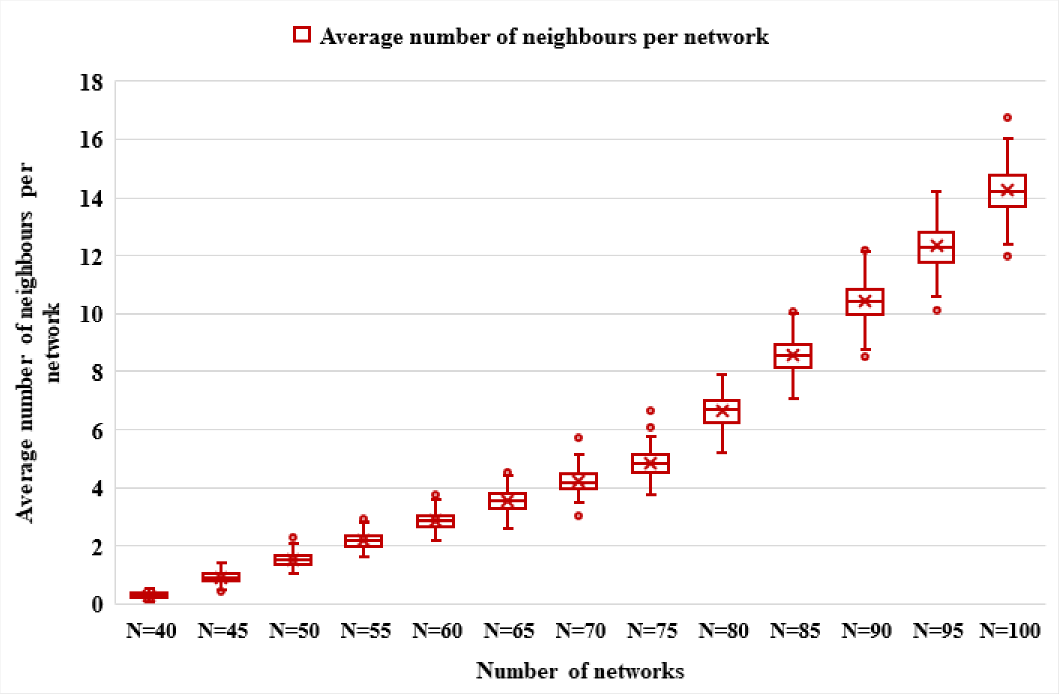


Figure 5.16: Interference characterisation of test scenario 2.

When K=2

At $N = 40$, 2 channels are sufficient to have all the 1 km-radius networks operational. However, when the 5 km-radius networks start to join, this number of available channels is no longer sufficient and average performance starts to drop from 100%. However, the rate of performance decline is slower for the hypergraph-based method than for the graph-based method, such that at $N = 75$, the hypergraph-based method achieves, on average, 56.31 operational networks, representing 75%, whereas the graph-based method achieves 52.65 operational networks, representing 70% of the total competing networks. When the 10 km-radius networks start to join, the interference level increases and the number of available channels becomes even inadequate than before. Nonetheless, the hypergraph-based method maintains better performance than the graph-based method. At the end of the simulation, the hypergraph-based method achieves performance that is 4% higher than that of the graph-based method.

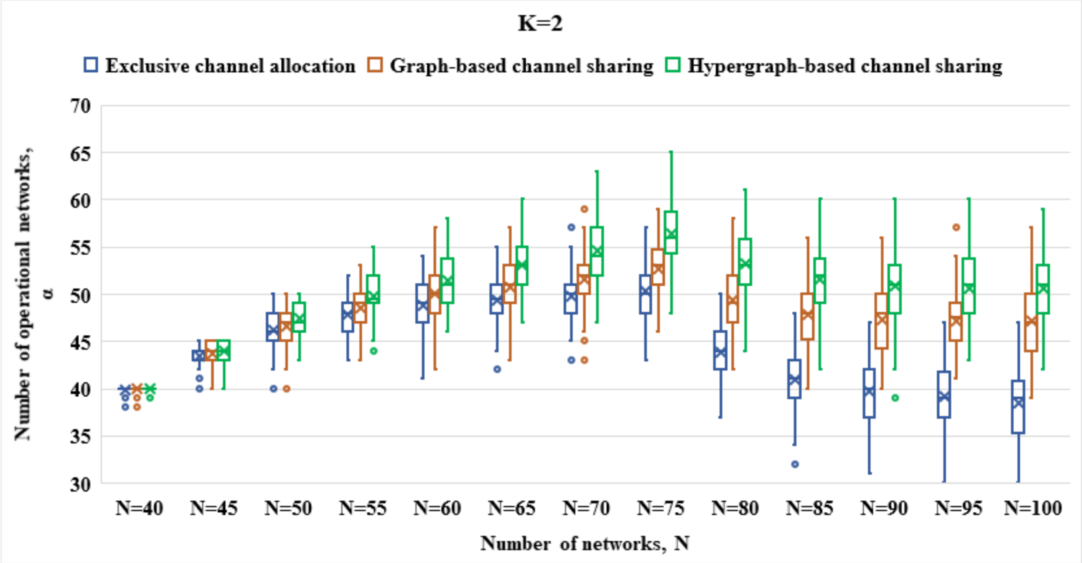


Figure 5.17: Number of operational networks for test scenario 2 when $K = 2$.

When K=3

When the number of available channels is increased to 3, it is nearly sufficient up to $N = 50$. Thereafter, performance of both methods starts to drop from 100%. Nonetheless, the hypergaph-based method out-performs the graph-based method. At $N = 75$, on average, the hypergraph-based method achieves 69.89 operational networks, representing about 93%, while the graph-based method achieves 65.09 operational networks, representing about 87% of the total competing networks. When $N = 100$, the hypergraph-based method maintains 5% better performance than the graph-based method.

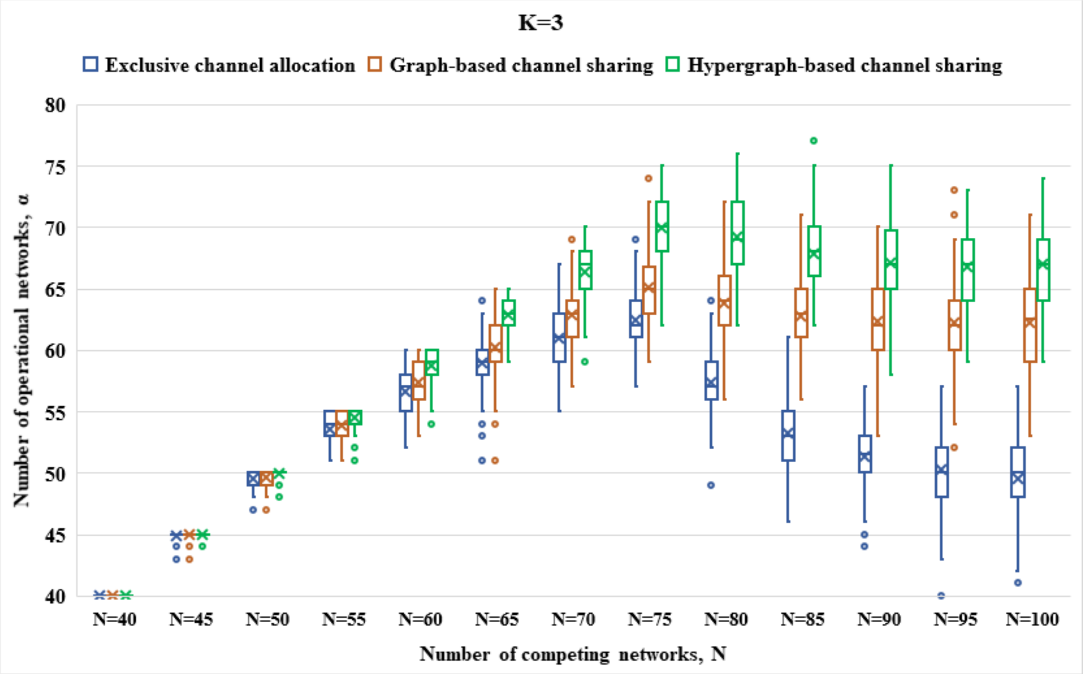


Figure 5.18: Number of operational networks for test scenario 2 when $K = 3$.

5.6.1.3 Test Scenario 3

The third test scenario consists of 100 networks in the ratio 50:50 for 1 km-radius and 10 km-radius networks, respectively. It is assumed that there are initially 50 networks of 1 km-radius in the test area. It can be seen from Figure 5.19 that at this network density, the average number of neighbours per network is 0.3. Then 50 networks of 10 km-radius are added, five at a time. The average number of neighbours per network rises to 18.5 at $N = 100$. The simulation results for the number of operational networks when there are 2 and 3 available channels are given in Figures 5.20 and 5.21, respectively.

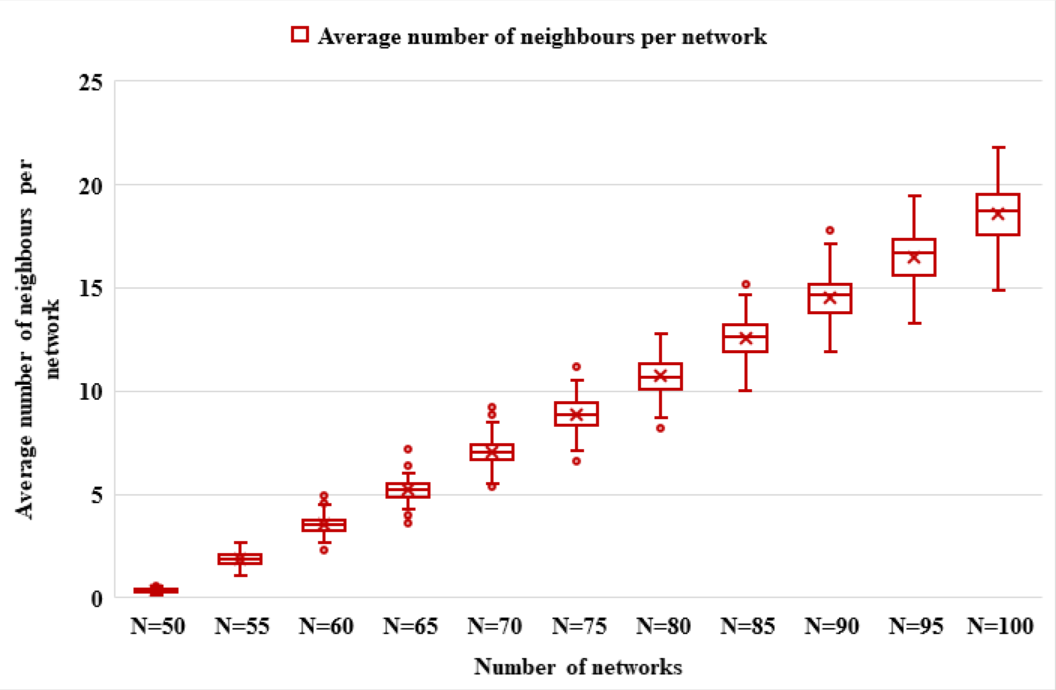


Figure 5.19: Interference characterisation of test scenario 3.

When K=2

At $N = 50$, the number of networks is nearly sufficient for the 50 networks of 1 km-radius since the interference level is very low. As the 10 km-radius networks start to join the ecosystem, the performance of both models starts to drop because the number of channels is insufficient. Nonetheless, the hyergraph-based model maintains better performance than the graph-based model. At $N = 100$, the hypergraph-based model achieves 50% operational networks whereas the graph-based model achieves 45%.

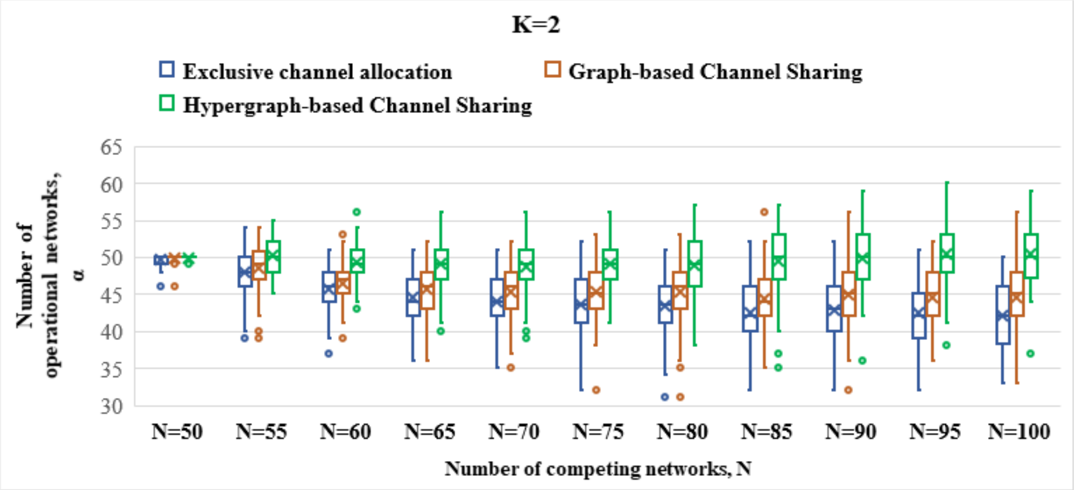


Figure 5.20: Number of operational networks for test scenario 3 when $K = 2$.

When K=3

At $K = 3$, this number of channels is nearly sufficient up to $N = 55$, after which performance of both models start to drop from 100%. Nevertheless, the hypergraph-based model performs better than the graph-based method, and at $N = 100$, it achieves

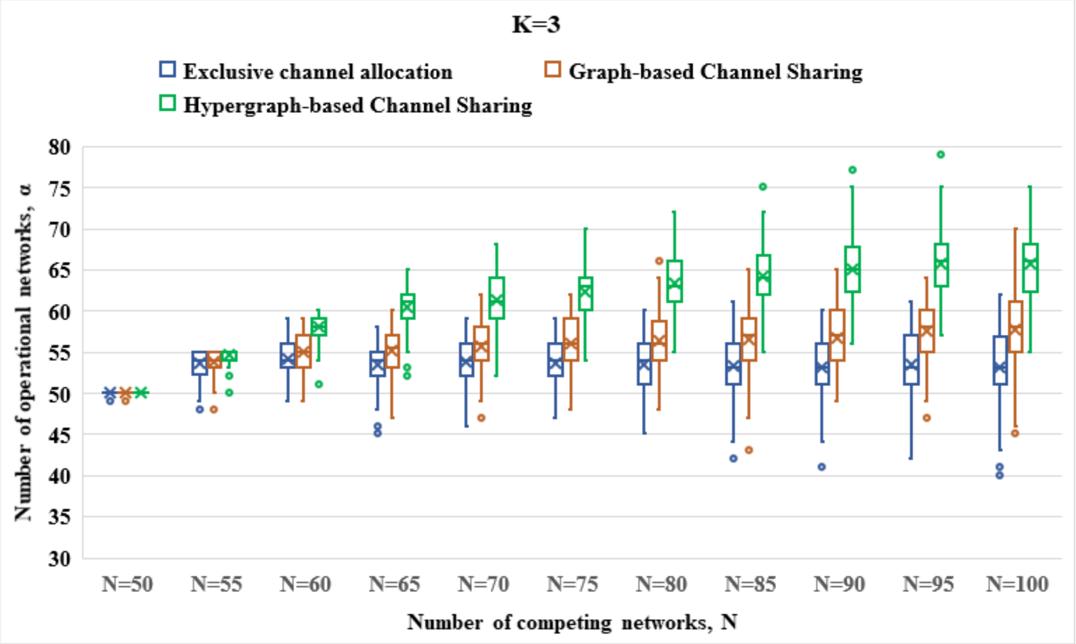


Figure 5.21: Number of operational networks for test scenario 3 when $K = 3$.

66% operational networks, which is 8% higher than the performance achieved by the graph-based method.

5.6.1.4 Interpretation of Results

Table 5.3 presents a summary of the results for the 3 test scenarios when $N = 100$. The results show that the hypergraph-based method performs better than the graph-based method, on average, by up to 8% more operational networks in scenario 3 when $K = 3$. It can be seen that, as the interference level is increased from test scenario 1 to test scenario 2 and then to test scenario 3, the difference in performance between the two models becomes greater. Similarly, as the number of available channels is increased from $K = 2$ to $K = 3$, the gap in performance of the two models also becomes wider.

Table 5.3: Summary of results for average percentage of operational networks.

Number of operational networks, α (%)						
No. of channels	K=2			K=3		
Test scenarios	1	2	3	1	2	3
Graph-based channel sharing	67%	47%	45%	84%	62%	58%
Hypergraph-based channel sharing	70%	51%	50%	89%	67%	66%

In the graph-based channel sharing method, some 1 km-radius networks begin to lose their operating channels to the long range networks when they start to join the ecosystem. This is because the graph-based method assigns channels in the order of decreasing vertex degree. The vertices that represent the 5 km-radius and 10 km-radius networks in the interference graph are likely to have a higher vertex degree than the 1 km-radius networks since these are likely to have a higher average number of neighbours per network than the 1 km-radius networks. Thus, opportunities for spatial re-use of the channels are reduced. Although graph-based channel sharing enables networks that use the same type of RAT to share the same channel, channel sharing options are dependent on the previous allocations. On the other hand, in the hypergraph-based model, as more long range networks join, they are more likely to be assigned the same channel to share than in the graph-based method, because the competing networks are first organised into interference coordination groups before channel assignment. Thus, the hypergraph model performs better than the graph method, owing to efficient modelling of both spatial and spectral coexistence information into the RF environment model that is input for the channel assignment algorithm.

5.6.2 Number of Operational Networks as a Function of Number of Available Channels

This test compares the efficiency of the two models in terms of number of channels required to achieve, on average, 100% operational networks, from 20 simulations. The number of available channels is increased, starting at $K = 4$, while the interference level is held constant by maintaining the same radio ecosystem throughout the experiment.

5.6.2.1 Test Scenario 1

In the first test scenario, there are 50 networks in the ratio 25:15:10 for 1 km-, 5 km-, and 10 km- radius networks, respectively. The number of competing networks is held constant at $N = 50$, while the number of available channels is increased steadily from $K = 4$. The results in Figure 5.22 show that, whereas the graph-based model requires 8 channels to achieve, on average, 100% operational networks, the hypergraph-based model requires only 6 channels.

5.6.2.2 Test Scenario 2

Figure 5.23 shows the results for the second test scenario, where there are 100 networks in the ratio 40:35:25 for 1 km-, 5 km-, and 10 km- radius networks, respectively. The interference level is constant as the number of competing networks is held constant at $N = 100$, but the number of available channels is increased steadily from 4. The results show that while graph-based channel sharing requires 12 channels to achieve, on average, 100% operational networks in all the 20 simulations, the hypergraph-based channel sharing requires only 9 channels.

5.6.2.3 Test Scenario 3

In the third test scenario, there are also 100 networks, but in the ratio 50:50 for 1 km-, and 10 km- radius networks, respectively. The number of competing networks

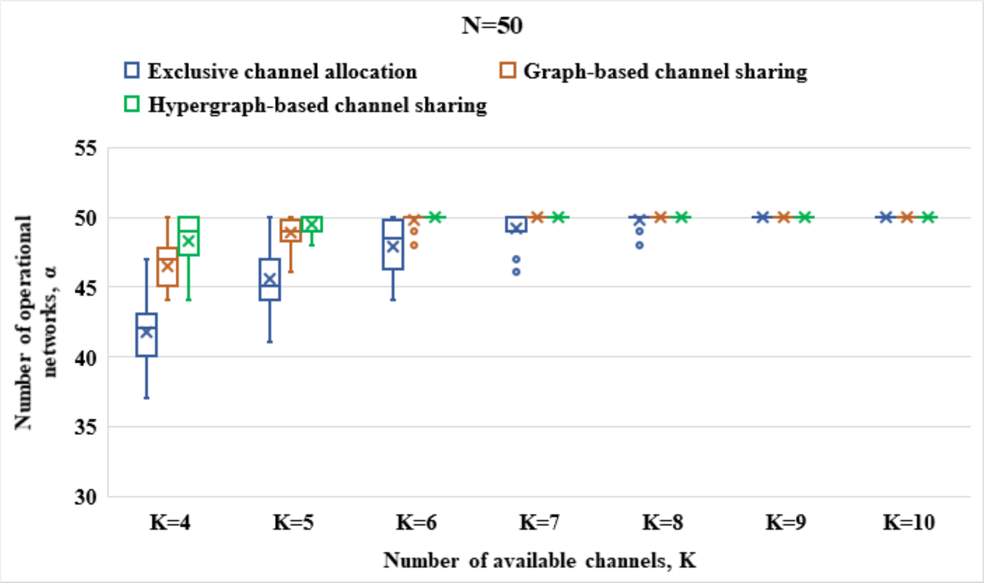


Figure 5.22: Number of operational networks for test scenario 1 when $N = 50$ and $4 \leq K \leq 10$.

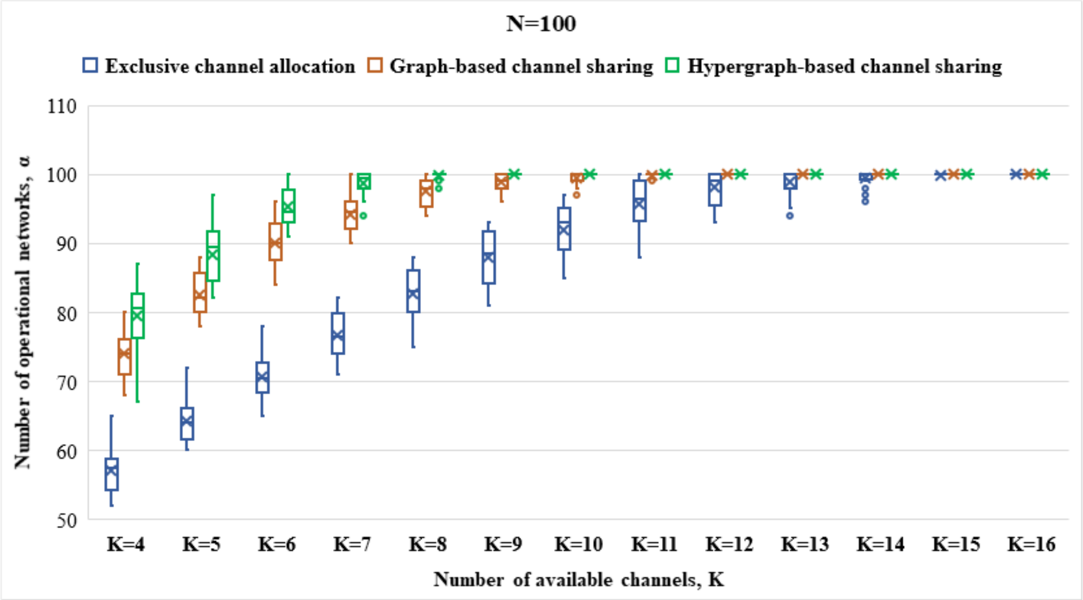


Figure 5.23: Number of operational networks for scenario 2 when $N = 100$ and $4 \leq K \leq 16$.

is held constant at $N = 100$ to keep the interference level constant while the number of available channels is increased steadily from 4. The results are given in Figure 5.24. It can be seen that, whereas the graph-based channel requires 14 channels, the hypergraph-based model still requires only 9 channels.

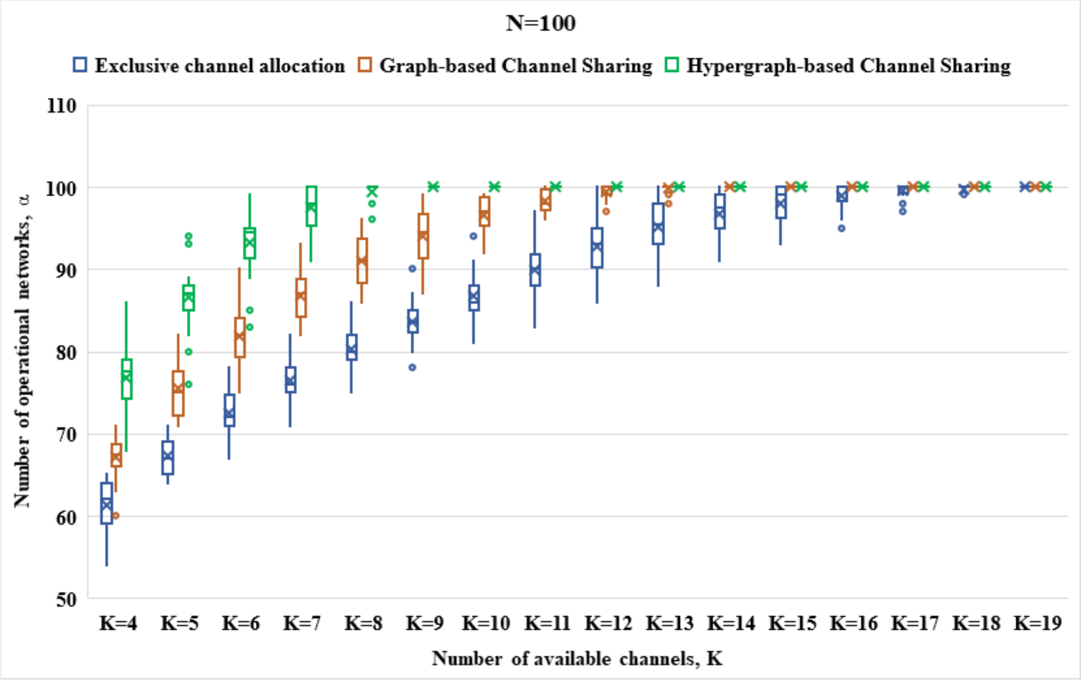


Figure 5.24: Number of operational networks for test scenario 3 when $N = 100$ and $4 \leq K \leq 19$.

5.6.2.4 Interpretation of Results

The results show that to achieve, on average, 100% operational networks, the hypergraph-based channel sharing technique requires up to 5 fewer channels than the graph-based channel sharing technique, representing 36% less spectrum requirement. The results also show that as the interference level increases, the gap between the two models increases. This is because, although both models use the same vertex colouring algorithm, the hypergraph-based modelling enables reduction of the size of the hypergraph to a minor graph which is colourable by fewer colours than the original interference graph that is used in the graph model.

Table 5.4: Summary of results for percentage of operational networks as a function of number of channels.

Number of channels required for 100% operational networks			
Test scenarios	1	2	3
Graph-based channel sharing	8	12	14
Hypergraph-based channel sharing	6	9	9

5.7 Application in Dynamic Spectrum Sharing

Traditional graph modelling is sufficient for exclusive channel allocation, whereas the hypergraph-based model is suitable for channel sharing allocation. Graph chromatic properties can be used for decision making on which model to employ. The chromatic number of a graph $G(V, E)$, denoted by $\chi(G)$, is the least number of distinct colours with which $G(V, E)$ can be properly coloured. For a complete graph, $\chi(G) = \Delta + 1$, where Δ is the maximum vertex degree of graph $G(V, E)$ [85]. This property can be used in determining which algorithm to use for radio resource allocation. The decision tree is illustrated in Figure 5.25. When the interference graph is colourable by the number of available channels, that is when $K \geq \chi(G)$, then exclusive channel allocation will result in 100% operational networks, otherwise hypergraph-based channel sharing is required.

5.8 Chapter Summary

In this chapter, simulation of channel sharing algorithms was performed in order to compare performance of the hypergraph-based and graph-based models. The results show that for the same RF environment, spectral coexistence criteria and number of available channels, the hypergraph-based model achieves, on average, up to 8% more operational networks than the graph-based model. The results also show that, for the same RF environment, the hypergraph model requires up to 36% fewer channels to achieve, on average, 100% operational networks, than the graph model. Thus, the results have demonstrated that the hypergraph-based model is more efficient at modelling

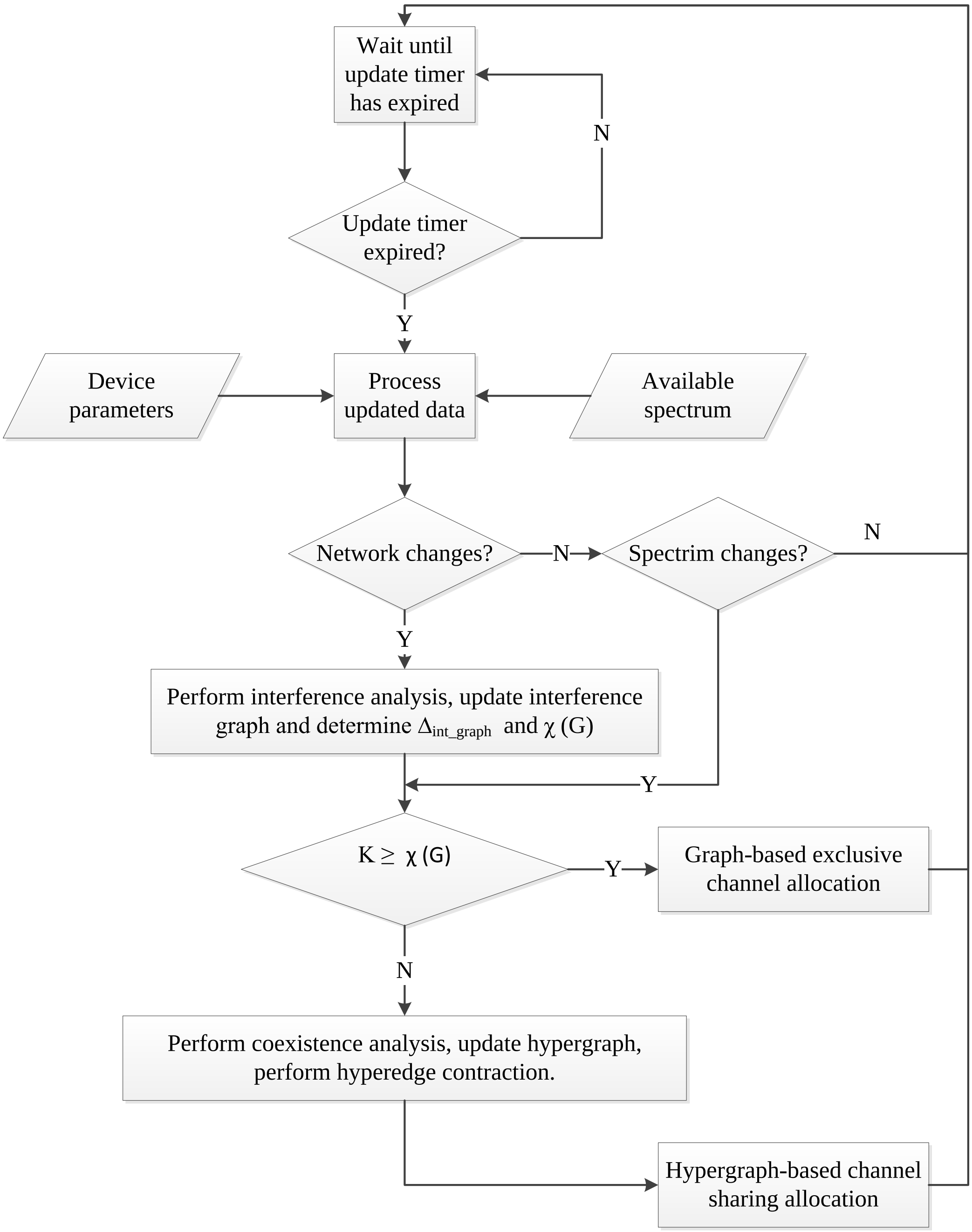


Figure 5.25: Decision flow chart for choice of radio resource allocation model.

the channel sharing problem in terms of spectrum utilisation. This better performance is attributed to the design of the hypergraph-based model which enables more efficient spectrum utilisation than the graph-based model because information about spectral coexistence is represented in the hypergraph before any channel allocation algorithm is applied, unlike in the graph model where spectrum sharing is limited by the outcome of the initial exclusive channel allocation. The next chapter will analyse performance of the hypergraph-based channel sharing algorithm in terms of computational cost.

Chapter 6

Computational Cost Analysis of the Hypergraph Model

6.1 Introduction

The contribution of this chapter is an asymptotic analysis of the computational cost of the algorithm of the hypergraph model that has been developed in this thesis. This is done through estimation of the performance of the algorithm for a given input size, which in the number of networks. Time complexity analysis is used to approximate the rate of growth of the running time of the two algorithms, with respect to the size of the input. The analysis includes a comparison of the computational complexity of the hypergraph-based and graph-based channel sharing algorithms that were simulated in Chapter 5 are compared. The chapter goes further to propose application of hypergraph modelling to realise an efficient bandwidth allocation scheme for spectrum coordination applications. Computational complexity of the proposed hypergraph-based bandwidth allocation scheme is also compared with that of a graph-based method.

6.2 Overview of Time Complexity Analysis

Computational cost of an algorithm refers to the amount of resources required to run it, in terms of time and memory requirements. This chapter analyses the computational cost in terms of running time only. Time complexity is an abstract way to represent the amount of time taken by an algorithm to run, in terms of rate of growth only, as a function of the input size [85]. Time complexity analysis of algorithms is generally carried out for three purposes, and in this thesis it is being done for the first purpose.

1. Deciding which is the most efficient algorithm among two or more algorithms.
2. Estimating algorithm performance for different sizes of inputs especially large values of input size, to determine how far, in terms of input size, the algorithm would remain usable.
3. Understanding the nature of the code with the purpose of examining room for further optimisation.

Input size is defined as the number of items present in the input. Each line of code in an algorithm is referred to as an operation. Basic operations include arithmetic, relational, logical, assignment, and increment/decrement. The running time of the algorithm is estimated in terms of the number of operations executed in the algorithm because the running time of an algorithm for a given size depends on the number of operations executed. To achieve this, time complexity analysis is based on the following critical assumptions for analysing algorithms.

1. Each line of code in an algorithm will take constant time to execute.
2. Algorithm analysis is studied independent of system-related parameters, that is, programming language used to implement the algorithm, compiler, hardware specifications because for the given specification of a system, these parameters as constant.
3. The variable parameter is the input size according to the problem specification, that is, the running time is estimated as a function of the input size.
4. The input size is analysed for a large value of input size because, in real-life applications, the input data size is mostly huge.

Thus, time complexity represents the rate of growth of the algorithm's running time with respect to the inputs taken during the program execution, irrespective of the kind of computer that it runs on, because the number of operations that an algorithm will run is in proportion to the size of its input only.

Time complexity is estimated by counting the number of operations in the best, worst and average-case scenarios. Only the worst-case scenario, which represents the upper bound, will be used in this thesis. The Big O notation is an asymptotic notation which is used to define the time complexity of the worst-case scenario and is expressed as $O(n)$, where O is the growth rate function in the worst-case scenario and n indicates the input size [85]. Examples of common time complexities in algorithms are as follows.

1. **Constant time complexity** $O(1)$ represents an algorithm which performs a constant number of operations regardless of the input size.
2. **Linear time complexity** $O(n)$ represents an algorithm which processes each input in $O(1)$ time.
3. **Quadratic time complexity** $O(n^2)$ represents an algorithm has a rate of growth of running time which is directly proportional to the square of the input size, often as a result of a nested loop.
4. **Cubic time complexity** $O(n^3)$ represents an algorithm which has a rate of growth of running time which is directly proportional to the cube of the input size, often as a result of three loops.

The Big O notation simplifies time complexity analysis by ignoring the operations that do not have much impact on the rate of growth of the algorithm with respect to input size, e.g. instructions that are executed only once are ignored. The difference between multiplicative constants is also ignored, that is, $f(n) = 2n$ and $f(n) = n$ are identical in the Big O analysis. The number of operations inside a loop is an example of a multiplicative constant since, to find the total number of operations in the loop, it is multiplied by the number of times the loop is executed. However, a nested loop can result in a higher-order number of operations which cannot be ignored. For example, when a loop that iterates n times is nested in another loop that iterates n times, the resulting number of operations is n^2, which cannot be ignored. Thus, the steps to perform analysis and comparison of time complexity of algorithms can be summarised as follows.

1. First count the number of critical operation performed by all the algorithms with respect to the input size, n, e.g. $an^2 + bn + c$.
2. Then, ignore the lower-order terms and coefficients and represent the remaining terms in the form of the Big O notation, e.g. $O(n^2)$.
3. Finally, compare the higher-order terms present in the Big O notations of the respective algorithms and decide which algorithm is more efficient than the others.

6.3 Time Complexity Analysis of Coexistence Management

This section analyses the time complexity of the spectrum sharing algorithms that were presented in Chapter 5 in order to compare the computational complexity of the graph-based and hypergraph-based spectrum sharing techniques. The coexistence management function consists of four procedures: interference analysis, spectral coexistence analysis, RF environment modelling and channel allocation. Interference analysis and spectral coexistence analysis procedures will not be considered since they are common to both graph-based and hypergraph-based models. RF environment modelling involves construction of the hypergraph, which makes use of the output from interference and spectral coexistence analysis functions, involves relational, logical, assignment and increment/decrement operations only since all the arithmetic calculations are done in the interference and spectral coexistence analysis functions.

6.3.1 Inputs and Assumptions

The main input that has an impact on the number of operations for both the graph-based and hypergraph-based spectrum sharing algorithms is the number of networks

(N). This is represented by the number of vertices in the interference graph. There are two other parameters that affect the number of operations. In the graph-based model, the number of available channels (K) affects the number of networks that cannot be assigned an exclusive channel by the graph colouring algorithm and need to be considered for spectrum sharing. In the hypergraph-based model, the maximum number of channels that can be allowed to share the same channel, that is the maximum cardinality of the interference coordination subsets (herein denoted by M), has an impact on the number of vertices that can be represented by a single vertex, and hence affects the size of the minor graph that can be realised and the number of vertices that can be coloured by the number of available colours (K). Therefore, in this analysis, the value of K will be varied while the value of M is held constant, and vice versa. To this end, the following assumptions are made about the networks in this analysis:

1. The RF environment is highly congested, such that every network is adjacent to every other network. Thus, each network has $N - 1$ neighbours.
2. The distribution of the heterogeneous radio networks in the RF environment is such that it is possible to form interference coordination subsets of the set maximum cardinality (M).
3. A network can be assigned to only one interference coordination subset at a time.

6.3.2 Time Complexity of Graph-Based Spectrum Sharing Algorithm

Let time complexity for the graph-based spectrum sharing algorithm be denoted by C_G. The pseudocode for graph-based spectrum sharing is presented in Algorithm 3 on page 128. It has two subprograms: exclusive channel allocation using the vertex colouring algorithm and spectrum sharing allocation.

The subprogram for exclusive channel allocation has three loops. The outer loop (line 4) is of size $N-1$. In the worst case, the inner loop (line 6) would execute for all K colours, and at each iteration every element in the neighbour list, that is $N-1$ elements, would be visited to check its colour assignment (line 7). Therefore, the time complexity of this subprogram is: $O(K(N-1)^2)$. Ignoring constants, the time complexity of this subprogram can be approximated to $\approx O(N^2)$.

The spectrum sharing allocation has three loops. The number of operations for the outer loop (line 17) is equal to the number of networks that could not be assigned an operating channel from the list of available channels by the initial exclusive channel allocation. Let N_{NC-G} denote the number of vertices that could not be assigned a colour by the exclusive channel allocation in the graph-based model. Since it is assumed that every network is adjacent to every other network, it means that every vertex has an edge with every other vertex. As such, the number of vertices that can be coloured by the vertex colouring algorithm is equal to the number of available channels, K. Therefore, the number of uncoloured vertices in the graph-based model is given by Equation 6.1.

$$N_{NC-G} = N - K \tag{6.1}$$

In the worst case scenario, the inner loop (line 18) would execute for all K colours and on each iteration, it would visit every element in the neighbour list, that is $N-1$ elements (line 19). The time complexity of the spectrum sharing allocation is therefore approximately $O(K(N-1)(N_{NC-G}))$, which can be simplified to $\approx O(N(N_{NC-G}))$ by ignoring constants.

The total time complexity for the graph-based channel sharing algorithm is given in Equation 6.2.

$$C_G \approx O(N^2 + N(N_{NC-G})) \tag{6.2}$$

6.3.3 Time Complexity of Hypergraph-Based Spectrum Sharing Algorithm

Let time complexity for the hypergraph-based spectrum sharing algorithm be denoted by C_{HG}. According to the hypergraph-based channel sharing pseudocode in Algorithm 6 on page 134, four subprograms are considered: hypergraph construction, hyperedge contraction, colour assignment and checking for possible additional colour assignments.

The hypergraph construction procedure, which is given in Algorithm 4 on page 130, has a nested loop (lines 2 and 8). In the worst case scenario, the outer loop would be of size N because every vertex would be visited and the inner loop would visit $N - 1$ adjacent vertices at every iteration. Thus the time complexity of hypergraph construction is $O(N(N-1))$, which can be simplified to $\approx O(N^2)$.

The hyperedge contraction procedure is given in Algorithm 5 on page 132. The number of operations of the outer loop in line 1 is equal to the number of hyperedges. Since, it is assumed that a network can only belong to one interference coordination set at a time, no hyperedge is adjacent to another hyperedge, that is, the intersection of the hyperedges is an empty set. Since it is also assumed that the distribution of the heterogeneous networks is such that it is possible to form interference coordination subsets of maximum cardinality M, the number of hyperedges is given by N/M. In the inner loop in line 3, $M-1$ vertices of the hyperedge are visited for hyperedge contraction. Thus, the time complexity of hyperedge contraction is $O((N/M) * (M-1))$, which is approximately $O((N/M) * M)$ and can be simplified to $O(N)$.

Since every hyperedge is contracted to a single vertex, the minor graph would have N/M vertices. As such, time complexity of vertex colouring of the minor graph (line 5 of Algorithm 6 on page 134) is $O(((N/M) - 1)^2)$, which can be simplified to $\approx O((N/M)^2)$. The time complexity of the loop in line 6 of Algorithm 6 on page 134 is $O(N)$ since in the worst case scenario, every vertex would be visited when applying the colour map. Thus the total time complexity of the channel assignment subprogram is $\approx O((N/M)^2 + N)$. Ignoring lower order terms, the time complexity of this subprogram can be approximated to $O((N/M)^2)$.

To check for possible additional channel assignments that were masked by hyperedge contraction, the loop in line 9 of Algorithm 6 on page 134 iterates over every node that remains uncoloured. Since it is assumed that every network is adjacent to every other network, it means that every vertex in the minor graph has an edge with every other vertex. As such, the number of vertices that can be coloured by the vertex colouring algorithm is equal to the number of available channels, K. When the colour map is applied to the original hypergraph, the number of coloured nodes is equal to KM. Therefore, the number of uncoloured vertices in the hypergraph-based model is given by Equation 6.3.

$$N_{NC-HG} = N - KM \tag{6.3}$$

Thus, in the worst case scenario, the loop in line 9 would iterate over N_{NC-HG} nodes, whereas the loop in line 10 would iterate over all K colours and on each iteration, it would visit every element in the neighbour list, that is $N-1$ elements, to check for any possible colour assignments that do not violate coexistence constraints. Since K is constant, the time complexity of the spectrum sharing allocation is $O(K(N_{NC-HG})(N-1))$. Ignoring constants, the total time complexity of the additional colour assignment subprogram is therefore $O(N(N_{NC-HG}))$.

The total time complexity for the hypergraph-based channel sharing algorithm is given in Equation 6.4. The Equation is simplified further in Equation 6.5 by ignoring lower order terms.

$$C_{HG} \approx O(N^2 + N + (N/M)^2 + N(N_{NC-HG})) \tag{6.4}$$

$$C_{HG} \approx O(N^2 + (N/M)^2 + N(N_{NC-HG})) \tag{6.5}$$

6.3.4 Comparison of Time Complexity

Equations 6.2 and 6.5 show that the time complexity of both the graph-based and the hypergraph-based spectrum sharing algorithms is quadratic. The time complexity of the two algorithms is therefore generally comparable. The difference in number of operations is dependent on the values of K and M, which have an impact on the number of uncoloured vertices according to Equations 6.1 and 6.3. Therefore, the comparative study investigates how the time complexity of the two algorithm is affected by the values of K and M, as the input size (N), that is the number of networks, is increased. Time complexity data is plotted in the form of a line graph of the number of operations as a function of the number of networks.

6.3.4.1 When $K = 10$

Figure 6.1 shows a plot of the number of operations when $K = 10$, $M = 2$. It can be seen that as the number of networks increases, the time complexity of the two methods is nearly the same up to about $N = 40$. Figure 6.2 is a subplot which zooms into the plot of the number of operations when $N = \{10, 20, 30, 40, 50\}$. When $N = 10$, the number of channels is sufficient for each network to be assigned an exclusive channel. As such, the graph-based method is slightly more efficient than the hypergraph-based model since it's not necessary to group the networks into interference coordination groups for spectrum sharing. When $N = 20$, K is no longer sufficient, and the hypergraph-based method exhibits slightly better computation efficiency up to $N = 30$. The time complexity of the two methods becomes the same at $N = 40$.

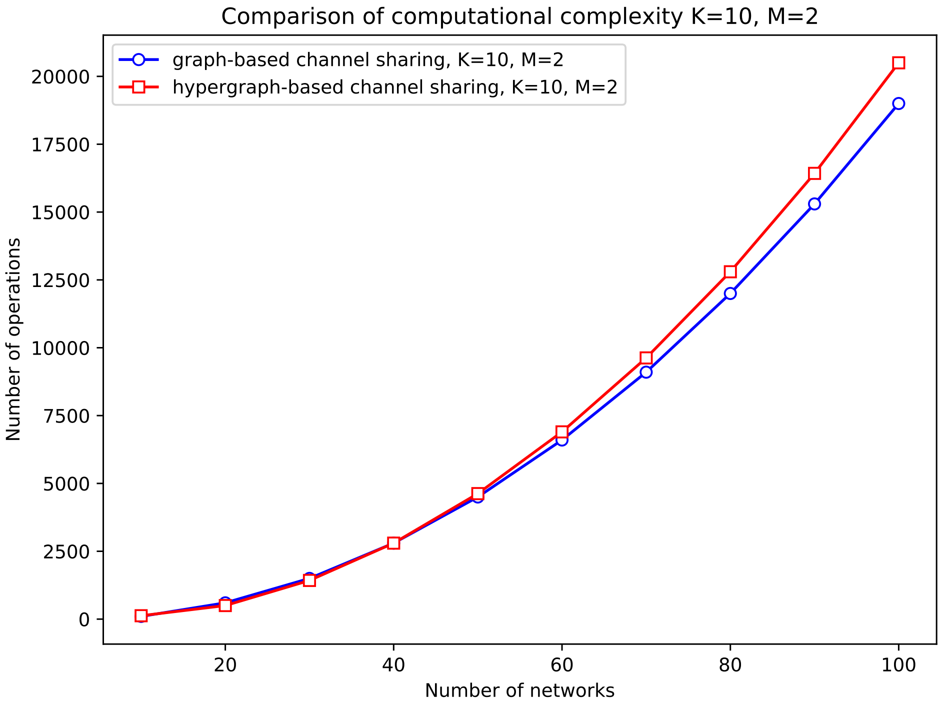


Figure 6.1: Time complexity when $K = 10$ and $M = 2$.

For $N > 40$, the time complexity of the hypergraph-based method becomes greater

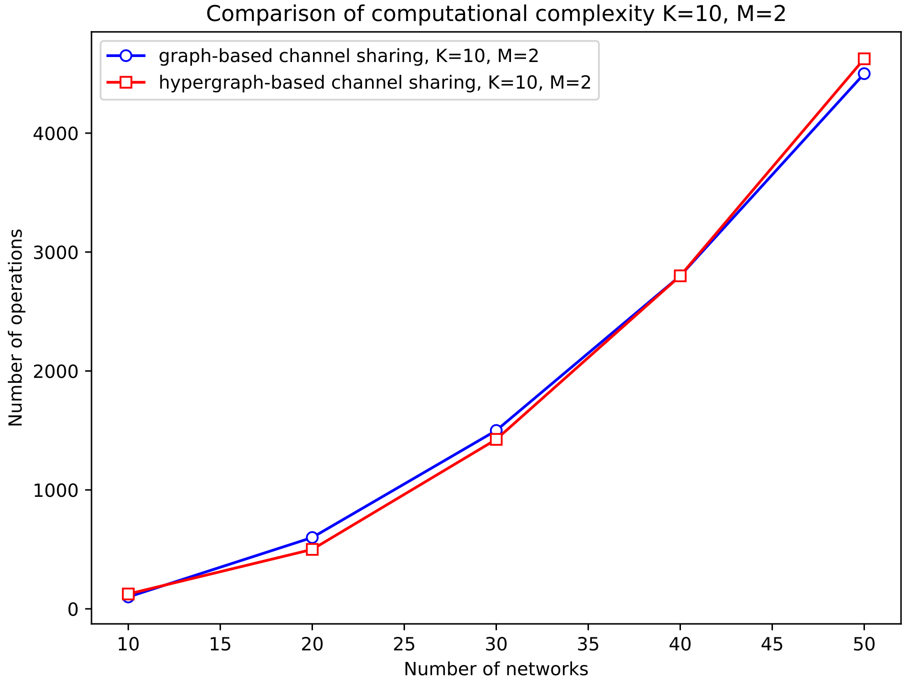


Figure 6.2: Time complexity when $0 \leq N \leq 50$, $K = 10$ and $M = 2$.

than that of the graph-based method, up to 1,500 more operations at $N = 100$. This is because the size of the interference coordination sets ($M = 2$) is not big enough to result in improved computational complexity. Figure 6.3 shows the plot of the time complexity when M is increased to 4, which results in hypergraph-based method exhibiting lower time complexity than the graph-based method for $0 < N \leq 100$. At $N = 100$, the hypergraph method requires 2,375 fewer operations than the graph method.

6.3.4.2 When $K = 20$

Figure 6.4 shows a plot of the number of operations when $K = 20$, $M = 2$. It can be seen that as the number of networks increases, the time complexity of the two methods is nearly the same. Figure 6.5 is a subplot which zooms into the plot of the number of operations when $N = \{10, 20, 30, 40, 50\}$. When $10 \leq N \leq 20$, the graph-based method is more efficient since the number of available channels is sufficient for exclusive channel allocation. When $N = 30$, K is no longer sufficient, and the hypergraph-based method exhibits slightly better computation efficiency, up to 400 less operations at

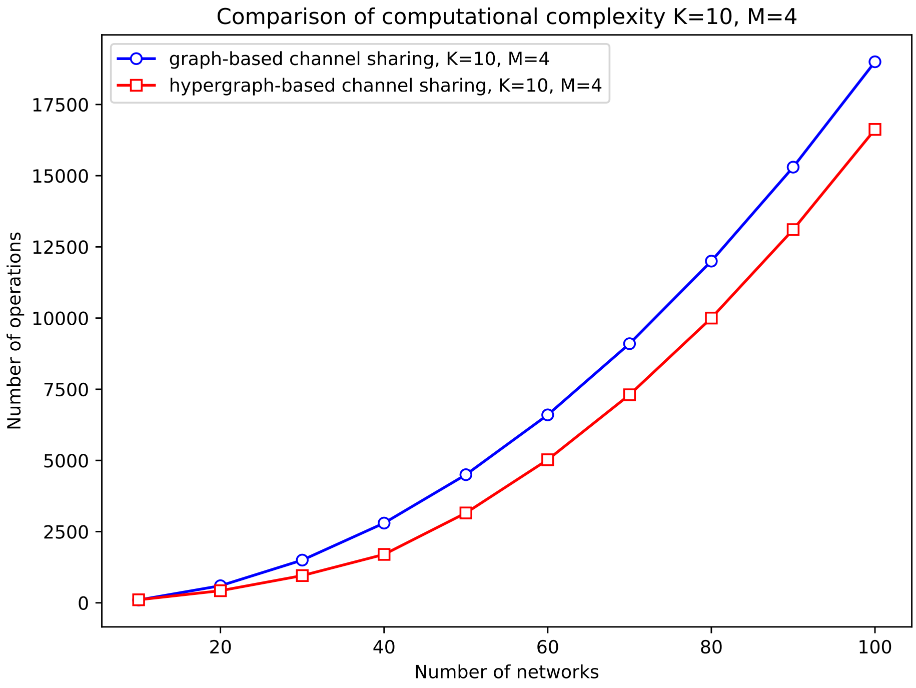


Figure 6.3: Time complexity when $K = 10$ and $M = 4$.

$N = 40$. The difference in time complexity between the two methods narrows down and their number of operations becomes the same at $N = 80$. For $N > 80$, the time complexity of the hypergraph-based method becomes greater than that of the graph-based method by up to 500 more operations at $N = 100$. This is because the size of the interference coordination sets $(M = 2)$ is not sufficient to result in improved computational complexity.

In Figure 6.6, M is increased to 4, which results in hypergraph-based method exhibiting lower time complexity than the graph-based method for $0 < N \leq 100$. Thus, at $N = 100$, the hypergraph-based method requires 5,375 fewer operations than the graph-based model.

6.3.4.3 When $N > 100$

The growth rate of quadratic-time algorithms in response to increasing number of inputs allows the algorithms to remain usable up to about $n = 10{,}000$ [85]. Table 6.1 presents a comparison of the number of operations between the graph-based and hypergraph-based

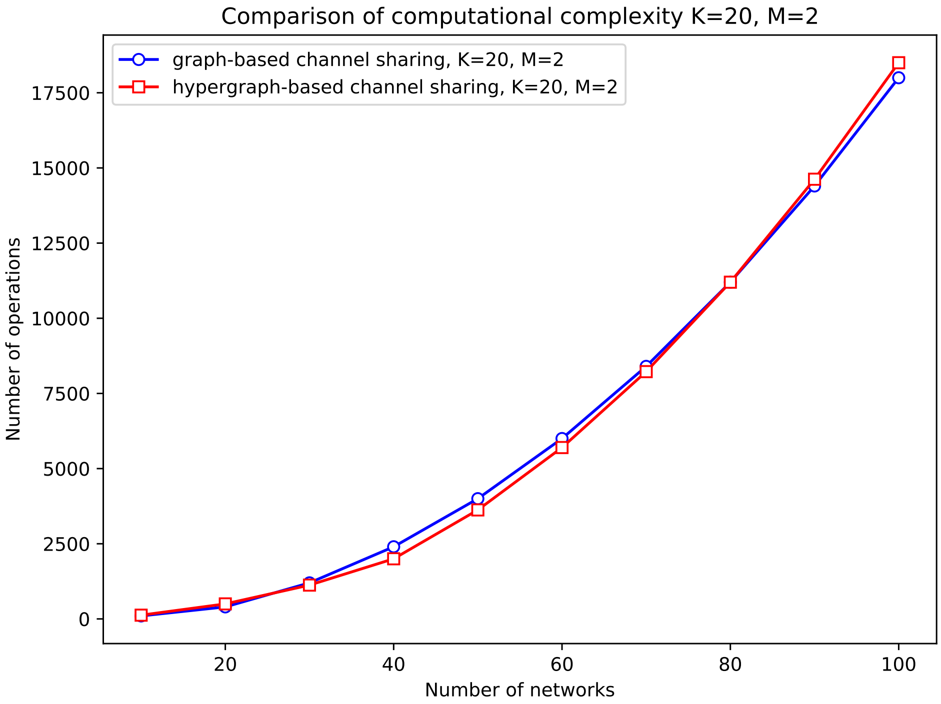


Figure 6.4: Time complexity when $K = 20$ and $M = 2$.

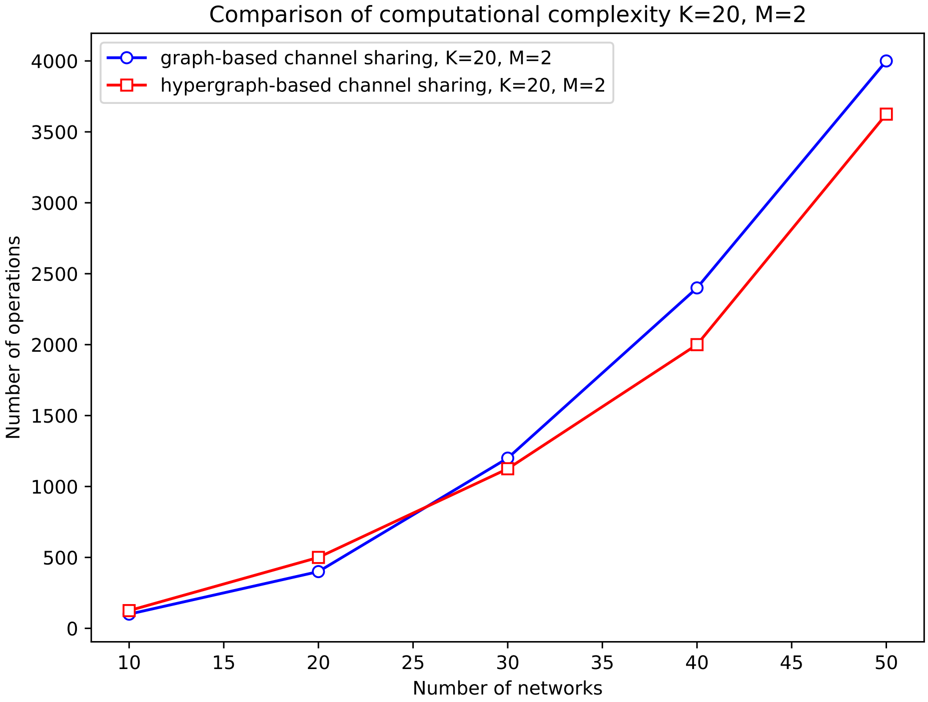


Figure 6.5: Time complexity when $0 \leq N \leq 50$, $K = 20$ and $M = 2$.

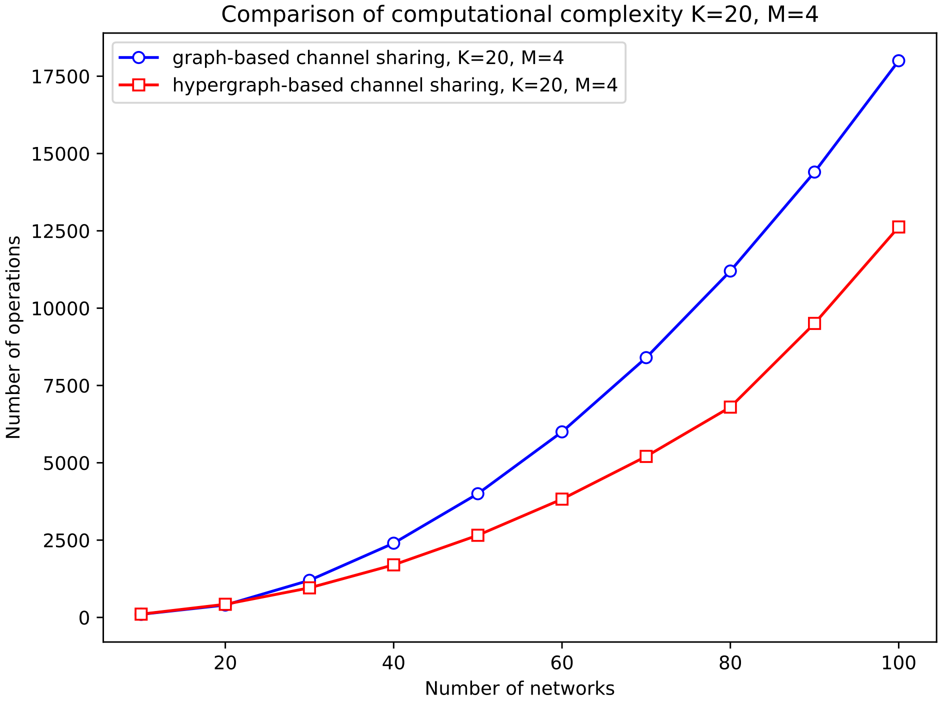


Figure 6.6: Time complexity when $K = 20$ and $M = 4$.

spectrum sharing algorithms when $K = 20$, $M = 8$ and $N = \{10, 100, 1000, 10000\}$. As expected, the results show that the performance of the hypergraph-based method is better than that of the graph-based method when the number of available channels (K) is less than the number of competing networks (N). At $N = 100$, the number of operations of the hypergraph-based method is about 56% of the number of operations of the graph-based method. At $N = 1,000$ the hypergraph-based method requires up to 94% of the number of operations required by the graph-based method. The performance of the two models equalises at $N = 10,000$; this is because, the number of networks N is too great and the number of networks that can share the same channel ($M = 8$) is too small to make a difference for the hypergraph model.

Table 6.1: Time complexity of graph-based and hypergraph-based spectrum sharing algorithms.

Input size	Number of operations when $K = 20$ and $M = 8$	
N	Graph-based spectrum sharing algorithm	Hypergraph-based spectrum sharing algorithm
10	100	101.56
100	18,000	10,156.25
1,000	1,980,000	1,855,625.00
10,000	199,800,000	199,962,500.00

6.3.4.4 Verification of Time Complexity Using Actual Run Time of Algorithms

The actual run time of the algorithms that were implemented in Chapter 5 was analysed to verify the results of the time complexity analysis. The simulation used the test scenario which consists of 100 networks in the ratio 50:50 for 1 km-radius and 10 km-radius networks, respectively, as described in Section 5.6.2.2. Execution time of the algorithms was recorded for an input size of {10, 20, 30, 40, 50, 60, 70, 80, 90, 100} networks (N). A total of 20 simulations were carried out for each of these input sizes. The simulations were conducted for three different values of the number of available channels (K). $K = 3$ represents a scenario when the number of available channels is insufficient for the number of networks that are competing for these channels. The values of $K = 9$ and $K = 14$ were chosen for the simulation because, according to the simulation results in Section 5.6.2.2, the hypergraph-based and graph-based models require 9 and 14 channels, respectively, to accommodate 100% of the competing networks.

The results are presented in Figures 6.7, 6.8, and 6.9. The results show that the rate of growth of the run time of both algorithms is quadratic in nature as per the time complexity analysis. The results also show that the hypergraph-based model exhibited a slightly higher execution time than the graph-based model.

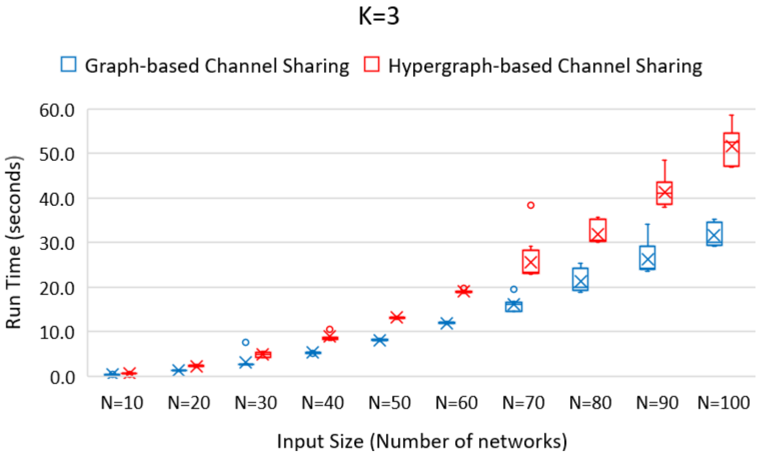


Figure 6.7: Algorithm run time when $K = 3$.

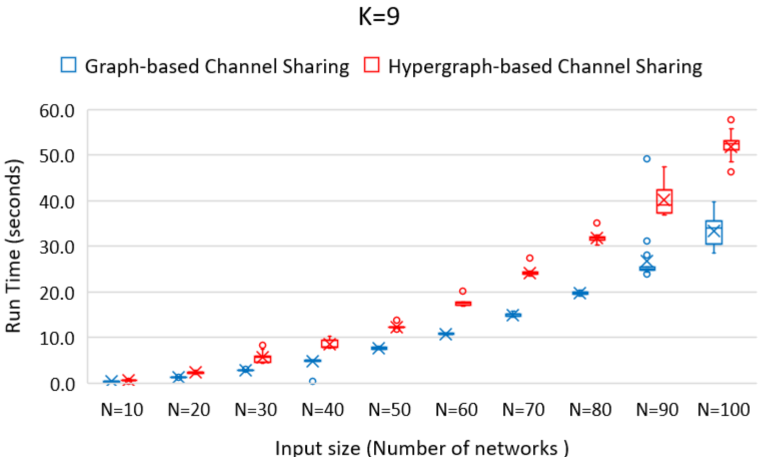


Figure 6.8: Algorithm run time when $K = 9$.

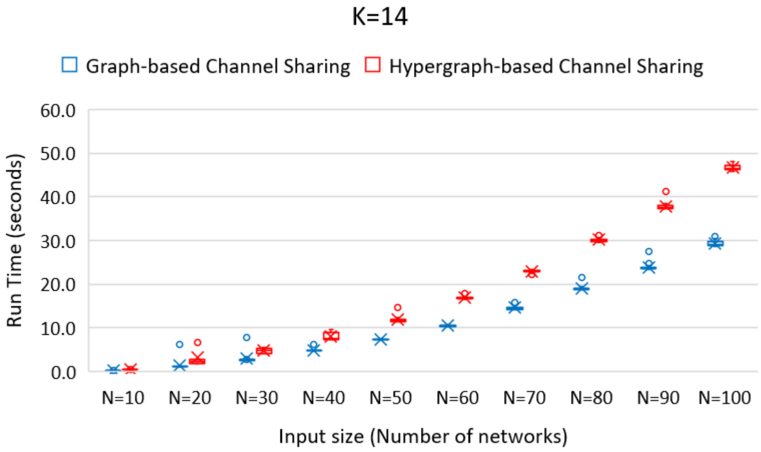


Figure 6.9: Algorithm run time when $K = 14$.

6.3.4.5 Interpretation of Results

As expected, the results show that the time complexity of the hypergraph model is comparable to that of the graph model since the rate of growth of the run time of both algorithms is quadratic. The results of the actual execution time of the algorithms confirm that that the rate of growth of the execution time of the algorithms follows the same shape of curve as the input size is increased. The results of the asymptotic analysis further show that the hypergraph model could enable reduced number of operations. The extent to which the number of operations is reduced increases as the number of coexisting networks that share the same channel is increased and as the number of available channels is increased. When the number of coexisting networks that can be allocated the same channel is increased, it means that an increased number of networks are represented by a single vertex in the minor graph, thus reducing the size of the input that the graph colouring algorithm has to handle. When the number of available channels is increased, an increased number of networks are assigned a channel through colouring of the minor graph, such that the algorithm has to visit a reduced number of uncoloured vertices when checking for additional colour assignments that were masked by hyperedge contraction. However, in the results of the actual execution time, the hypergraph-based model had a higher run time than the graph-based model for all values of the input size. This could be so because the number of coexisting networks was not enough to result in a significant reduction of the number of operations.

6.4 Application of Hypergraph Model to Spectrum Coordination

The WInnForum has published three approaches to GAA spectrum coordination. This chapter is focused on Approach 1 [36]. Two types of spectrum coordination are specified in [37]: (a) inter-CxG coordination, which makes decisions about coordination of spectrum use among CxGs, (b) intra-CxG coordination which manages spectrum use within a specific CxG. This chapter is focused on inter-CxG coordination. The SAS implements inter-CxG spectrum coordination. A CBSD network operator can establish its own CxG and implement a coexistence manager according to its own interference management policy.

The technical specifications specify the use of graph colouring to model bandwidth allocation to CxGs following the creation of an interference graph and identification of connected components in the interference graph which represent networks that require frequency coordination. Allocation of bandwidth to a CxG involves computing its chromatic number (χ). Let BW denote the total bandwidth available for the GAA users. Let χ_i be the chromatic number of CxG_i. If there are P number of CxGs in the connected set, then the total chromatic number of the connected set is given by Equation 6.6.

$$\chi = \sum_{i=1}^{P} \chi_i \tag{6.6}$$

Bandwidth allocated to CxG_i is calculated by Equation 6.7.

$$BW_i = \frac{\chi_i}{\chi}.BW \tag{6.7}$$

First, the graph-based model that is specified in the WInnForum scheme is presented. Then, a modified scheme that is based on a hypergraph-based model is proposed. Finally, computational complexity of the two models is analysed.

6.4.1 Graph-Based Spectrum Coordination Process

Consider a CBRS GAA ecosystem consisting of CBSDs that are registered with the SAS. It is envisioned that operators would create CxGs to facilitate coexistence within the groups. The procedure for inter-CxG coordination is summarised and illustrated as follows:

1. A CBSD interference graph is created for all registered CBSDs. An edge between a pair of CBSDs represents one-way or mutual interference between the CBSDs and their end user devices. Edges are assigned weights that represent the level of interference and an edge weight threshold is set such that an edge is established

between a pair of CBSDs only when the edge weight is greater than the threshold. An example CBSD interference graph is illustrated in Figure 6.10.

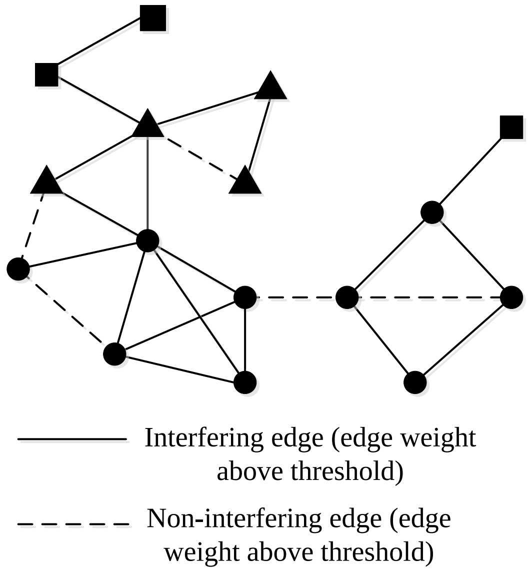


Figure 6.10: An example of a CBSD interference graph.

2. Connected set(s) are then generated from the CBSD interference graph. Any pair of CBSDs in a connected set are connected directly through an edge or indirectly through other CBSDs in the interference graph. An example of an interference graph consisting of two connected sets is illustrated in Figure 6.11.

3. Based on CBSD grouping information, the interference graph for each connected set is modified as follows: (i) no edge is created among any pairs of CBSDs that belong to the same No Edge Group (NEG) since these can share the same channel, (ii) if CBSDs in a Common Node Group (CNG) are in multiple connected sets, all vertices in the CNG are contracted to one vertex, since CBSDs in a CNG require to be assigned at least one common channel. Figure 6.12 shows 4 CBSDs that belong to the same NEG, and therefore no edge is created between the CBSDs.

4. Graph colouring is applied to each connected set in order to determine the chromatic number (χ) of each CxG in the connected set. In Figure 6.13, there are

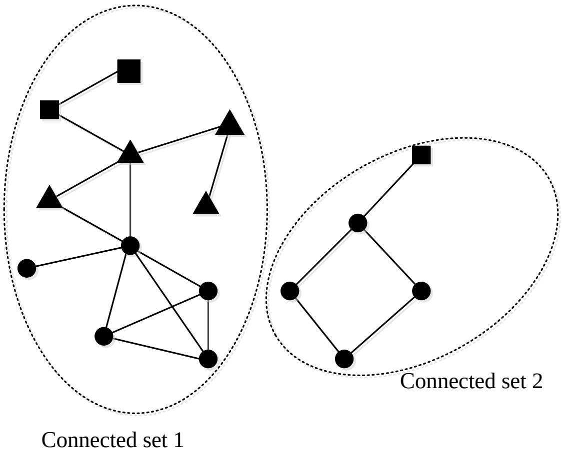


Figure 6.11: An example of connected sets.

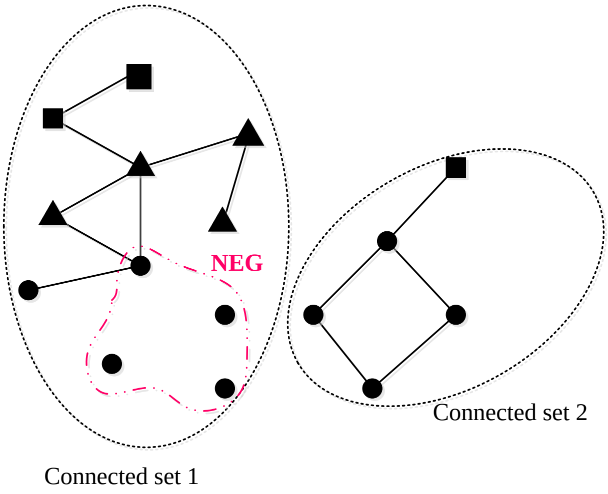


Figure 6.12: An example of a NEG in a connected set.

3 CxGs, and vertices that belong to the same CxG are represented by the same symbol: square, or triangle, or circle. In connected set 1, all three CxGs have a chromatic number of 2. In connected set 2, the CxG that is represented by square vertices has a chromatic number of 1 and the the CxG that is represented by circular vertices has a chromatic number of 2. Bandwidth is then allocated to each CxG in each connected set using Equation 6.7. For instance, assuming 60 MHz of available spectrum, for the CxG that is represented by circular vertices, its CBSDs that are in connected set 1 will be allocated 20 MHz, whereas the CBSDs that are in connected set 2 will be allocated 40 MHz.

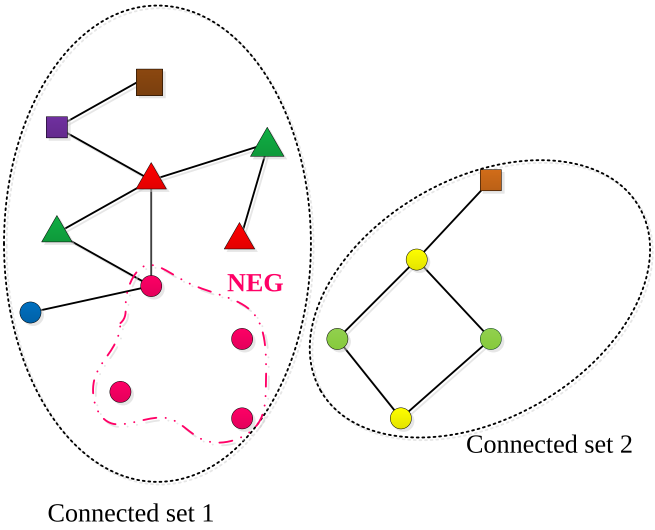


Figure 6.13: An example of graph colouring for bandwidth allocation.

6.4.2 Proposed Hypergraph-Based Spectrum Coordination

A hypergraph could be employed to model interference relationships and spectral co-existence relationships in the same model using edges and hyperedges, respectively. CBSD groups, that is NEGs and CNGs, can best be represented by hyperedges since these groups can comprise more than two CBSDs. Figure 6.14 is an illustration of a hypergraph model in which a NEG is represented by a hyperedge.

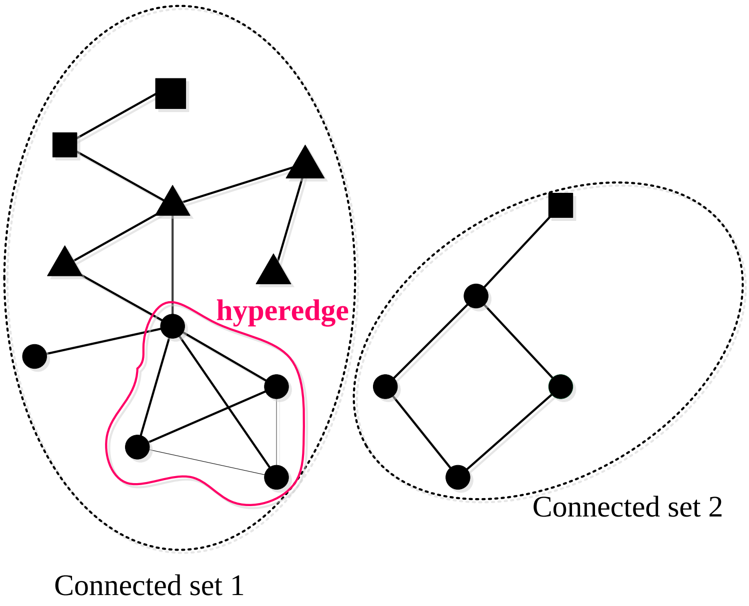


Figure 6.14: An example of a hypergraph model in which a NEG is represented by a hyperedge.

Hypergraph size reduction is a common approach for reducing computational complexity of algorithms [89]. Figure 6.15 illustrates how hyperedge contraction could be used to collapse all CBSDs within an NEG into one vertex, without affecting the interference constraints for computing the chromatic number of the connected set in the interference graph. Representing an NEG by a single vertex has no implication on the outcome of the graph colouring algorithm in inter-CxG spectrum coordination since, unlike in intra-CxG spectrum coordination, interference relationships among networks in the same NEG are not considered. Thus, hypergraph-based modelling has the potential to reduce the time complexity of the process of bandwidth allocation by reducing the size of the input graph.

6.4.3 Time Complexity Analysis

In both the graph-based and the proposed hypergraph-based bandwidth allocation schemes, there are three common procedures: creation of interference graph, finding connected sets in the interference graph and graph colouring of the connected sets.

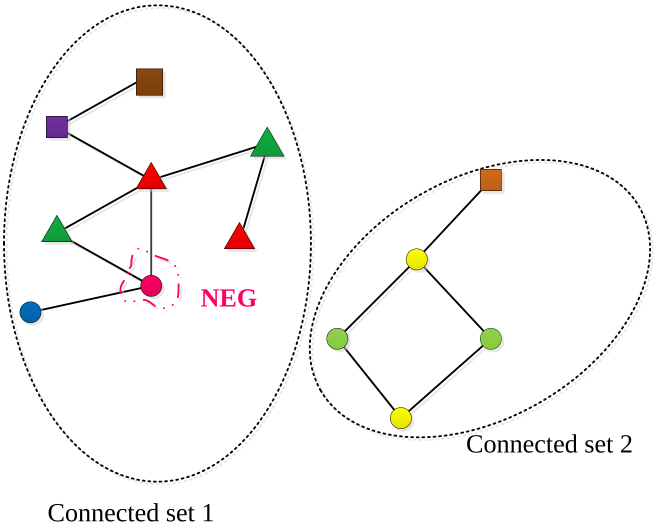


Figure 6.15: An example of vertex colouring of a minor graph after hyperegde contraction.

Construction of interference graph will not be considered in the time-complexity analysis since the algorithm and input size are the same for both models. The key algorithms for bandwidth allocation are: (i) graph traversal algorithm for finding the connected sets within an interference graph, (ii) graph colouring algorithm to find the chromatic numbers of the CxGs in the connected sets.

Graph traversal algorithms, such as depth-first search (DFS) or breadth-first search (BFS) can be used. Both methods start by initializing the connected-component-number field for each vertex to 0, and start the search for connected component number 1 from vertex v_1. As each vertex is visited, this field is set to the count of the current connected component number. When the initial search ends, the connected component number count is incremented and the traversal starts again from the first vertex whose connected-component-number-field is still 0. The BFS graph traversal algorithm visits all the vertices once and each edge twice in the case of an undirected graph $G(V, E)$ that is represented by adjacency lists. Thus, the algorithm runs in $O(V + E)$ time [85]. Time-complexity of a greedy graph colouring algorithm is $O(V^2 + E)$ in the worst case. Thus the total time complexity of graph traversal and graph colouring is

$O(V^2 + V + 2E)$. Ignoring the lower order terms, and since the number of vertices V is equal to the number of input networks N, the time complexity of graph traversal and colouring, denoted by C_{GTC}, is given in Equation 6.8.

$$C_{GTC} \approx O(N^2) \tag{6.8}$$

As described in Section 6.4, the hypergaph-based and graph-based models vary in this way. The hypergraph-based model includes additional procedures for construction of the hyperedges, representing NEGs and contraction of the hyperedges, which results in a minor graph with fewer vertices than the original interference graph. Thus, the input size for the graph traversal and graph colouring algorithms is different for the two models.

6.4.3.1 Graph-Based Bandwidth Allocation

Let C_{GBW} denote the time complexity of the graph-based bandwidth allocation. C_{GBW} is equal to the time complexity of the graph traversal and colouring which is given in Equation 6.8.

$$C_{GBW} \approx O(N^2) \tag{6.9}$$

6.4.3.2 Hypergraph-Based Bandwidth Allocation

In the WInnForum specification, a network provides the SAS with information about the NEG that it belongs to, if any. Thus, construction of the hyperedges would involve visiting every vertex, checking if it belongs to any NEG and adding the vertex to the hyperedge that represents its NEG. Thus, every vertex would be visited once and the time complexity is therefore $O(N)$.

Similarly, in the hyperedge contraction procedure that is presented in Algorithm 5 in Chapter 5, every hyperedge is visited once when the loop in line 1 executes and all vertices, except one, that are incident on the hyperedge are visited once when the loop in line 3 executes. In the worst case scenario, every vertex would belong to a NEG.

Assuming that the number of networks in a NEG is uniform, let M denote the number of nodes in a NEG. Thus, the number of hyperedges would be N/M. Hence, the loop in line 1 will execute N/M times and the inner loop in line 3 would execute $M - 1$ times. The time complexity of hyperedge contraction reduces to approximately $O(N)$.

Hyperedge contraction reduces the number of nodes in the interference graph from N to N/M, thus reducing the size of the input of the graph traversal and colouring algorithms. Thus the time complexity of graph traversal and colouring, which is given in Equation 6.8, can be modified to $\approx O((N/M)^2)$. Let C_{HGBW} denote the time complexity of the hypergraph-based bandwidth allocation. The total time complexity for hypergraph construction, hyperedge contraction, graph traversal and colouring is $O(N + N + (N/M)^2)$. Ignoring the lower order terms, the expression for C_{HGBW} is given in Equation 6.10.

$$C_{HGBW} \approx (N/M)^2 \tag{6.10}$$

6.4.4 Comparison of Time Complexity

The time complexity of the hypergraph-based bandwidth allocation model is comparable to that of the graph-based model because both models have quadratic time complexity. However, it can be seen from Equations 6.9 and 6.10 that the hypergraph-based model has the potential to significantly reduce the number of operations depending on the number of NEGs and the number of networks in each NEG. Table 6.2 illustrates the extent to which hypergraph-based modelling could reduce the number of operations required. Assuming that the number of networks in a NEG (M) is 2, the number of operations is reduced by a factor of 4. When M is doubled to 4, the number of operations is reduced by a factor of 16.

6.5 Chapter Summary

In this chapter, the computational cost of the hypergraph based spectrum sharing model that was developed in Chapter 5 has been analysed using the Big O notation for

Table 6.2: Time complexity of graph-based and hypergraph-based bandwidth allocation.

Input size	Number of operations		
N	Graph-based bandwidth allocation	Hypergraph-based bandwidth allocation	
		$M = 2$	$M = 4$
10	100	25	6.25
100	10,000	2,500	625
1,000	1,000,000	250,000	65,500
10,000	100,000,000	25,000,000.00	6,250,000

the worst-case scenario. Results show that, despite the additional procedures for hypergraph construction and hyperedge contraction, the time complexity of the hypergraph-based method is generally comparable to that of the graph-based method because the rate of growth of the running time of both algorithms is quadratic. The results show that the hypergraph-based spectrum sharing algorithm could be more efficient than the graph-based algorithm when the number of available channels is not sufficient for each network to be assigned an exclusive channel using the vertex colouring algorithm. Analytical results show that, for the same input size, the hypergraph-based algorithm requires fewer operations than the graph-based algorithm as the maximum number of networks that can share the same channel is increased and as the number of available channels is increased because this results in reduced size of the input to the algorithm.

Furthermore, a hypergraph-based model for bandwidth allocation in a CBRS GAA spectrum coordinator has been proposed. Time complexity of the hypergraph-based bandwidth allocation scheme is also quadratic, as is the the graph-based method that is proposed in the WInnForum technical specification for GAA spectrum coordination. Analytical results show that the hypergraph-based method has the potential to result in reduced time-complexity through hyperedge contraction that reduces the size of the input graph for the graph colouring algorithm, depending on the number of groups of networks that can coordinate interference among themselves and the number of networks in each of these groups.

Chapter 7

Conclusion

7.1 Summary

This thesis has presented the work that was carried out to investigate the suitability of hypergraph theory in modelling of the RF environment for coexistence management and spectrum allocation. Hypergraph theory was chosen because it allows representation of relationships that involve any number of elements, rather just two elements as is the case with traditional graphs. A hypergraph-based model for co-channel sharing that ensures coexistence of heterogeneous wireless networks in licence-exempt TVWS spectrum has been designed, implemented and simulated. The results show that the hypergraph-based method outperforms the graph-based method in terms of spectrum utilisation and computational complexity. A hypergraph-based model for bandwidth allocation in spectrum coordination schemes has also been proposed. Time complexity analysis results show that the hypergraph-based method has the potential to result in lower time complexity than the graph-based method.

Chapter 2 provided background to the research problem and to the hypergraph modelling technique being investigated as a mathematical tool for solving the research problem. DSA is regarded as a solution for maximising spectrum utilisation by allowing secondary users' networks to access vacant licensed spectrum, called white space, on a non-interference basis. DSA was first approved in the vacant spectrum of the TV band, which is called TVWS, around 2008. US and UK regulators have approved licence-exempt access to TVWS to stimulate growth of broadband services, and access is managed by a Geo-location Spectrum Database (GLSD). However, the GLSD does not coordinate allocation of TVWS spectrum to secondary user networks. In 2017, the FCC also approved DSA in the 3.5 GHz band, which is called CBRS. GAA has been designated for the lowest-tier access to CBRS spectrum. GAA users are required to coordinate interference management among themselves.

Heterogeneous RAT standards are targeted for TVWS and CBRS. While cognitive radios are capable of spectrum mobility and transmission power control to mitigate the impact of interference, there is a challenge regarding switching from one channel to another without disruption of services when the available TVWS is not sufficient for each network to operate exclusively in its own channel, and in the absence of a spectrum coordination entity. Thus, the research problem for the thesis was established as coexistence among heterogeneous wireless networks operating in licence-exempt DSA systems.

A literature review of the use of hypergraph theory in modelling coexistence management was presented to compare the work in this thesis with related works. Hypergraph theory has found application in modelling of cumulative interference and network dependency. The novelty in this thesis is that hyergraph theory is used to model spectral coexistence. To reduce computational complexity, a hypergraph procedure called hyperedge contraction is used to decompose the hypergraph to make it amenable for graph colouring, which is less complex computationally than hypergraph colouring.

A survey of state-of-the-art heterogeneous coexistence mechanisms for TVWS and CBRS radio systems was presented in Chapter 3. The survey included a taxonomy of the mechanisms and an analysis of the capabilities and limitations of the mechanisms. The main purpose of the survey was to establish how hypergraph modelling could be applied in PHY/MAC-based coexistence mechanisms. It is envisioned that coexistence information could involve complex data and multiple relationships that could be represented sufficiently by a hypergraph data model. It was concluded that the hypergraph data model could be used in modelling coexistence information databases that are used for information exchange between radio systems that cannot communicate directly due to incompatible wireless protocols. Hypergraph data models could also be used in modelling learning databases that are used in machine learning applications for dynamic adjustment of parameters of coexistence mechanisms.

Chapter 4 was a survey of state-of-the-art models for coexistence management and spectrum coordination of heterogeneous wireless networks operating in DSA systems under licence-exemption or GAA policy. The main drawback of this approach is the need for a centralised database architecture for coexistence data storage and decision making. However, both TVWS and CBRS frameworks are based on database architectures such that spectrum coordination and coexistence management could be offered as a value-added service by spectrum database operators. The IEEE 802.19.1 standard for wireless network coexistence methods and the Wireless Innovation Forum (WInnForum) GAA Spectrum Coordination specification are based on this database approach. Algorithmic implementation of the standardised mechanisms is left to the industry.

The survey therefore focused on analysis of techniques for modelling the RF environment and spectrum assignment. The solutions in the literature were classified into three: graph-based, hypergraph-based and ecology-based models. It was argued that the concept of an edge in a graph, which is a two-element subset, is not sufficient to model multiple relationships. On the other hand, hypergraph theory is suitable for modelling multiple relationships. In the surveyed papers, hypergraph theory is used to model network dependency and cumulative interference. Alternatively, this thesis investigates use of hypergraph theory to model spectral coexistence in order to solve the problem of spectrum allocation on a co-sharing basis in the time domain. At this point, the first specific objective of the thesis, as described in Section 1.2 of Chapter 1, was met.

In Chapter 5, an application for coexistence management was implemented using the Python programming language. The coexistence decision method that was implemented in the application is based on the method called “co-sharing based on network geometry classification”, which is specified in the IEEE 802.19.1 standard. Channels were allocated either on a non-interfering basis or on a coordinated sharing basis. The application was implemented using a graph-based model and a hypergraph-based model, in order to compare the performance of the two models in terms of efficiency of spectrum utilisation.

In Chapter 6, the time complexity of the hypergraph-based model that was developed in Chapter 5 was analysed and compared with that of the graph-based model. Furthermore, a hypergraph-based model for bandwidth allocation in spectrum coordination applications was proposed. The model is based on the WInnForum GAA Spectrum Coordination specification. The time complexity of the proposed hypergraph-based bandwidth allocation scheme was compared with that of a graph-based method.

7.2 Key Results

In Chapter 4 a high-level framework for radio resource management was proposed. The distinctive feature of the framework is that, apart from interference relationships, spectral coexistence relationships are also included in the RF environment model, and hence in the data structure that is input to the radio resource allocation algorithm. This representation is only possible with the hypergraph data model which allows modelling of relationships involving any number of elements and the relationships can be multifaceted, which allows modelling of various features at the same time. This output meets the second specific objective of the thesis, as described in Section 1.2 of Chapter 1.

In Chapter 5 it was demonstrated that hypergraph-based modelling enables more efficient spectrum sharing than graph-based modelling. The chapter exhaustively meets specific objectives 3-5, as described in Section 1.2 of Chapter 1. The performance metric that was used to compare performance of hypergraph-based and graph-based spectrum sharing is spectrum utilisation which is measured by the percentage of the competing networks that are operational, having been assigned an operating channel from the available channels or by the number of channels required to achieve a given percentage of operational networks. The simulation involved varying two factors that have an impact on the output of the channel allocation algorithm: interference level, and the number of available channels. The results showed that the hypergraph-based model achieves, on average, up to 8% more operational networks than the graph-based model. This is because, unlike in the graph model where current spectrum sharing options are limited by the outcome of the previous channel allocations, in the hypergraph-based model, spectral analysis is done when there are changes in the radio ecosystem, and information about spectral coexistence is represented in the hypergraph model before any channel allocation algorithm is applied, in order to accommodate more networks.

The results also show that the hypergraph model requires fewer channels, up to 36% fewer channels, to achieve, on average, 100% operational networks for the same RF environment. These results are attributed to the fact that, although both models use the same vertex colouring algorithm, the hypergraph model involves reduction of the hypergraph into a minor graph by representing groups of coexistent networks by a single vertex. The minor graph is colourable by fewer colours than the original interference graph that is used in the graph model.

In Chapter 6, computational complexity of the hypergraph-based spectrum sharing model, which was developed in Chapter 5, was analysed and compared with that of the graph-based model. This analysis exhaustively meets specific objective numbers 3 to 5, as described in Section 1.2 of Chapter 1. Big O notation was used to compute the number of operations for a given input size, in the worst case scenario. The analytical results show that the time complexity of the hypergraph-based model is comparable to that of the graph-based model since both models have quadratic run time. This is because, the algorithm employs the hypergraph procedure called hyperedge contraction, which is used to decompose the hypergraph into the form of a normal graph for graph colouring, which is less complex computationally than hypergraph colouring. The results further show that the hypergraph-based model has potential to result in lower time complexity than the graph-based method as the number of networks that can share the same channels is increased and as the number of available channels is increased, because this results in a reduced input size in the hypergraph-based model.

Furthermore, a hypergraph-based model for bandwidth allocation in spectrum coordination applications was proposed. The time complexity of the hypergraph-based model was analysed and compared with that of the graph-based model. The model is designed for inter-coexistence group bandwidth allocation. Hyperedge contraction is used to collapse vertices that represent a group of networks that can coordinate interference among themselves into a single vertex, without affecting interference constraints for computation of bandwidth allocation. The analytical results show that the time complexity of the hypergraph-based model is comparable to that of the graph-based model since both models have quadratic run time. The results further show that the hypergraph-based model has potential to result in lower time complexity than the graph-based method as the number of interference coordination groups increases and as the number of networks within an interference coordination group increases.

7.3 Further Work

For future work, there are several points for further investigation.

1. In the simulations that were conducted in this thesis, device parameters of networks were stored in Excel comma separated values (csv) files. It would be interesting to explore storage of device parameters, and interference and spectral coexistence relationships between the devices in the form of a hypergraph data model in a database. Hypergraph database solutions, such as Vaticle's TypeDB database [137], are suitable for storage of complex data with n-ary relationships.
2. In this thesis, the effect of terrain and clutter on signal propagation was estimated using an attenuation factor. The next step would be to integrate a terrain-based propagation model in the interference analysis and spectral coexistence functions. Furthermore, measurement reports could be included in the analysis. Finally, it would be interesting to include machine learning techniques in these functions.
3. In Chapter 5, objectives of the channel allocation algorithm were to maximise spectrum utilisation and minimise interference, while meeting channel load constraints. However, the approach that was taken, whereby the algorithm could rearrange spectrum assignment in order to accommodate new assignments, presents a trade-off between spectrum utilisation and spectrum assignment stability. It

would be interesting to add channel invariability to the objectives, not only because of the trade-off in this particular algorithm design, but also because this is an important issue in dynamic spectrum access systems because channel availability and spectrum usage is dynamic.

4. Testing of dynamic radio resource management prototypes through large-scale test-beds is essential to inspire stakeholders' trust that DSA networks can be managed seamlessly despite the highly dynamic nature of spectrum availability. A real-time secondary spectrum trading platform that was developed by the EU project called COGnitive radio systems for efficient sharing of TV white space in EUropean context (COGEU) was demonstrated in Munich, Germany, and outdoor trials were done in Bratislava, Slovakia [178, 179]. Large scale test-beds for TVWS networks operating under licence-exempt policy have been implemented [60,61,180–185]. However, there is scarcity of literature on large-scale outdoor demonstration of autonomous, real-time, dynamic radio resource management for heterogeneous networks operating under licence-exempt policy. Proof-of-concept demonstrations of a dynamic spectrum manager in licence-exempt policy covering a heterogeneous radio environment remains a potential research area.

7.4 Final Remarks

This thesis has analysed application of hypergraph modelling for coexistence management systems and spectrum coordination schemes. However, the model can find wider application in a number of aspects of future networks.

7.4.1 RF Environment Knowledge Database

Use of databases has been proposed as a means for indirect exchange of coexistence-related information between radios/networks that cannot communicate directly due to the use of incompatible wireless protocols, and for machine learning applications. This information is used by networks to select optimal operating parameters or to adjust parameters of the Media Access Control (MAC) mechanism and/or the physical (PHY) layer and to perform spectrum allocations. Efficient representation of coexistence information will enable sufficiently fast and accurate coexistence decisions in collaborative MAC/PHY layer-based coexistence mechanisms and in coexistence management systems. It is envisioned that such data could involve multiple relationships that can be be represented with sufficient accuracy using a hypergraph data model.

7.4.2 Automated Network Management

In DSA systems, the RF environment is dynamic. Furthermore, in licence-exempt DSA systems, secondary user network operators would not have knowledge of other secondary user networks operating in the locality. Manual network management would therefore be nearly impossible when network operators begin to roll out large scale secondary user networks, hence the need for automated dynamic radio resource management. Furthermore, less complex algorithms would ensure timely decisions in the network management application. Coexistence management and spectrum allocation are key aspects of network management. The hypergraph-based model that has been developed in this thesis is not computationally complex. As such, it can be applied in automated dynamic network management systems.

7.4.3 Dynamic Spectrum Management

The geo-location spectrum database approach has successfully been applied for radio spectrum management in hierarchical DSA frameworks of TVWS and CBRS spectrum bands, and is also earmarked for LSA by Ofcom [24, 186]. In addition to these standard systems, customised geo-location spectrum databases for coexistence management among users with an equal priority leve,l such as licence-exempt GAA users, were forecast to be in operation by early 2021 [186,187]. In licensed shared access and in priority access, users are guaranteed exclusive access to shared spectrum. In the CBRS framework, in the spirit of “use it or share it”, priority access users are allowed to auction their spectrum on a secondary market when they are not ready to roll out. However, it is envisioned that light users should be able to share their spectrum with other users at a guaranteed contention ratio in the spirit of “use it most of the time, or time-share it". Alternatively, in highly congested RF environments, such as dense urban areas, more networks can be accommodated by offering priority access licences with a certain guaranteed contention ratio. Modelling of such a spectrum sharing framework would involve multiple relationships for spectral coexistence that can be modelled sufficiently using hypergraph data models.

7.4.4 Frequency Planning Tool

Frequency planning is an important function that is carried out by network operators during capacity planning of their radio networks. The main objective of frequency planning, together with capacity planning, is to maximise radio traffic flow over the wireless medium without reducing transmission quality. Frequency planning starts with specification of either the number of channels that are required to maintain a target level of network capacity or the number of networks that can be supported by the number of available channels.

In licence-exempt white space spectrum, frequency planning would be difficult because, although the GLSD provides a list of channels that are not being used by the primary users, operators of secondary user networks would not have knowledge of other secondary user networks that are also using the available channels. However, GLSD operators would have knowledge of secondary user networks since secondary users are required by regulation to register their networks and to provide their channel usage parameters to the GLSD operator. The channel allocation algorithm developed in this thesis could be adapted in simulating channel sharing to determine if a prospective user's target capacity could be supported by the presently available white space spectrum.

Appendix A

Overview of TVWS Regulatory Frameworks

A.1 FCC Approach

In 2004, the FCC became the first regulator to propose licence-exempt use of TVWS spectrum by secondary users for other services such as wireless internet service [10]. The objective was to enable efficient and effective use of the TV band, to stimulate development of new services or to increase the coverage range of existing services. Secondary users are required to register their devices with a database and each device is issued an FCC identifier. The FCC recognises the geo-location capability and database access method as the main mechanism to ensure that the license-exempt secondary devices do not cause harmful interference to licensed users.

WSDs are referred to as TVBDs in the regulations. All TVBDs are required to have capability for transmission power control. TVBDs are classified into two main categories: *fixed* and *personal/portable* devices. Personal/portable devices are further classified into *Mode I* and *Mode II*. A summary of the characteristics of these classes of TVBDs is given in Table A.1.

A fixed device is a transceiver that operates from a fixed location. It has capability to determine its own geo-location or its geo-location coordinates may be entered in the

Table A.1: Classification of TV Band Devices (TVBDs).

Property		Fixed	Personal/Portable	
			Mode I	Mode II
Position	Fixed	Y		
	Mobile		Y	Y
Geo-location	Inbuilt GPS	Y		Y
	Manual input	Y		
Access to GLSD	Direct IP connection	Y		Y
	Indirect through a fixed TVBD	Y		Y
	Indirect through a Mode II TVBD			Y
Operation mode	Can form a network	Y		Y
	Managed by a fixed/Mode II TVBD		Y	

radio system by a professional installer at the time of installation or relocation of the fixed device. It has capability to access a database to obtain a list of frequencies that are available at its location and the corresponding maximum permitted power for each available channel, to select an operating channel from this list, and to initiate a network of one or more fixed devices and/or personal/portable devices.

A personal/portable device transmits/receives radio signals at unspecified locations that may change. A Mode I device does not have internal capability to determine its geo-location and does not have access to a database. It can only operate under the management of a Fixed device or a Mode II personal/portable device. A Mode II device uses internal geo-location capability and is able to access a white space database either directly through an IP connection or indirectly through a fixed device or another Mode II device. A Mode II device must provide a Mode I device with the same list of channels that are available to it. A fixed device must provide a list of available channels to the Mode I device that is the same as the list of channels available to the fixed device; however, a Mode I device may only operate on those channels that are permissible for Mode I devices. A *sensing only* personal/portable TVBD uses spectrum sensing to determine which channels are vacant. Sensing only devices need to be approved by the FCC before being used and are restricted to a maximum transmit power of 50 mW only. The sensing requirements are as follows; Digital TV: -114 dBm over 6 MHz; Analogue TV: -114 dBm over 100 kHz, wireless microphones: -107 dBm over 200 kHz.

A summary of the requirements of these four device types is given in Table A.2.

Channel availability is determined using the data about protected primary users stored in the database, the specific interference protection criteria for each of the services, and the geo-location information of the requesting TVBD. The primary services include: digital television transmitter stations, digital and analogue Class A TV, low power TV, TV translator and TV booster emitter stations, Private Land Mobile Radio Service (PLMRS)/Commercial Mobile Radio Service (CMRS) operations, offshore radio-telephone service, Wireless Medical Telemetry Service (WMTS), Radio Astronomy Service (RAS), 600MHz service band licensees where they have commenced operations, Multi Video Programming Distributor (MVPD) receive sites and licensed wireless microphones. In addition, primary users in border areas near Canada and Mexico shall also be protected. The regulations specify interference protection requirements for all these protected services.

The database determines protected contours around protected digital TV stations using F(50,90) propagation curve model whereas analogue Class A TV, low power TV, TV translator and TV booster stations are protected using F(50,50) propagation curve models. While the propagation curve models are based on Longley-Rice terrain modelling, the models take into account the average height of terrain, without taking into account terrain features like hills, buildings, vegetation which have a significant impact on signal propagation. This results in either over-protection of primary users where undulating terrain blocks signals or under-protection in flat terrain where signals travel further than what the model predicts.

TVBDs that are using the same channel or channels adjacent to the channel being used by the protected TV station must be located outside the protected contours at a distance higher than the required co-channel and adjacent-channel separation distance from the protected contour. This is illustrated in Figure A.1. In the regulations, separation distances are specified for each device type, and for various antenna height levels and transmission power levels of fixed devices. The specified separation distances apply to a TVBD with a location accuracy of +/-50 metres. The separation distance is increased when the location uncertainty of a TVBD exceeds +/-50 metres. In border

Table A.2: FCC Rules: Requirements of TV Band Devices (TVBDs).

Devices	**Fixed**	**Mode II**	**Mode I**	**Sensing-only**
Geo-location capability	geo-location coordinates and geo-location uncertainty (in metres), with confidence level 95%	geo-location coordinates and geo-location uncertainty (in metres), with confidence level 95%	optional	optional
Transmit power limit (EIRP) (6 MHz)	up to 4 W; above 4 W only in less congested areas	up to 100 mW	up to 100 mW	50 mW
In-band PSD limit (100 kHz)	up to 12.6 dBm (conducted power)	up to 2.6 dBm (EIRP)	up to 2.6 dBm (EIRP)	-0.4 dBm (EIRP)
Adjacent Channel emission limit (100 kHz)	up to -42.8 dBm (conducted power)	up to -52.8 dBm (EIRP)	up to -52.8 dBm (EIRP)	-55.8 dBm (EIRP)
Permissible TV Frequencies	VHF band (54-72 MHz, 76-78 MHz, 174-216 MHz), UHF Band (490-698 MHz)	UHF Band (490-698 MHz)	UHF Band (490-698 MHz)	UHF Band (490-698 MHz
Source of operating parameters	geo-location spectrum database	geo-location spectrum database	received form a fixed or Mode II device	channel sensing technology
Maximum Update Time / Distance	once a day	once a day or when location changes by more than 100m	once every 60 sec	once every 60 sec

areas, the required separation distances from protected contours of TV stations in Canada and Mexico apply if the portions of the protected contours of Canadian and Mexican TV station fall within the US.

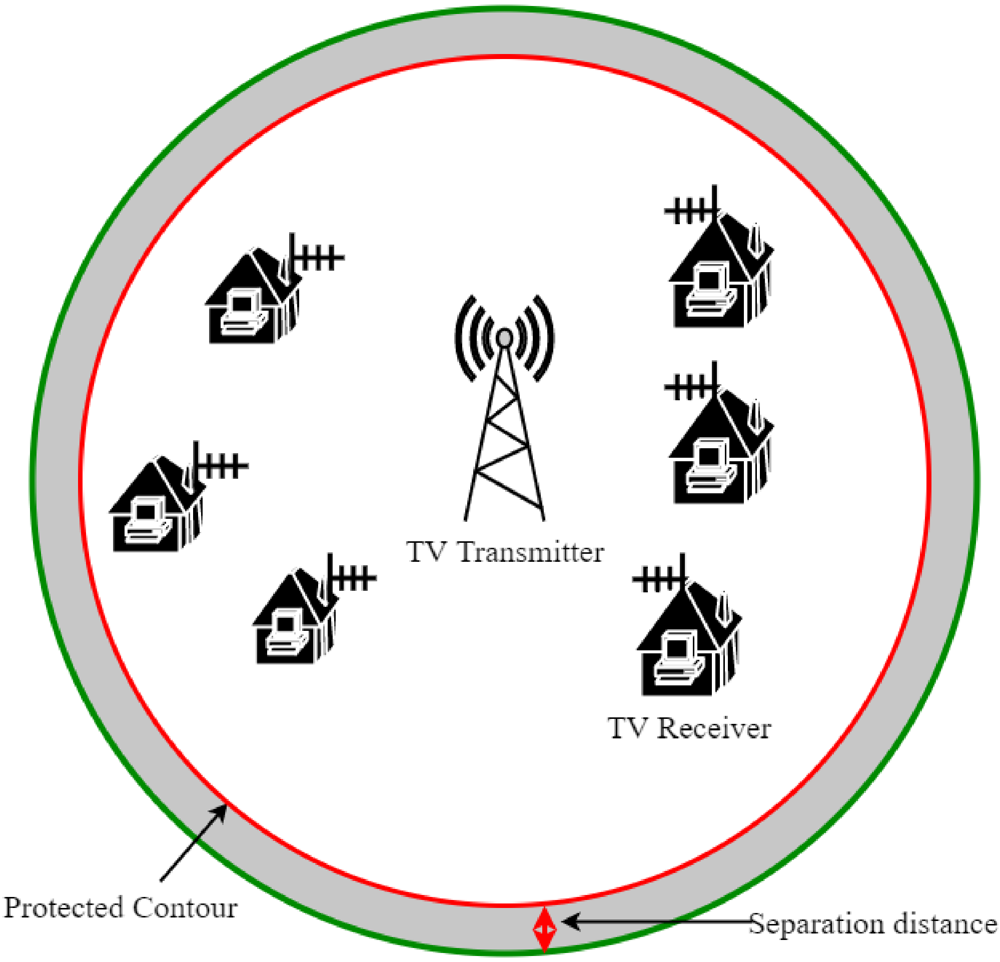


Figure A.1: FCC Rules: Interference Protection of TV Stations.

To protect the PLMRS/ CMRS services in these areas, TVBDs are not allowed to operate on channels 14 - 20 in 11 metropolitan areas at distances less than 134 km and less than 131 km for co-channel and adjacent channel operation, respectively. In regions other than these 11 metropolitan areas, TVBDs are not allowed at distances less than 54 km (for co-channel operation) or less than 51 Km (for adjacent channel operation).

A protected area of a 600 MHz service band licensee shall be defined by polygonal area encompassing base stations or other radio facilities that have been deployed. TVBDs must comply with the co-channel and adjacent channel minimum separation distances between the TVBD and any point along the edge of the polygon area that have been specified in the regulation. The regulations also specify co-channel and adjacent channel separation distances from WMTS sites that operate in the the 608-614 MHz band (channel 37).

The rest of the primary services are protected as follows. TVBDs are not allowed to operate on TV channels (15-18) that assigned to offshore radio service within the specified geographical area. Low power auxiliary services such as licensed or unlicensed wireless microphones must register with database and must define the time interval and area where they want to be protected from other TVBDs. Fixed and personal/portable TVBDs are not permitted to operate on the same channel as low power auxiliary sites within 1 km and 400 metres of the coordinates of registered sites, respectively. To protect RAS services, operation of all types of TVBDs is not allowed on all channels within 2.4 km of the locations of 15 identified sites. Finally, TVBDs are not permitted to operate in the 488-494 MHz band in Hawaii.

A.2 ETSI/Ofcom Regulatory Approach

The Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) and Ofcom have had TV white space operation under consideration since 2005. In 2009, the ECC formed a project team to define technical and operational requirements for the possible operation of cognitive radio systems in the white spaces of the UHF TV Band (470 - 790 MHz, DTT channels 21 - 60). The preliminary results were published in the ECC Report 159 at the beginning of 2011 [188]. The report made the following recommendations on protection of primary services:

- Geo-location combined with database method is the most appropriate method to protect TV broadcasting services, because current sensing technology cannot adequately meet the demanding requirements for autonomous sensing and radio beacon service does not attract interested investors.

- The metric used to protect TV broadcasting should be DTT location probability, which is defined as the probability with which a DTT receiver would operate correctly at a specific location where the median wanted signal level is appropriately greater than a minimum threshold value.
- The maximum permissible transmit power should be location specific and shall take into account the ACLR characteristics of the WSD, which renders additional complexity to the computations but it is expected to improve the white space spectrum availability.
- Programme Making and Special Events (PMSE) primary services should be protected by defining safe harbour channels for the service.
- Protection of RAS services in the 608-614 MHz should be implemented by the database in the form of exclusion zones around the facilities.
- Additional studies were required to determine protection methodology for Aeronautical Radio-Navigation Services (ARNS), mobile/fixed service in the band 790-862 MHz, and Private Mobile Radio Service (PMRS) below 470 MHz.

In 2014, the ETSI published the ETSI EN 301 598 Harmonised European Standard for WSDs [189], based on the regulatory principles that were published in the 2013 ECC Report 186 [190]. Two equipment types have been defined in this standard. Type A refers to fixed radio equipment that may have integral, dedicated or external antenna whereas Type B refers to equipment that is not intended for fixed use and can only have integral or dedicated antenna. WSDs may transmit in a single 8 MHz DTT channel or they may operate concurrently in multiple contiguous or non-contiguous DTT channels.

The standard requires WSDs to have control and monitoring function to prevent a master device from operating without communicating with an approved database and a slave device from transmitting without communications with a master device. At start-up, a master device shall consult a web-listing of databases that have been approved by the national regulatory authority. A master device shall contact the database at regular update intervals to check if its device parameters and those of its slave devices are still valid. If the operational parameters are no longer valid, the WSD shall stop transmission and shall instruct its slave device to cease transmission.

WSDs may operate as master or slave devices in a network. The standard specifies device parameters of master and slave devices that must be submitted to the database, which are used to determine permissible operating parameters. Device parameters of a slave device are submitted via the master device. The database shall provide Specific Operating Parameters (SOPs) if it has received specific device parameters of the slave devices, else, the database shall provide more stringent General Operating Parameters (GOPs) to a master device that may be used by its slave devices in the coverage area of the serving master device. The master device is also required to communicate to the database information about the radio frequencies and powers that it intends to use prior to transmission. This set of parameters is referred to as *channel usage parameters*. This feedback is in line with the regulatory framework requirement for database operators to provide an information system of WSDs that provides spectrum occupancy data for investigating interference cases [15].

The RF power spectral density per 100 kHz or 8 MHz radiated from a WSD shall not exceed the maximum levels specified in the operating parameters received from the database. In the case of simultaneous operation on multiple DTT channels, the database may direct a WSD not to exceed the minimum of the RF power spectral densities of the concerned DTT channels. The standard also specifies the maximum unwanted emissions outside the 470 - 790 MHz band. For instance, the out-of-band unwanted emissions in the PMRS band (230-470 MHz) and in the mobile/fixed service band (790-862 MHz) shall not exceed -36 dBm and -54 dBm, respectively. The standard also specifies ACLR for five standard device emission classes. Manufacturers of WSDs are obliged to declare the device emission class of their product. Within the 470-790 MHz band, the out-of-block unwanted emission limit shall be the maximum of either the difference between in-block EIRP spectral density per 8 MHz and the ACLR for the device's emission class or -84 dBm / 100 kHz.

Ofcom was the first national regulatory authority in Europe to publish its TVWS regulations. On 12th February 2015, Ofcom released a statement on how dynamic spectrum sharing of the TV band between primary users (DTT and PMSE) and WSDs would be implemented [15]. Regulations for WSDs operating in the TV band were published on 31st December 2015 [12].

WSDs are permitted in the entire TV band except for channel 38 (606 MHz to 614 MHz) which is reserved for PMSE, and channel 60 (782MHz to 790MHz) in order to ensure coexistence with LTE mobile services that are allocated the 800MHz band (791MHz to 862MHz). The rest of the operating rules of master and slave WSDs under Ofcom legislation are summarised in Table A.3

Table A.3: Ofcom Regulations - Requirements of White Space Devices (WSDs).

Devices	**Master**	**Slave**
Geo-location capability	geo-location coordinates and geo-location uncertainty (in metres), with confidence level 95%	optional
Transmit power limit (EIRP) (8 MHz)	up to 4 W	up to 4 W
Permissible TV Frequencies	470-606 and 614-782 MHz	470-606 and 614-782 MHz
Source of operating parameters	TVWS spectrum database	TVWS spectrum database via master device
Maximum update time/distance	15 minutes or 50 m	15 minutes or 50 m

A proprietary statistical model called the United Kingdom Planning Model (UKPM) is used to estimate the statistical probability that each 100m by 100m locality (known as a pixel) has got DTT coverage, i.e. the received DTT signal strength is greater than the minimum required signal level specified for a particular receiver (in the UK, the law requires every TV user to obtain a licence). The impact of terrain is taken into account in the propagation model. WSDs are treated as additional sources of interference that can further reduce the estimated location probability. To protect TV users from WSDs, the UKPM is modified to include WSD interference in the protection ratio and mutual coupling between the DTT antenna and the WSD antenna. A threshold for permitted reduction in location DTT coverage probability is set which is used to determine which channels are available and the permitted maximum transmit powers for each available channel. The algorithm applies a transmit power cap of 36 dBm in order to reduce the aggregate probability of WSD interference resulting in TV picture breakup [15].

Appendix B

Preliminary Testing of Hypergraph-based Modelling

This section presents results of preliminary testing of the channel sharing algorithm to demonstrate that the algorithms have been implemented according to specification. A network environment with high interference constraints is used as a test scenario because it is in such a constrained environment that channel allocation becomes a challenge. The test environment consists of 12 networks that are geo-located in the same locality. It is assumed that the set of available channels is available at all network locations. The propagation loss model that was used is given in Chapter 5, Equation 5.6. The rest of the simulation parameters are given in Table B.1.

The hypergraph-based spectrum sharing algorithm (Algorithm 6) that is presented in Chapter 5 was used. The subsections below provide the output of the Python code for hypergraph construction, hyperedge contraction and channel allocation results.

B.1 Hypergraph Construction

The constructed hypergraph is illustrated in Fig. B.1. Five hyperedges were generated to represent groups of networks that can coexist in the same channel based on technology compatibility, channel load and communication range constraints:

1: *[0,1]*, 2: *[2, 3, 9]*, 3: *[4, 7, 8]*, 4: *[5, 6]*, 5: *[10, 11]*

Table B.1: Parameters for Simulation.

RAT	802.22 WRAN	Outdoor 802.11 TVHT
Number of networks	3 (ids 4,7, and 8)	9
Cell coverage (m)	10,000^{a}; 1,500^{b}	300
BS / AP conducted power (dBm)	31^{c}; 20^{d}	15
BS/AP antenna gain (dB)	5	5
CPE/UE antenna gain (dB)	11	0
BS/AP antenna height (m)	15^{d}; 12^{e}	10
CPE/UE antenna height (m)	10^{f}; 6^{g}	1.5
Receiver Sensitivity (dBm)	-88	-88
Attenuation factor, α	4	4
Channel Occupancy Rate (COR)	0.25	0.3
SINR/SNR threshold, δ (dB)	10	10
Centre frequency (MHz)	474	474

$^{a\ c\ d\ f}$Network ids 4,8. $^{b\ d\ e\ g}$ Network id 7.

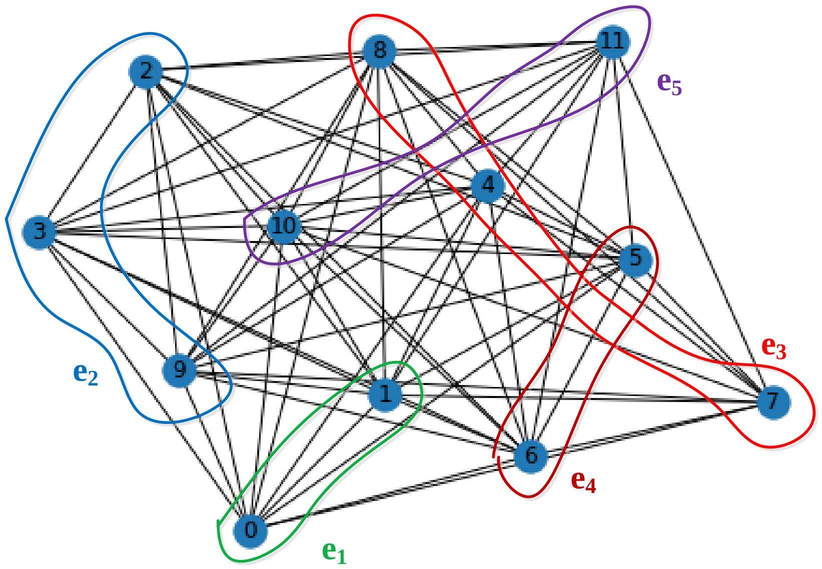
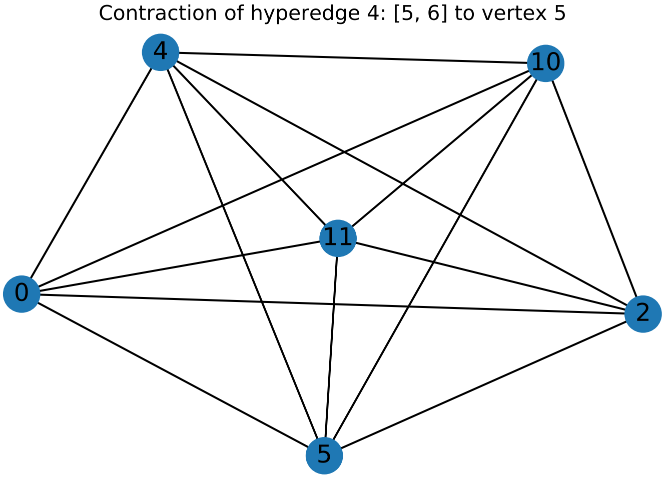


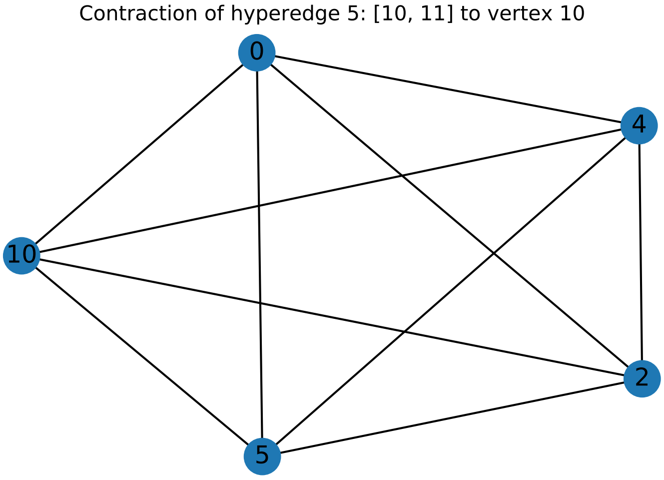
Figure B.1: Illustration of hypergraph model representing pair-wise interferers as edges between pairs of vertices and coexistence information as hyperedges comprising multiple vertices representing networks that can coexist in the same channel.

B.2 Hyperedge Contraction

The hyperedges are contracted sequentially until all hyperedges are processed. Fig. B.2 (a) to (e) shows the output of the algorithm at each stage of contraction of the 5 hyperedges.

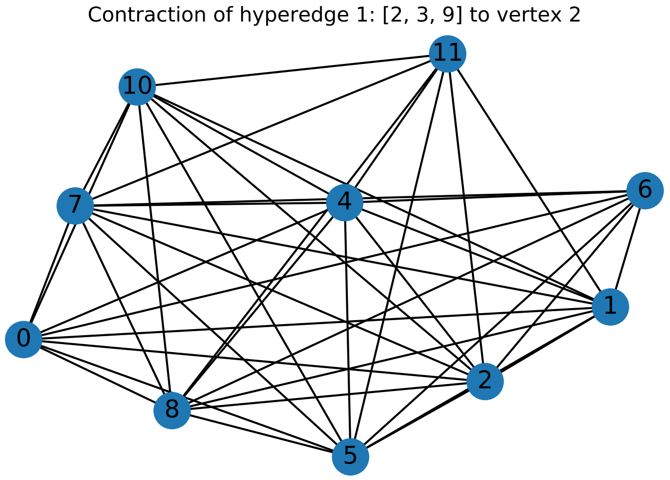


(d)

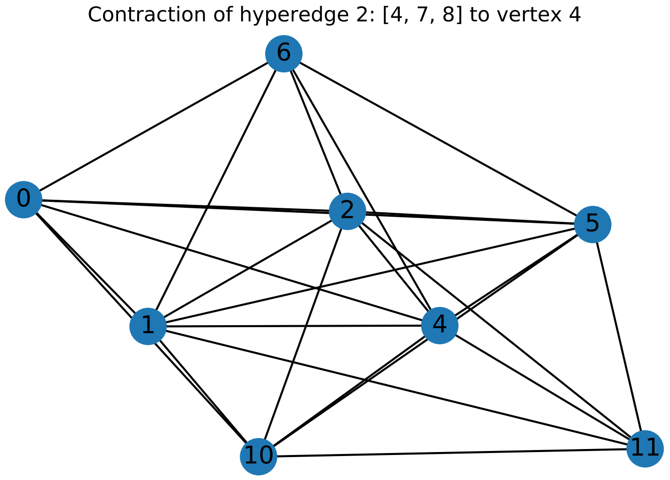


(e)

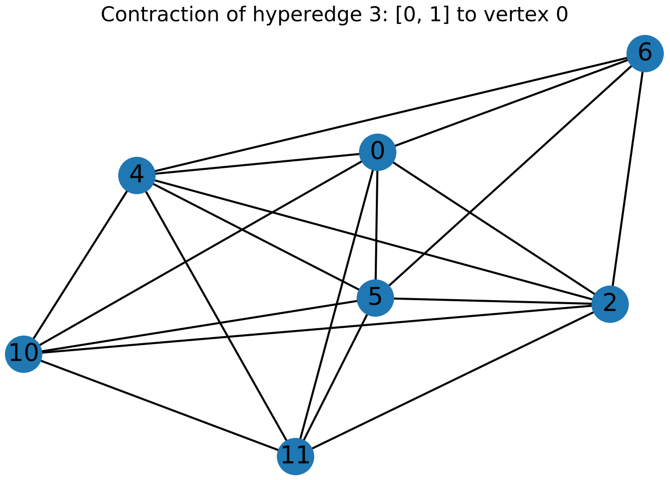
Figure B.2: Results of the stages of decomposition of the hypergraph through sequential contraction of five hyperedges.


Contraction of hyperedge 1: [2, 3, 9] to vertex 2
11
10
7
4
6
1
0
2
8
5

(a)


Contraction of hyperedge 2: [4, 7, 8] to vertex 4
6
0
2
5
1
4
10
11

(b)


Contraction of hyperedge 3: [0, 1] to vertex 0
6
0
4
5
2
10
11

(c)

B.3 Channel Allocation Results for Hypergraph-based Channel Sharing Algorithm

When a vertex colouring algorithm was applied to the minor graph of Fig. B.2e. When there are 3 available channels, only contracted vertices *0*, *2* and *4* are coloured, which results in hyperedges {*0*,*1*}, {*2*,*3*,*9*} and *4*,*7*,*8*} being assigned channels 1, 2 and 3 respectively. The channel allocation result is given in Figure B.3.

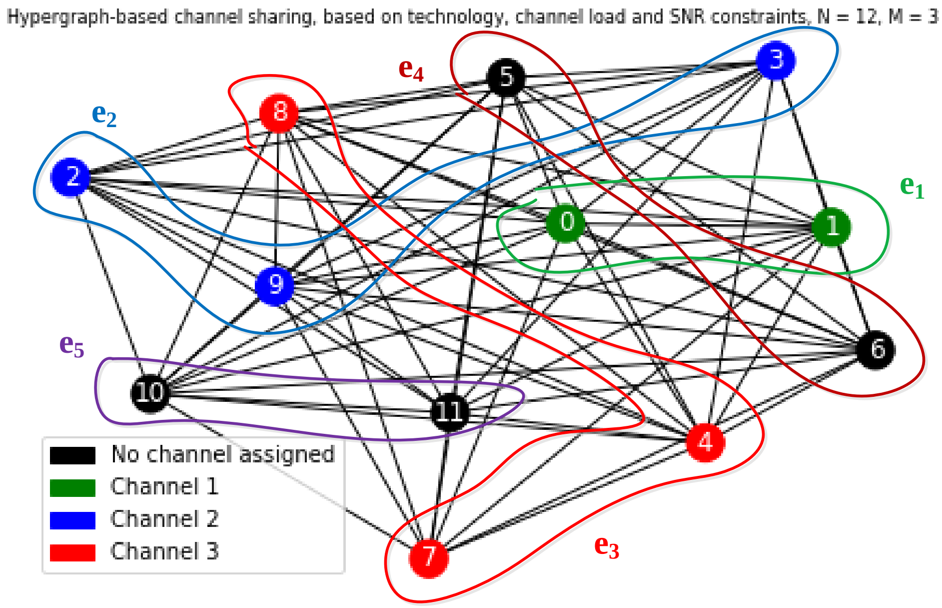


Figure B.3: Channel allocation for the hypergraph-based channel sharing algorithm when there are three available channels - 8 out of the 12 networks are assigned an operating channel from the 3 available channels.

References

[1] Ericsson. "Ericsson mobility report," jun. 1, 2021. [Online]. Available: https://www.ericsson.com/49cd40/assets/local/mobility-report/documents/2021/june-2021-ericsson-mobility-report.pdf

[2] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C. S. Hood, "Chicago spectrum occupancy measurements & analysis and a long-term studies proposal," in *Proceedings of the First International Workshop on Technology and Policy for Accessing Spectrum*, ser. TAPAS '06. New York, NY, USA: ACM, 2006. [Online]. Available: http://doi.acm.org/10.1145/1234388.1234389

[3] M. H. Islam, C. L. Koh, S. W. Oh, X. Qing, Y. Y. Lai, C. Wang, Y. Liang, B. E. Toh, F. Chin, G. L. Tan, and W. Toh, "Spectrum survey in Singapore: Occupancy measurements and analyses," in *2008 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2008)*, May 2008, pp. 1–7.

[4] V. Valenta, R. Maršálek, G. Baudoin, M. Villegas, M. Suarez, and F. Robert, "Survey on spectrum utilization in Europe: Measurements, analyses and observations," in *2010 Proceedings of the Fifth International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, June 2010, pp. 1–5.

[5] T. Shimomura, T. Oyama, and H. Seki, "Analysis of TV white space availability in Japan," in *2012 IEEE Vehicular Technology Conference (VTC Fall)*, Sep. 2012, pp. 1–5.

[6] M. Zennaro, E. Pietrosemoli, J. Mlatho, M. Thodi, and C. Mikeka, “An assessment study on white spaces in Malawi using affordable tools,” in *2013 IEEE Global Humanitarian Technology Conference (GHTC)*, Oct 2013, pp. 265–269.

[7] IEEE, “IEEE standard for definitions and concepts for dynamic spectrum access: Terminology relating to emerging wireless networks, system functionality, and spectrum management - redline,” *IEEE Std 1900.1-2019 (Revision of IEEE Std 1900.1-2008) - Redline*, pp. 1–144, April 2019.

[8] M. Nekovee, “Cognitive radio access to TV white spaces: Spectrum opportunities, commercial applications and remaining technology challenges,” in *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)*, April 2010, pp. 1–10.

[9] M. Nekovee, “A survey of cognitive radio access to TV white spaces,” in *2009 International Conference on Ultra Modern Telecommunications Workshops*, Oct 2009, pp. 1–8.

[10] FCC. (2015) Electronic code of federal regulations, title 47, chapter i, subchapter a, part 15, subpart h-white space devices. [Online]. Available: http://www.ecfr.gov/

[11] IDA. (2014, Jun.) Regulatory framework for TV white space operations in the vhf/uhf bands. ExplanatoryMemo.pdf. [Online]. Available: https://www.imda.gov.sg/-/media/Imda/Files/Inner/PCDG/Consultations/20130617_whitespace/

[12] UKGov. (2015) The wirelesss telegrapghy (white space devices) (exemption) (regulations) 2015. [Online]. Available: http://www.legislation.gov.uk/uksi/2015/2066/contents/made

[13] Government of Canada. (2020, Jan.) DBS-01 – White Space Database Specifications. [Online]. Available: http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10928.html

[14] ICASA. (2014, Jun.) Regulatory framework for TV white space operations in the VHF/UHF bands. [Online]. Available: https://www.icasa.org.za/legislation-and-regulations/regulations-on-the-use-of-television-white-spaces-2018

[15] Ofcom. (2015, Feb.) Implementing TV white spaces. tvws-statement.pdf. [Online]. Available: https://www.ofcom.org.uk

[16] T. Nyasulu, D. H. Crawford, and C. Mikeka, "Malawi's TV white space regulations: A review and comparison with FCC and ofcom regulations," in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, 2018, pp. 1–6.

[17] IEEE, "IEEE standard for radio interface for white space dynamic spectrum access radio systems supporting fixed and mobile operation," *IEEE Std 1900.7-2015*, pp. 1–67, Feb 2016.

[18] IEEE, "IEEE standard for information technology– local and metropolitan area networks– specific requirements– part 22: Cognitive wireless RAN medium access control (MAC) and physical layer (PHY) specifications: Policies and procedures for operation in the TV bands," *IEEE Std 802.22-2011*, pp. 1–680, July 2011.

[19] IEEE, "IEEE standard for information technology—telecommunications and information exchange between systems local and metropolitan area networks—specific requirements - part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," *IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012)*, pp. 1–3534, Dec 2016.

[20] IEEE, "IEEE standard for low-rate wireless networks," *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, pp. 1–709, April 2016.

[21] ECMA International. "ECMA-392 MAC and PHY for operation in TVwhite space 2nd edition," jun. 1, 2012. [Online]. Available: https://www.ecma-international.org/publications-and-standards/standards/ecma-392/

[22] C. Ghosh, S. Roy, and D. Cavalcanti, “Coexistence challenges for heterogeneous cognitive wireless networks in TV white spaces,” *IEEE Wireless Communications*, vol. 18, no. 4, pp. 22–31, August 2011.

[23] FCC. “part 96—citizens broadband radio service” jul. 1, 2021. [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?node=pt47.5.96&rgn=div5

[24] Ofcom. “enabling wireless innovation through local licensing,” jul. 25, 2019. [Online]. Available: https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

[25] IEEE802.15-99/088r2. (2015) Coexistence, interoperability, and other terms. [Online]. Available: http://grouper.ieee.org/groups/802/15/pub/1999/Nov99/99114r0P802-15-Coexistance-Interoperability-and-other-Terms.doc

[26] A. M. Cavalcante, E. Almeida, R. D. Vieira, S. Choudhury, E. Tuomaala, K. Doppler, F. Chaves, R. C. D. Paiva, and F. Abinader, “Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands,” in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, 2013, pp. 1–6.

[27] S. Sagari, I. Seskar, and D. Raychaudhuri, “Modeling the coexistence of LTE and WiFi heterogeneous networks in dense deployment scenarios,” in *2015 IEEE International Conference on Communication Workshop (ICCW)*, 2015, pp. 2301–2306.

[28] B. Chen, J. Chen, Y. Gao, and J. Zhang, “Coexistence of LTE-LAA and Wi-Fi on 5 GHz with corresponding deployment scenarios: A survey,” *IEEE Communications Surveys Tutorials*, vol. 19, no. 1, pp. 7–32, 2017.

[29] O. Karatalay, S. Erküçük, and T. Baykaş, “Busy tone based coexistence algorithm for wran and wlan systems in tv white space,” *IET Communications*, vol. 12, pp. 1630–1637(7), August 2018. [Online]. Available: https://digital-library.theiet.org/content/journals/10.1049/iet-com.2017.0740

[30] O. Karatalay, S. Erküçük, and T. Baykaş, "Analysis of extended busy tone performance for coexistence between WRAN and WLAN TVWS networks," in *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Aug 2015, pp. 1957–1962.

[31] F. M. Abinader, E. P. Almeida, F. S. Chaves, A. M. Cavalcante, R. D. Vieira, R. C. Paiva, A. M. Sobrinho, S. Choudhury, E. Tuomaala, K. Doppler, and V. A. Sousa, "Enabling the coexistence of LTE and Wi-Fi in unlicensed bands," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 54–61, 2014.

[32] X. Feng, Q. Zhang, and B. Li, "Enabling co-channel coexistence of 802.22 and 802.11af systems in TV white spaces," in *2013 IEEE International Conference on Communications (ICC)*, June 2013, pp. 6040–6044.

[33] IEEE, "IEEE standard for information technology–telecommunications and information exchange between systems – local and metropolitan area networks – specific requirements – part 19: TV white space coexistence methods," *IEEE Std 802.19.1-2014*, pp. 1–326, June 2014.

[34] IEEE, "IEEE standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks–specific requirements–part 19: TV white space coexistence methods - amendment 1: Coexistence methods for geo-location capable devices operating under general authorization," *IEEE Std 802.19.1a-2017 (Amendment to IEEE Std 802.19.1-2014)*, pp. 1–295, Dec 2017.

[35] IEEE, "Ieee standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks–specific requirements–part 19: Wireless network coexistence methods - redline," *IEEE Std 802.19.1-2018 - Redline*, pp. 1–701, Nov 2018.

[36] Wireless Innovation Forum. "Operations for Citizens Broadband Radio Service (CBRS); GAA Spectrum Coordination-Approach 1 Technical Report

Document WINNF-TR-2003 Version V1.0.0," may. 31, 2019. [Online]. Available: https://winnf.memberclicks.net/assets/work_products/Recommendations/WINNF-TR-2003-V1.0.0%20GAA%20Spectrum%20Coordination-Approach%201.pdf

[37] Wireless Innovation Forum. "Operations for Citizens Broadband Radio Service (CBRS); GAA Spectrum Coordination - Approach 2 Document WINNF-TR-2004 Version V1.0.0 16," may. 16, 2019. [Online]. Available: https://winnf.memberclicks.net/assets/work_products/Recommendations/WINNF-TR-2004-V1.0.0%20GAA%20Spectrum%20Coordination-Approach%202.pdf

[38] Wireless Innovation Forum. "Operations for Citizens Broadband Radio Service (CBRS); GAA Spectrum Coordination-Approach 3 Technical Report Document WINNF-TR-2005 Version V1.0.0," may. 16, 2019. [Online]. Available: https://winnf.memberclicks.net/assets/work_products/Recommendations/WINNF-TR-2003-V1.0.0%20GAA%20Spectrum%20Coordination-Approach%201.pdf

[39] OnGo. "CBRS Coexistence Technical Specifications CBRSA-TS-2001 V3.0.0 ," feb. 18, 2020. [Online]. Available: https://ongoalliance.org/wp-content/uploads/2020/02/CBRSA-TS-2001-V3.0.0_Approved-for-publication.pdf

[40] H. Zhang, L. Song, Z. Han, and Y. Zhang, *Basics of Hypergraph Theory.* Cham: Springer International Publishing, 2018, pp. 1–19. [Online]. Available: https://doi.org/10.1007/978-3-319-60469-5_1

[41] H. Zhang, L. Song, and Z. Han, "Radio resource allocation for device-to-device underlay communication using hypergraph theory," *IEEE Transactions on Wireless Communications*, vol. 15, no. 7, pp. 4852–4861, 2016.

[42] Z. Li, S. Chen, and C. Guo, "Location-aware hypergraph coloring based spectrum allocation for D2D communication," in *2018 15th International Symposium on Wireless Communication Systems (ISWCS)*, 2018, pp. 1–6.

[43] Y. Ren and G. Chuai, “Low-complexity uplink resource allocation algorithm based on hypergraph clustering for D2D communications,” in *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2017, pp. 1–6.

[44] Y. Sun, Q. Wu, Y. Xu, Y. Zhang, F. Sun, and J. Wang, “Distributed channel access for device-to-device communications: A hypergraph-based learning solution,” *IEEE Communications Letters*, vol. 21, no. 1, pp. 180–183, 2017.

[45] Y. Dai, M. Sheng, K. Zhao, L. Liu, J. Liu, and J. Li, “Interference-aware resource allocation for d2d underlaid cellular network using SCMA: A hypergraph approach,” in *2016 IEEE Wireless Communications and Networking Conference*, 2016, pp. 1–6.

[46] G. Nychis, C. Tsourakakis, S. Seshan, and P. Steenkiste, “Centralized, measurement-based, spectrum management for environments with heterogeneous wireless networks,” in *2014 IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN)*, April 2014, pp. 303–314.

[47] L. Kulacz, P. Kryszkiewicz, A. Kliks, H. Bogucka, J. Ojaniemi, J. Paavola, J. Kalliovaara, and H. Kokkinen, “Coordinated spectrum allocation and coexistence management in CBRS-SAS wireless networks,” *IEEE Access*, vol. 7, pp. 139 294–139 316, 2019.

[48] N. Wiebusch and U. Meier, “Evolutionary resource allocation optimization for wireless coexistence management,” in *2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1, 2018, pp. 1197–1200.

[49] H. Ahmed and Asaduzzaman, “Channel assignment augmentation algorithm to mitigate interference for heterogeneous ”TV white space” users,” in *2018 Joint 7th International Conference on Informatics, Electronics Vision (ICIEV) and 2018 2nd International Conference on Imaging, Vision Pattern Recognition (icIVPR)*, June 2018, pp. 200–205.

[50] K. Khalil, G. Farhadi, and A. Ito, “Coexistence management for heterogeneous networks in white spaces,” in *2014 International Conference on Computing, Networking and Communications (ICNC)*, Feb 2014, pp. 691–697.

[51] T. Nyasulu and D. H. Crawford, “Hypergraph-based model for coexistence management of heterogeneous wireless networks,” in *2021 Wireless Days (WD)*, 2021, pp. 1–8.

[52] Nyasulu, Tawachi and Crawford, David H., “Comparison of graph-based and hypergraph-based models for wireless network coexistence,” in *2021 IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*, 2021, pp. 203–208.

[53] T. Nyasulu. (2021) Rf environment modelling techniques for heterogeneous network management. [Online]. Available: https://conference.wirelessinnovation.org/winncomm-2021-top-ten

[54] FCC. (2010) Connecting america: The national broadband plan. [Online]. Available: https://transition.fcc.gov/national-broadband-plan/national-broadband-plan.pdf

[55] European Commission. (2012) Radio spectrum policy programme: the roadmap for a wireless europe. [Online]. Available: https://ec.europa.eu/digital-single-market/en/radio-spectrum-policy-programme-roadmap-wireless-europe

[56] Federal Communications Commission. (2002, Nov.) Spectrum policy task force. [Online]. Available: https://www.fcc.gov/document/spectrum-policy-task-force

[57] M. M. Buddhikot, “Understanding dynamic spectrum access: Models,taxonomy and challenges,” in *2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, April 2007, pp. 649–663.

[58] Ofcom. (2009, Jul.) Digital dividend: Cognitive access - statement on licence-exempting cognitive devices using interleaved spectrum. statement.pdf. [Online]. Available: https://www.ofcom.org.uk/

[59] M. Zennaro, E. Pietrosemoli, A. Arcia-Moret, C. Mikeka, J. Pinifolo, C. Wang, and S. Song, "TV white spaces, i presume?: The quest for TVWS in Malawi and Zambia," in *Proceedings of the Sixth International Conference on Information and Communications Technologies and Development: Notes - Volume 2*, ser. ICTD '13. New York, NY, USA: ACM, 2013, pp. 175–178. [Online]. Available: http://doi.acm.org/10.1145/2517899.2517926

[60] C. McGuire, M. R. Brew, F. Darbari, S. Weiss, and R. W. Stewart, "Enabling rural broadband via TV "white space"," in *2012 5th International Symposium on Communications, Control and Signal Processing*, May 2012, pp. 1–4.

[61] O. Holland, S. Ping, A. Aijaz, J. Chareau, P. Chawdhry, Y. Gao, Z. Qin, and H. Kokkinen, "To white space or not to white space: That is the trial within the ofcom TV white spaces pilot," in *2015 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Sep. 2015, pp. 11–22.

[62] S. Roberts, P. Garnett, and R. Chandra, "Connecting africa using the TV white spaces: from research to real world deployments," in *The 21st IEEE International Workshop on Local and Metropolitan Area Networks*, April 2015, pp. 1–6.

[63] H. Harada, K. Ishizu, and H. Murakami, "A wireless network system in TV white space," in *2013 16th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, June 2013, pp. 1–5.

[64] F. Darbari, M. Brew, S. Weiss, and W. S. Robert, "Practical aspects of broadband access for rural communities using a cost and power efficient multi-hop/relay network," in *2010 IEEE Globecom Workshops*, Dec 2010, pp. 731–735.

[65] J. Markendahl, P. Gonzalez-Sanchez, and B. Molleryd, "Impact of deployment costs and spectrum prices on the business viability of mobile broadband using

TV white space," in *2012 7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM).* IEEE, 2012, pp. 124–128.

[66] R. Thanki. (2012) The economic significance of licence-exempt spectrum to the future of the internet. [Online]. Available: https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/spectrum-economic-significance-of-license-exempt-spectrum-report_thanki.pdf

[67] A. Bourdena, G. Kormentzas, C. Skianis, E. Pallis, and G. Mastorakis, "Real-time TVWS trading based on a centralized CR network architecture," in *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, Dec 2011, pp. 964–969.

[68] A. Bourdena, G. Kormentzas, E. Pallis, and G. Mastorakis, "A centralised broker-based CR network architecture for TVWS exploitation under the RTSSM policy," in *2012 IEEE International Conference on Communications (ICC)*, June 2012, pp. 5685–5689.

[69] A. Bourdena, E. Pallis, G. Kormentzas, C. Skianis, and G. Mastorakis, "QoS provisioning and policy management in a broker-based CR network architecture," in *2012 IEEE Global Communications Conference (GLOBECOM)*, Dec 2012, pp. 1841–1846.

[70] A. Bourdena, E. Pallis, G. Kormentzas, and G. Mastorakis, "A radio resource management framework for TVWS exploitation under an auction-based approach," in *2012 8th international conference on network and service management (cnsm) and 2012 workshop on systems virtualiztion management (svm)*, Oct 2012, pp. 204–208.

[71] A. Bourdena, E. Pallis, E. Karditsis, G. Mastorakis, and G. Kormentzas, "A radio resource management framework for TVWS exploitation under the RTSSM policy," in *2012 International Conference on Telecommunications and Multimedia (TEMU)*, July 2012, pp. 1–6.

[72] J. W. Mwangoka, P. Marques, and J. Rodriguez, “Broker based secondary spectrum trading,” in *2011 6th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, June 2011, pp. 186–190.

[73] Engineering Telecommunications Standards Institute. (2015) ETSI TS 103 145 V1.1.1 (2015-01)Reconfigurable Radio Systems (RRS);System Architecture and High Level Procedures for Coordinated and Uncoordinated Use of TV White Spaces. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/103100_103199/103145/01.01.01_60/ts_103145v010101p.pdf

[74] S. W. Oh, Y. Ma, M. Tao, and E. Peh, *TV White Space: The First Step Towards Better Utilisation of Frequency Spectrum.* New Jersey: John Wiley & Sons, 2016.

[75] W. Zhang, G. Zhang, Y. Zheng, L. Yang, and C. K. Yeo, “Spectrum sharing for heterogeneous networks and application systems in TV white spaces,” *IEEE Access*, vol. 6, pp. 19 833–19 843, 2018.

[76] Wireless Innovation Forum. “Requirements for Commercial Operation in the U.S. 3550-3700 MHz Citizens Broadband Radio Service Band Document WINNF-TS-0112 Version V1.9.1 11 March 2020,” mar. 11, 2020. [Online]. Available: https://winnf.memberclicks.net/assets/CBRS/WINNF-TS-0112.pdf

[77] T. Baykas, M. Kasslin, M. Cummings, H. Kang, J. Kwak, R. Paine, A. Reznik, R. Saeed, and S. J. Shellhammer, “Developing a standard for TV white space coexistence: technical challenges and solution approaches,” *IEEE Wireless Communications*, vol. 19, no. 1, pp. 10–22, February 2012.

[78] G. P. Villardi, H. Harada, and G. T. F. de Abreu, “Stochastic-geometric model of expected service area for cognitive TV white space wireless networks,” in *2011 6th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, June 2011, pp. 331–335.

[79] C. Sum, M. Zhou, L. Lu, F. Kojima, and H. Harada, "Performance and coexistence analysis of multiple IEEE 802 WPAN/WLAN/WRAN systems operating in TV White Space," in *2014 IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN)*, April 2014, pp. 145–148.

[80] H. Kang, D. Lee, B. Jeong, and A. C. Kim, "Coexistence between 802.22 and 802.11af over TV white space," in *ICTC 2011*, Sep. 2011, pp. 533–536.

[81] Antipolis, Sophia. "LTE in unlicensed spectrum," jun. 19, 2020. [Online]. Available: https://www.3gpp.org/news-events/1603-lte_in_unlicensed

[82] R. Karaki and A. Mukherjee, "Coexistence of contention-based general authorized access networks in 3.5 GHz CBRS band," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018, pp. 1–6.

[83] MulteFire Alliance. "about multefire release 1.1 specification" nd. [Online]. Available: https://www.mfa-tech.org/technology/specifications-2/

[84] Y. Ye, D. Wu, Z. Shu, and Y. Qian, "Overview of LTE spectrum sharing technologies," *IEEE Access*, vol. 4, pp. 8105–8115, 2016.

[85] S. S. Skiena, *The Algorithm Design Manual.* London: Springer, 2008.

[86] V. Voloshin, *Introduction to Graph and Hypergraph Theory.* New York: Nova Science Publishers, Incorporated, 2009.

[87] D. Brélaz, "New methods to color the vertices of a graph," *Communications of the ACM*, vol. 22, no. 4, pp. 251–256, 1979.

[88] A. Bretto, *Hypergraph Theory: An Introduction.* Springer Publishing Company, Incorporated, 2013.

[89] A. Ducournau, S. Rital, and A. Bretto, "A hypergraph-based image database clustering framework," in *2010 5th International Symposium On I/V Communications and Mobile Network*, 2010, pp. 1–4.

[90] H. Zhang, L. Song, Z. Han, and Y. Zhang, *Resource Allocation for Cross-Cell Device-to-Device Communications.* Cham: Springer International Publishing, 2018, pp. 41–56. [Online]. Available: https://doi.org/10.1007/978-3-319-60469-5_3

[91] J. Liu, S. Sun, J. Liu, and Y. He, "Hypergraph-based intercell interference coordination for QoS guarantees in dense femtocell networks," in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*, 2015, pp. 1–6.

[92] L. Chen, L. Ma, Y. Xu, and V. C. M. Leung, "Hypergraph spectral clustering based spectrum resource allocation for dense NOMA-hetnet," *IEEE Wireless Communications Letters*, vol. 8, no. 1, pp. 305–308, 2019.

[93] ITU-R. (2017) Recommendation itu-r sm.1046-3 definition of spectrum use and efficiency of a radio system. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1046-3-201709-I!!PDF-E.pdf

[94] J. Wang, T. Baykas, S. Filin, M. A. Rahman, C. Song, and H. Harada, "Coexistence protocol design for autonomous decision-making systems in TV white space," in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2012, pp. 3249–3254.

[95] H. Zhang, L. Song, Z. Han, and Y. Zhang, *Radio Resource Allocation for Device-to-Device Underlay Communications.* Cham: Springer International Publishing, 2018, pp. 21–39. [Online]. Available: https://doi.org/10.1007/978-3-319-60469-5_2

[96] H. Zhang, Y. Ji, L. Song, and H. Zhu, "Hypergraph based resource allocation for cross-cell device-to-device communications," in *2016 IEEE International Conference on Communications (ICC)*, 2016, pp. 1–6.

[97] C. Chen, B. Wang, and R. Zhang, "Interference hypergraph-based resource allocation (IHG-RA) for NOMA-integrated V2X networks," *IEEE Internet of Things Journal*, vol. 6, no. 1, pp. 161–170, 2019.

[98] B. Wang, R. Zhang, C. Chen, X. Cheng, and L. Yang, “Interference hypergraph-based resource allocation (IHG-RA) for NOMA-integrated V2X networks,” in *2018 IEEE Global Communications Conference (GLOBECOM)*, 2018, pp. 1–6.

[99] B. Gao, J. Park, Y. Yang, and S. Roy, “A taxonomy of coexistence mechanisms for heterogeneous cognitive radio networks operating in TV white spaces,” *IEEE Wireless Communications*, vol. 19, no. 4, pp. 41–48, August 2012.

[100] M. Labib, J. H. Reed, A. F. Martone, and A. I. Zaghloul, “Coexistence between radar and LTE-U systems: Survey on the 5 ghz band,” in *2016 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM)*, 2016, pp. 1–2.

[101] G. Naik, J. Liu, and J.-M. J. Park, “Coexistence of wireless technologies in the 5 GHz bands: A survey of existing solutions and a roadmap for future research,” *IEEE Communications Surveys Tutorials*, vol. 20, no. 3, pp. 1777–1798, 2018.

[102] A. M. Voicu, L. Simić, and M. Petrova, “Survey of spectrum sharing for inter-technology coexistence,” *IEEE Communications Surveys Tutorials*, vol. 21, no. 2, pp. 1112–1144, 2019.

[103] M. Beluri, E. Bala, Yuying Dai, R. Di Girolamo, M. Freda, J. Gauvreau, S. Laughlin, D. Purkayastha, and A. Touag, “Mechanisms for LTE coexistence in TV white space,” in *2012 IEEE International Symposium on Dynamic Spectrum Access Networks*, Oct 2012, pp. 317–326.

[104] Y. Han, E. Ekici, H. Kremo, and O. Altintas, “Resource allocation algorithms supporting coexistence of cognitive vehicular and IEEE 802.22 networks,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 2, pp. 1066–1079, Feb 2017.

[105] N. C. Prasad, S. Deb, and A. Karandikar, “Feasibility study of LTE middle-mile networks in TV white spaces for rural india,” in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2016, pp. 1–6.

[106] S. Filin, F. Kojima, D. Noguet, J. Dore, B. Mawlawi, O. Holland, M. Z. Shakir, and H. Harada, “IEEE 1900.7 standard for white space dynamic spectrum access radio systems,” in *2015 IEEE Conference on Standards for Communications and Networking (CSCN)*, Oct 2015, pp. 218–223.

[107] C. R. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. J. Shellhammer, and W. Caldwell, “IEEE 802.22: The first cognitive radio wireless regional area network standard,” *IEEE Communications Magazine*, vol. 47, no. 1, pp. 130–138, January 2009.

[108] IEEE, “IEEE recommended practice for information technology - telecommunications and information exchange between systems wireless regional area networks (WRAN) - specific requirements - part 22.2: Installation and deployment of IEEE 802.22 systems,” *IEEE Std 802.22.2-2012*, pp. 1–44, Sep. 2012.

[109] IEEE, “IEEE Standard for Information Technology–Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)–Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and procedures for operation in the TV bands amendment 1: Management and Control Plane Interfaces and Procedures and Enhancement to the Management Information Base (MIB),” *IEEE Std 802.22a-2014 (Amendment to IEEE Std 802.22-2011)*, pp. 1–519, May 2014.

[110] IEEE, “IEEE Standard for Information Technology–Telecommunications and information exchange between systems - Wireless Regional Area Networks (WRAN)–Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications:Policies and Procedures for Operation in the TV Bands - Amendment 2: Enhancement for Broadband Services and Monitoring Applications,” *IEEE Std 802.22b-2015 (Amendment to IEEE Std 802.22-2011 as amended by IEEE Std 802.22a-2014)*, pp. 1–299, Oct 2015.

[111] A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, and S. Pandey, "IEEE 802.11af: a standard for TV white space spectrum sharing," *IEEE Communications Magazine*, vol. 51, no. 10, pp. 92–100, October 2013.

[112] D. H. Kang, K. Balachandran, and M. Buchmayer, "Coexistence performance of GAA use cases using LTE-TDD technologies in 3.5 GHz CBRS spectrum," in *2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2018, pp. 1–7.

[113] M. Palola, M. Höyhtyä, P. Aho, M. Mustonen, T. Kippola, M. Heikkilä, S. Yrjölä, V. Hartikainen, L. Tudose, A. Kivinen, R. Ekman, J. Hallio, J. Paavola, M. Mäkeläinen, and T. Hänninen, "Field trial of the 3.5 GHz citizens broadband radio service governed by a spectrum access system (SAS)," in *2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2017, pp. 1–9.

[114] Tarazi, Ayad. "Let the PAL journey begin" apr. 19, 2021. [Online]. Available: https://www.federatedwireless.com/let-the-pal-journey-begin/

[115] FCC. "FCC announces winning bidders of 3.5 GHz band auction" oct. 1, 2020. [Online]. Available: https://www.fcc.gov/document/fcc-announces-winning-bidders-35-ghz-band-auction

[116] Federal Communications Commission. "3.5 GHz band overview" mar. 10, 2020. [Online]. Available: https://www.fcc.gov/35-ghz-band-overview

[117] G. P. Villardi, Y. D. Alemseged, C. Sun, C. Sum, T. H. Nguyen, T. Baykas, and H. Harada, "Enabling coexistence of multiple cognitive networks in TV white space," *IEEE Wireless Communications*, vol. 18, no. 4, pp. 32–40, August 2011.

[118] B. Gao, Y. Yang, and J. J. Park, "A credit-token-based spectrum etiquette framework for coexistence of heterogeneous cognitive radio networks," in *IEEE INFOCOM 2014 - IEEE Conference on Computer Communications*, April 2014, pp. 2715–2723.

[119] S. Filin, T. Baykas, H. Harada, F. Kojima, and H. Yano, "IEEE Standard 802.19.1 for TV white space coexistence," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 22–26, March 2016.

[120] C. Cano and D. J. Leith, "Coexistence of WiFi and LTE in unlicensed bands: A proportional fair allocation scheme," in *2015 IEEE International Conference on Communication Workshop (ICCW)*, 2015, pp. 2288–2293.

[121] T. Nihtilä, V. Tykhomyrov, O. Alanen, M. A. Uusitalo, A. Sorri, M. Moisio, S. Iraji, R. Ratasuk, and N. Mangalvedhe, "System performance of LTE and IEEE 802.11 coexisting on a shared frequency band," in *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, 2013, pp. 1038–1043.

[122] K. Bian, J. Park, L. Chen, and X. Li, "Addressing the hidden terminal problem for heterogeneous coexistence between TDM and CSMA networks in white space," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 9, pp. 4450–4463, Nov 2014.

[123] E. Almeida, A. M. Cavalcante, R. C. D. Paiva, F. S. Chaves, F. M. Abinader, R. D. Vieira, S. Choudhury, E. Tuomaala, and K. Doppler, "Enabling LTE/WiFi coexistence by LTE blank subframe allocation," in *2013 IEEE International Conference on Communications (ICC)*, 2013, pp. 5083–5088.

[124] A. K. Sadek, "Carrier Sense Adaptive Transmission (CSAT) in unlicensed spetrum," U.S. Patent 201 500858684, Mar. 2015.

[125] V. Sathya, M. Mehrnoush, M. Ghosh, and S. Roy, "Analysis of CSAT performance in Wi-Fi and LTE-U coexistence," in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2018, pp. 1–6.

[126] C. Cano and D. J. Leith, "Unlicensed LTE/WiFi coexistence: Is LBT inherently fairer than CSAT?" in *2016 IEEE International Conference on Communications (ICC)*, 2016, pp. 1–6.

[127] A. S. Cacciapuoti, M. Caleffi, and L. Paura, “On the coexistence of cognitive radio ad hoc networks in TV white space,” in *2015 IEEE International Conference on Communication Workshop (ICCW)*, 2015, pp. 509–513.

[128] H. Maloku, E. Hamiti, Z. Limani, V. Papadopoulou, A. Pitsillides, and M. Rajarajan, “A decentralized approach for self-coexistence among heterogeneous networks in TVWS,” *IEEE Transactions on Vehicular Technology*, vol. PP, pp. 1–1, 09 2017.

[129] M. Tonnemacher, C. Tarver, V. Chandrasekhar, H. Chen, P. Huang, B. L. Ng, J. Charlie Zhang, J. R. Cavallaro, and J. Camp, “Opportunistic channel access using reinforcement learning in tiered CBRS networks,” in *2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2018, pp. 1–10.

[130] R. Yin, G. Yu, A. Maaref, and G. Y. Li, “Adaptive LBT for licensed assisted access LTE networks,” in *2015 IEEE Global Communications Conference (GLOBECOM)*, 2015, pp. 1–6.

[131] A. M. Baswade and B. R. Tamma, “Channel sensing based dynamic adjustment of contention window in LAA-LTE networks,” in *2016 8th International Conference on Communication Systems and Networks (COMSNETS)*, 2016, pp. 1–2.

[132] C. K. Kim, C. S. Yang, and C. G. Kang, “Adaptive listen-before-talk (LBT) scheme for LTE and Wi-Fi systems coexisting in unlicensed band,” in *2016 13th IEEE Annual Consumer Communications Networking Conference (CCNC)*, 2016, pp. 589–594.

[133] H. Ko, J. Lee, and S. Pack, “A fair listen-before-talk algorithm for coexistence of LTE-U and WLAN,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 10 116–10 120, 2016.

[134] A. Bhorkar, C. Ibars, A. Papathanassiou, and P. Zong, “Medium access design for LTE in unlicensed band,” in *2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 2015, pp. 369–373.

[135] R. Ratasuk, M. A. Uusitalo, N. Mangalvedhe, A. Sorri, S. Iraji, C. Wijting, and A. Ghosh, “License-exempt LTE deployment in heterogeneous network,” in *2012 International Symposium on Wireless Communication Systems (ISWCS)*, 2012, pp. 246–250.

[136] Wannstrom, Jeanette and Mallinson, Keith. “Heterogeneous Networks in LTE,” nd. [Online]. Available: https://www.3gpp.org/technologies/keywords-acronyms/1576-hetnet

[137] Vaticle. “Introducing TypeDB: a strongly-typed database” jul. 22, 2021. [Online]. Available: https://vaticle.com/

[138] E. Ahmed, A. Gani, S. Abolfazli, L. J. Yao, and S. U. Khan, “Channel assignment algorithms in cognitive radio networks: Taxonomy, open issues, and challenges,” *IEEE Communications Surveys Tutorials*, vol. 18, no. 1, pp. 795–823, 2016.

[139] Y. Han, E. Ekici, H. Kremo, and O. Altintas, “Spectrum sharing methods for the coexistence of multiple RF systems: A survey,” *Ad Hoc Networks*, vol. 53, pp. 53–78, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1570870516302153

[140] G. I. Tsiropoulos, O. A. Dobre, M. H. Ahmed, and K. E. Baddour, “Radio resource allocation techniques for efficient spectrum access in cognitive radio networks,” *IEEE Communications Surveys Tutorials*, vol. 18, no. 1, pp. 824–847, 2016.

[141] E. Z. Tragos, S. Zeadally, A. G. Fragkiadakis, and V. A. Siris, “Spectrum assignment in cognitive radio networks: A comprehensive survey,” *IEEE Communications Surveys Tutorials*, vol. 15, no. 3, pp. 1108–1135, 2013.

[142] J. D. Murray, *Mathematical biology. I An introduction*, 3rd ed., ser. Interdisciplinary applied mathematics. New York: Springer, 2002.

[143] G. Pyke, “Optimal foraging theory: Introduction,” in *Encyclopedia of Animal Behavior*, M. D. Breed and J. Moore, Eds. Oxford: Academic Press, 2010, pp.

601–603. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780080453378002102

[144] A. J. Lotka, *Elements of mathematical biology*, 1956, 1956.

[145] S. Filin, K. Ishizu, F. Kojima, and H. Harada, "Implementation of TV white space coexistence system based on IEEE 802.19.1 standard," in *2015 IEEE Conference on Standards for Communications and Networking (CSCN)*, Oct 2015, pp. 206–211.

[146] H. Kang, G. Ko, I. Kim, J. Oh, M. Song, and J. Choi, "Overlapping BSS interference mitigation among WLAN systems," in *2013 International Conference on ICT Convergence (ICTC)*, Oct 2013, pp. 913–917.

[147] T. Baykas, S. Filin, and H. Harada, "Verification of TVWS coexistence system based on P802.19.1 draft standard," in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, June 2013, pp. 1–5.

[148] S. Filin, T. Baykas, M. A. Rahman, and H. Harada, "Performance evaluation of IEEE 802.19.1 coexistence system," in *2011 IEEE International Conference on Communications (ICC)*, June 2011, pp. 1–6.

[149] T. Baykas, J. Wang, M. A. Rahman, H. N. Tran, C. Song, S. Filin, Y. Alemseged, C. Sun, G. P. Villardi, C. Sum, Z. Lan, and H. Harada, "Overview of TV white spaces: Current regulations, standards and coexistence between secondary users," in *2010 IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops*, Sep. 2010, pp. 38–43.

[150] H. Kang, K. Kim, and J. Oh, "A channel allocation method for IEEE 802.19.1 coexistence service to mitigate interferences among heterogeneous wireless networks," in *2015 Seventh International Conference on Ubiquitous and Future Networks*, 2015, pp. 778–783.

[151] Y. Zhang, L. Chen, K. Bian, L. Song, and X. Li, “Enabling symbiotic coexistence of heterogeneous cognitive radio networks,” in *2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2018, pp. 1–5.

[152] M. Song and M. Zheng, “Ecology-based coexistence scheme for heterogeneous cognitive radio networks over TV white space,” *IET Communications*, vol. 12, no. 5, pp. 620–626, 2018.

[153] D. Zhang, Q. Liu, L. Chen, and W. Xu, “Ecology-based coexistence mechanism in heterogeneous cognitive radio networks,” in *2015 IEEE Global Communications Conference (GLOBECOM)*, Dec 2015, pp. 1–6.

[154] K. Bian, J. J. Park, X. Du, and X. Li, “Ecology-inspired coexistence of heterogeneous wireless networks,” in *2013 IEEE Global Communications Conference (GLOBECOM)*, Dec 2013, pp. 4921–4926.

[155] W. Gao and A. Sahoo, “Performance study of a GAA-GAA coexistence scheme in the CBRS band,” in *2019 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2019, pp. 1–10.

[156] W. Gao and A. Sahoo, “Performance impact of coexistence groups in a GAA-GAA coexistence scheme in the CBRS band,” *IEEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 1, pp. 184–196, 2021.

[157] Ying, Xuhang and Buddhikot, Milind M. and Roy, Sumit, “Coexistence-aware dynamic channel allocation for 3.5 GHz shared spectrum systems,” in *2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2017, pp. 1–2.

[158] W. Gao, A. Sahoo, and E. Bradford, “GAA-GAA coexistence in the CBRS band: Performance evaluation of approach 3,” in *2020 IEEE 45th LCN Symposium on Emerging Topics in Networking (LCN Symposium)*, 2020, pp. 39–47.

[159] Ying, Xuhang and Buddhikot, Milind M. and Roy, Sumit, “SAS-assisted coexistence-aware dynamic channel assignment in CBRS band,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 9, pp. 6307–6320, 2018.

[160] B. Bahrak and J. J. Park, “Coexistence decision making for spectrum sharing among heterogeneous wireless systems,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1298–1307, March 2014.

[161] D. H. Ackley, G. E. Hinton, and T. J. Sejnowski, “A learning algorithm for boltzmann machines,” *Cognitive science*, vol. 9, no. 1, pp. 147–169, 1985.

[162] J. Wang, S. Filin, and H. Harada, “Proposal of decision-making algorithm,” *IEEE 802.19 Wireless Coexistence Working Group*, 2011.

[163] J. Junnel, M. Kasslin, and P. Ruuska, “A coexistence decision approach proposal,” *IEEE 802.19 Wireless Coexistence Working Group*, 2012.

[164] M. Ridley, “‘Evolution and the Theory of Games’ by John Maynard Smith (Book Review),” *The London Review of Books*, vol. 5, no. 13, p. 10, 1983.

[165] M. E. Morocho-Cayamcela, H. Lee, and W. Lim, “Machine learning for 5G/B5G mobile and wireless communications: Potential, limitations, and future directions,” *IEEE Access*, vol. 7, pp. 137 184–137 206, 2019.

[166] O. Omotere, L. Qian, R. Jantti, M. Pan, and Z. Han, “Big RF data assisted cognitive radio network coexistence in 3.5 GHz band,” in *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, 2017, pp. 1–8.

[167] F. Luo, *Machine Learning for Optimal Resource Allocation*, 2020, pp. 85–103.

[168] M. Ayadi, A. Ben Zineb, and S. Tabbane, “A UHF path loss model using learning machine for heterogeneous networks,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 7, pp. 3675–3683, 2017.

[169] S. P. Sotiroudis, S. K. Goudos, K. A. Gotsis, K. Siakavara, and J. N. Sahalos, “Application of a composite differential evolution algorithm in optimal neural

network design for propagation path-loss prediction in mobile communication systems," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 364–367, 2013.

[170] S. Paul, A. Mitra, and C. Koner, "A review on graph database and its representation," in *2019 International Conference on Recent Advances in Energy-efficient Computing and Communication (ICRAECC)*, 2019, pp. 1–5.

[171] J. Zhou, G. Cui, S. Hu, Z. Zhang, C. Yang, Z. Liu, L. Wang, C. Li, and M. Sun, "Graph neural networks: A review of methods and applications," *AI Open*, vol. 1, pp. 57–81, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2666651021000012

[172] Y. Gao, Z. Zhang, H. Lin, X. Zhao, S. Du, and C. Zou, "Hypergraph learning: Methods and practices," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, pp. 1–1, 2020.

[173] S. Bai, F. Zhang, and P. H. Torr, "Hypergraph convolution and hypergraph attention," *Pattern Recognition*, vol. 110, p. 107637, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0031320320304404

[174] F. Lehser, J. Ramiro, M. A. R. Caumel, K. Hamied, and S. Pedraza, "The self-organizing networks (SON) paradigm," in *Self-Organizing Networks:self-planning, self-optimization and self-healing for GSM, UMTS and LTE*, J. Ramiro and K. Hamied, Eds. Chichester: John Wiley I& Sons Ltd, 2011, ch. 2, pp. 35–37.

[175] E. A. Hamm, "Heavenly mathematics: The forgotten art of spherical trigonometry by glen van brummelen," *Aestimatio*, vol. 11, pp. 127–130, 2014.

[176] C. Bron and J. Kerbosch, "Algorithm 457: finding all cliques of an undirected graph," *Communications of the ACM*, vol. 16, no. 9, pp. 575–577, 1973.

[177] J. Wang, S. Filin, T. Baykas, M. A. Rahman, C. Song, and H. Harada, "A feasible neighbor discovery algorithm for coexistence control system over TVWS,"

in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2012, pp. 3244–3248.

[178] COGEU. (2013, Jan.) Demonstrations and validation of COGEU secondary spectrum trading platform. 001-COGEUD7316012013.pdf. [Online]. Available: https://cordis.europa.eu/project/id/248560/reporting

[179] COGEU. (2012, Jul.) COGEU demonstrator development and integration. 001-COGEUD72ICT248560.pdf. [Online]. Available: https://cordis.europa.eu/project/id/248560/reporting

[180] K. Ishizu, K. Hasegawa, K. Mizutani, H. Sawada, K. Yanagisawa, T. Keat-Beng, T. Matsumura, S. Sasaki, M. Asano, H. Murakami, and H. Harada, "Field experiment of long-distance broadband communications in TV white space using IEEE 802.22 and IEEE 802.11af," in *2014 International Symposium on Wireless Personal Multimedia Communications (WPMC)*, 2014, pp. 468–473.

[181] D. L. Johnson and C. Mikeka, "Bridging Africa's broadband divide," *IEEE Spectrum*, vol. 53, no. 9, pp. 42–56, 2016.

[182] O. Holland, "O white space, white space, whatfore art thou white space?" in *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, 2016, pp. 1–6.

[183] O. Holland, N. Sastry, S. Ping, R. Knopp, F. Kaltenberger, D. Nussbaum, J. Hallio, M. Jakobsson, J. Auranen, R. Ekman, J. Paavola, A. Kivinen, H. Tran, K. Ishizu, H. Harada, P. Chawdhry, J. Chareau, J. Bishop, M. Bavaro, E. Anguili, Y. Gao, R. Dionisio, P. Marques, H. Kokkinen, and O. Luukkonen, "A series of trials in the UK as part of the ofcom TV white spaces pilot," in *2014 1st International Workshop on Cognitive Cellular Systems (CCS)*, 2014, pp. 1–5.

[184] M. Brew, F. Darbari, C. McGuire, G. Bolton, S. Weiss, and R. W. Stewart, "A low cost and power efficient TV white space technology solution for future rural broadband access networks," in *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, 2011, pp. 1024–1028.

[185] M. Brew, F. Darbari, L. Crockett, M. Waddell, M. Fitch, S. Weiss, and R. Stewart, "UHF white space network for rural smart grid communications," in *2011 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2011, pp. 138–142.

[186] H. Kokkinen, "Chapter 2 - TV white space spectrum sharing using geolocation databases," in *TV White Space Communications and Networks*, ser. Woodhead Publishing Series in Electronic and Optical Materials, R. Stewart, D. Crawford, and A. Stirling, Eds. Woodhead Publishing, 2018, pp. 29–43. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780081006115000035

[187] Beck, Andrew. "Understanding the CBRS coexistence paradigm" jan. 7, 2021. [Online]. Available: https://www.rcrwireless.com/20210107/opinion/readerforum/understanding-the-cbrs-coexistence-paradigm-reader-forum

[188] ECC. (2011) ECC report 159: Technical and operational requirements for the possible operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz. [Online]. Available: https://www.ecodocdb.dk/download/be051b35-91e9/ECCREP159.PDF

[189] ETSI. (2014, Apr.) ETSI EN 301 598 V1.1.1 (2014-04) White Space Devices (WSD). en_301598v010101p.pdf. [Online]. Available: http://www.etsi.org/

[190] ECC. (2013) ECC report 186: Technical and operational requirements for the operation of white space devices under geo-location approach. [Online]. Available: https://www.ecodocdb.dk/download/124023a2-73ee/ECCREP186.PDF