SPECTRUM SHARING AND COEXISTENCE IN FUTURE WIRELESS NETWORKS

by
Shubhekshya Basnet

Dissertation submitted in fulfilment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

under the supervision of

Prof Eryk Dutkiewicz

School of Electrical and Data Engineering
University of Technology Sydney
Sydney, Australia

September 2019

ABSTRACT

With the spectrum resource in wireless networks becoming more congested, spectrum sharing is more crucial to meet the demands of future networks. With the increasing growth of mobile data traffic in the next-generation wireless communications system, capacity maximisation has been a central focus for government, academia and industry. Regulatory bodies have proposed different spectrum sharing techniques to solve the significantly increasing spectrum demand. There are two main spectrum sharing frameworks: Spectrum Access System (SAS) in the U.S. and Licensed Shared Access in Europe. Our work focuses on the SAS in the 3.5 GHz band. SAS is a three-tier spectrum sharing framework proposed by the Federal Communications Commission. The SAS three tiers are Incumbent Access, Priority Access Licensee (PAL) and General Authorised Access (GAA).

The optimal transmit power allocation problem is investigated for GAA users considering the transmission time fraction of GAA users in the SAS. To increase the capacity of GAA users, we consider the transmission time fraction of each GAA user for the transmit power and the channel allocation. Our proposed method finds the optimal channel switching schedule that maximises the average capacity of GAA users while satisfying the interference constraint at the PAL protection area and ensuring the fairness among GAA users.

We have proposed transmit power and channel allocation method that ensures conflict-free co-channel coexistence between PAL and GAA users as well as GAA users in different sets. We proposed the transmit power ad-

justment method using the information of the sets that can hear each other, which maximises the GAA users capacity. For a conflict-free resource allocation to the GAA users, a channel utilisation budget adjustment method is proposed considering GAA users in single and multiple sets.

Furthermore, mobile GAA users are considered in our study which adds an additional challenge to the resource allocation problem. We propose an interfering angle based method for the transmit power allocation for both fixed and mobile GAA users considering the interfering sets of users that are time-varying due to their mobility. Based on the information regarding the overlapping area, the maximum allowed transmit power is proposed for the interfering angle.

The coexistence among GAA users in SAS is a crucial problem to be solved to enhance the system capacity and to meet the increasing traffic demand. In summary, the resource allocation methods are presented in this thesis which contributes to interference protection and capacity maximisation in the Spectrum Access System.

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Shubhekshya Basnet declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical and Data Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Production Note:
Signature of Student: Signature removed prior to publication.

Date: 20/09/2019

ACKNOWLEDGMENTS

First and foremost, I would like to acknowledge that this work has been supported by University of Technology Sydney.

I would like to express my sincerest gratitude to my supervisor Prof. Eryk Dutkiewicz (University of Technology Sydney) who has been supporting me with the precious opportunities to learn, explore and improve. I would like to thank my co-supervisors Dr. Ying He (University of Technology Sydney) and Dr. Beeshanga Abewardana Jayawickrama (University of Technology Sydney) for their continuous support and guidance. I could not have imagined having a better supervisor and mentor for my Ph.D study.

I would like to thank my Masters by Research supervisor Dr. Upul Gunawardana (Western Sydney University) and Associate Professor Khoa Le (Western Sydney University) who led me to the road of research.

Last but not least, I would like to thank my mum Indira and my late father Chitra Bahadur Basnet, whose love and guidance are with me in whatever I pursue. This thesis is dedicated to my late father who has been my constant source of inspiration. Most importantly, I wish to thank my loving and supportive husband, Kiran KC, my son Ryan Chhetri, and my three wonderful siblings, Richa, Alina and Ajay who provide unending inspiration.

To My Parents

Chitra Bahadur Basnet and Indira Basnet.

Contents

List of Figures

List of Tables

List of Publications

Journal publications

- S. Basnet, Y. He, E. Dutkiewicz and B. A. Jayawickrama, "Resource Allocation in Moving and Fixed General Authorized Access Users in Spectrum Access System," *IEEE Access*, vol. 7, pp. 107863-107873, 2019. (Corresponding to Chapter 5)

Conference publications

- S. Basnet, B. A. Jayawickrama, Y. He, E. Dutkiewicz and M. D. Mueck, "Opportunistic Access to PAL Channel for Multi-RAT GAA Transmission in Spectrum Access System," *2017 IEEE 85th Vehicular Technology Conference (VTC Spring),* Sydney, NSW, 2017, pp. 1-5. (Corresponding to Chapter 3)

- S. Basnet, B. A. Jayawickrama, Y. He and E. Dutkiewicz, "Considering switching overhead for transmit power allocation for GAA in spectrum access system," *2017 17th International Symposium on Communications and Information Technologies (ISCIT)*, Cairns, QLD, 2017, pp. 1-5. (Corresponding to Chapter 3)

- S. Basnet, B. A. Jayawickrama, Y. He and E. Dutkiewicz, "Transmit Power Allocation for General Authorized Access in Spectrum Access System Using

Carrier Sensing Range," *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, Chicago, IL, USA, 2018, pp. 1-5. (Corresponding to Chapter 4)

- S. Basnet, B. A. Jayawickrama, Y. He and E. Dutkiewicz, "Fairness Aware Resource Allocation for Average Capacity Maximisation in General Authorized Access User," *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, Chicago, IL, USA, 2018, pp. 1-5. (Corresponding to Chapter 3)

Chapter 1

Introduction

With the increasing growth of mobile data traffic in the future wireless communication systems, securing optimal use of spectrum is a common challenge for all the regulatory bodies, operators and researchers. To satisfy this demand regulatory bodies have proposed different spectrum sharing techniques. In the spectrum sharing techniques, interference protection, resource allocation and fairness are crucial factors.

This chapter provides an overview of this thesis. Section 1.1 states the background of the thesis, including the increasing traffic requirements of the future wireless networks, and spectrum sharing solutions proposed. Section 1.2 presents the challenges and motivation behind the thesis work. Section 1.3 describes the main contributions of the thesis. Section 1.4 introduces the organisation of the thesis.

1.1 Background

Mobile data traffic has increased by around 17 fold over the past five years, with the estimated 71 percentage increase in 2022 [1]. Figure 1.1 shows the growth in global mobile data traffic based on the regions. Asia Pacific region has the growth rate of 86 percent.

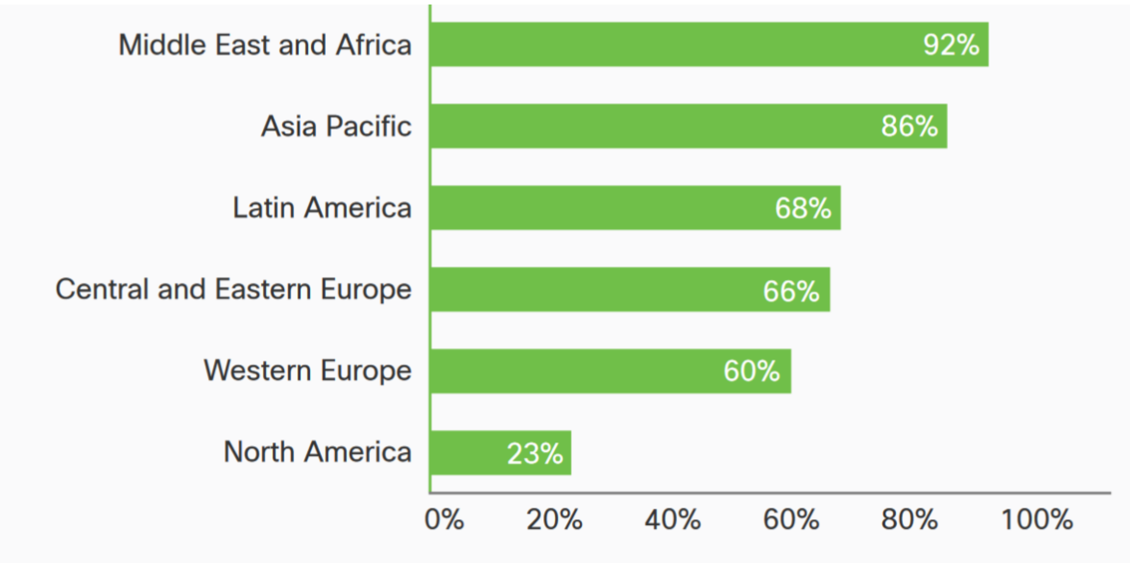


Figure 1.1: Global mobile data traffic growth [1]

1.1.1 5G and Future Wireless Networks Overview

The 5th generation (5G) mobile network aims to provide massive advancement in connectivity and mobile traffic capacity which will increase mobile broadband performance significantly by providing increased capacity, low latency, ultra high reliability [2, 3]. It is essential to build a future mobile network that will support the increasing demand for existing and new use cases. The future mobile network will also need to support more critical cases like drones and vehicles that have strict reliability and performance requirements [4].

International Telecommunications Union (ITU) has grouped the 5G services and application into three classes, which are enhanced mobile broadband, Massive Machine Type Communications and Ultra-reliable and low latency communications. 5G New Radio (NR) is a part of enhanced mobile broadband with low latency, high reliability and security.

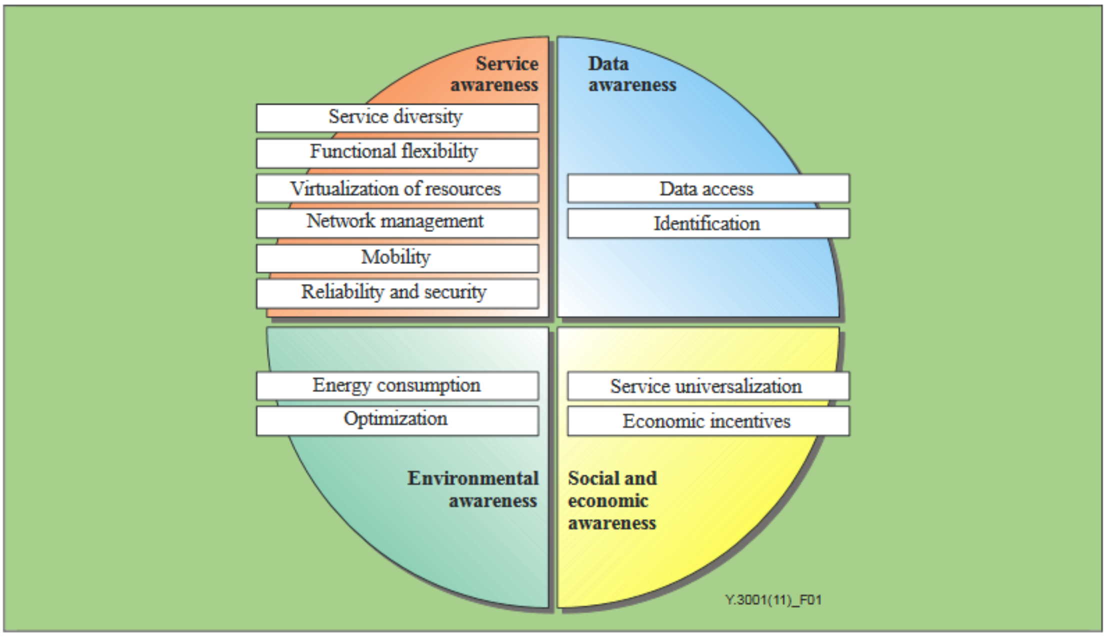


Figure 1.2: Future networks objectives and design goal [14]

Figure 1.2 shows the relationships between goals and objectives for the future wireless networks. According to ITU network management, mobility, identification, and reliability and security, may relate to multiple objectives. Future networks need to support a large number of mobile nodes with high speeds and large scale networks [14].

- Service Diversity

  Future networks need to support a large variety of new and existing technologies that require different latency, bandwidth, mobility, security and reliability.

- Virtualisation of resources

  Future networks need to support the cochannel coexistence of different users without interfering with each other.

- Mobility

  Future networks need to support a large number of mobile nodes with high speeds and large scale networks.

- Optimisation

  Future networks need to increase the performance to meet the increasing traffic demand by optimising the capacity of the network.

1.1.2 Spectrum Sharing

Spectrum sharing has been proposed for the efficient utilisation of spectrum in which priority users can share the spectrum when it is not in use at a particular location or time. The main focus of the spectrum sharing mechanism is to reduce interference while taking into consideration priority and fairness among different technologies. According to the Federal Communications Commission (FCC) and National Telecommunications and Information Administration (NTIA) the spectrum currently considered for sharing is the higher end of the radio spectrum starting from the TV white space (TVWS), Very High Frequency (VHF) and Ultra High Frequency (UHF) bands, to the 60 GHz unlicensed, the 70-80-90 GHz millimeter wave and Extremely High Frequency Band [5].

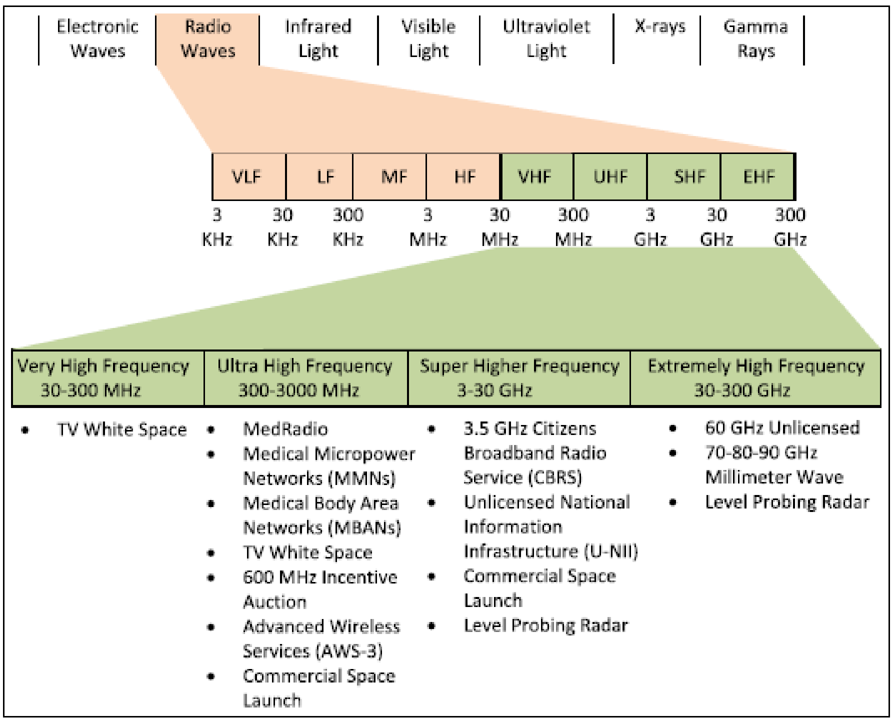


Figure 1.3: Radio frequency spectrum band [5]

Spectrum sharing provides an access to new spectrum to users where there is a higher need for spectrum usage and/or when the primary users are under-utilising it [6]. Spectrum sharing needs careful planning to coordinate the use of the same spectrum band by different tiers of users while protecting the higher tier users from harmful interference. Regulatory bodies in the US and Europe have proposed two different spectrum sharing frameworks to address future wireless networks spectrum needs, i.e. Licensed Shared Access (LSA) and Spectrum Access System (SAS) [7].

LSA is a framework proposed by European Telecommunication Standards Institute (ETSI) in Europe for the $2.3 - 3.4$ GHz band while SAS by Federal Communication Commission (FCC) is on the $3.55 - 3.7$ GHz band in the US. LSA is a two-tier sharing architecture between Incumbents and Licensees. Incumbent users are the prioritised users, and they provide prior information regarding the spectrum utilisation. There will be no co-channel interference between the two tiers as the licensees are allocated the channel when the incumbents are not utilising the channel. In LSA, if incumbents have to use the channel, tier 2 users need to vacate the spectrum band in required frequency, space and time. [11].

SAS is a three-tier spectrum sharing framework in which the highest priority users, i.e. federal users, receives the interference protection from Citizen Broadband Radio Service (CBRS) devices. Compared to LSA, in SAS prior information regarding the federal users spectrum usage is not known [12]. The CBRS consists of two tiers which are Priority Access Licensee (PAL) and General Authorized Access (GAA). GAA users need to opportunistically access 150 MHz frequency band. To increase the spectrum utilisation, PAL users are required to use or share the channel with the GAA users. In SAS, when there are multiple PAL users in a census tract using the same channel, GAA users interference should be below the threshold in the protection area of all PAL users. SAS framework provides increased spectrum utilisation by supporting the deployment of small cells with low power, which enables a smaller exclusion zone than a macrocell [13].

1.2 Challenge and Motivation

FCC has proposed the spectrum sharing framework in the US. In SAS, primary users are the naval shipborne and airborne radars, and secondary users are divided into PAL and GAA users. PAL users have a higher priority over the channel than the GAA users, and PAL users need to use the channel or share the channel while satisfying the PAL users interference protection criteria. Furthermore, in SAS priority users spectrum usage is not known as in the LSA. Therefore the interference mitigation between PAL and GAA users in SAS is more challenging.

Motivated by the spectrum sharing framework proposed in the US and Europe, i.e., SAS and LSA, we would like to enable spectrum sharing between GAA users and PAL users in an underlay mode while protecting PAL users from harmful interference. The major goals in this thesis are listed below:

- Interference protection of incumbents while maximising the capacity of increasing new services is an important issue.

  Resource allocation is an essential factor in SAS with three tiers of users. From the literature, we can see that there is still a lot of work to be done especially for the underlay mode. In SAS, the channel usage of priority access users is not known as in the LSA system. In addition, GAA users can access the PAL channel when it is not used by priority users or can access the channel at the same time while ensuring the interference received in the protection area is below the FCC proposed interference threshold.

- Fairness is a critical problem that emerges from the capacity maximisation schemes for resource allocation.

  In capacity maximisation schemes for resource allocation, the users which contribute to more capacity are given the transmission opportunity, which results in the fairness issue, i.e. some users get more transmission opportunity than others. With an increasing number of new services, fairness is an important issue that needs to be addressed.

- With the dense deployment of small cells, GAA users that are hidden from each other needs to be further studied to ensure the interference protection criteria are satisfied.

GAA users are hidden if they cannot hear each other, but the user equipments in the overlapped area interfere. We have defined the hidden problem in section 5.3. Small cells deployment is predicted to be increasing rapidly in the coming years. From the dense deployment of new services arises the hidden node issue, which results in the interference to user equipments in the overlapped area, but also may cause interference protection violation in the PAL users protection area.

- In most of the resource allocation works in the literature, static networks are assumed. With the deployment of the small cells in vehicles, it is essential to study the joint resource allocation for static and mobile users.

  It is important to investigate the impact of nodes mobility on the performance of the resource allocation. The static users located near the path will be interfered by the mobile users, and the set of users that can interfere with each other is time-dependent.

In summary, different resource allocation schemes are considered for SAS, i.e., transmit power allocation, channel allocation and transmission time fraction allocation for GAA users.

1.3 Contributions

Efficient resource allocation approaches are essential for the better usage of the limited spectrum to meet the increasing spectrum demand and to protect the primary users (PUs) from harmful interference. Resource allocation process could be the allocation of transmit power, transmit time, channel assignment using the surrounding radio environment information. The main contributions of this thesis are given as follows:

Chapter 3:

- To the best of our knowledge, for the first time, the optimal transmit power allocation problem is investigated for GAA users considering the transmission time fraction of GAA users in the SAS system.

We solve the problem of optimal transmission time fraction and transmit power allocation for GAA users such that the sum capacity of the GAA network is maximised. Multiple GAA users and a single PAL channel are considered. Our approach considers the average aggregated interference from GAA users to the PAL users, to protect the PAL user from harmful interference.

This work has been published as a conference paper "Opportunistic Access to PAL Channel for Multi-RAT GAA Transmission in Spectrum Access System".

• We propose a method that finds the channel switching schedules for GAA users to maximise the average capacity of GAA user considering the switching overhead and the interference threshold to PAL users.

We propose the method to calculate the switching overhead for the SAS. In this section, we consider multiple GAA users and multiple PAL channels. Switching overhead reduces the network performance and in our work, we propose a method to allocate a channel to GAA users based on the transmission time fraction. Our proposed method ensures the interference protection from the GAA users to all PAL users allocated to the same channel with the GAA users.

This work has been published as a conference paper "Considering switching overhead for transmit power allocation for GAA in spectrum access system".

• We propose a fair coexistence method for the set of GAA users that can hear each other.

To the best of our knowledge for the first time, fairness is considered for GAA users in the SAS, which is a critical issue to be solved in a dense area to meet the increasing traffic demand. To achieve the fair coexistence between GAA users that can hear each other, we find the transmission time fraction threshold for GAA users based on the number of GAA users in the set, and the number of sets a GAA user belongs to which have not been considered in previous works.

This work has been published as a conference paper “Fairness Aware Resource Allocation for Average Capacity Maximisation in General Authorized Access User”.

Chapter 4:

• Interference aware resource allocation method is proposed for GAA users in a PAL channel considering the GAA users that belong to a single set or multiple sets.

In this work, we propose a new resource allocation method for GAA users considering not only the coexistence between PAL and GAA users but also the coexistence between GAA users. Transmit power and channel allocation is done for GAA users in a more realistic scenario where the number of channels is less than the number of GAA users using the information of the set that can hear each other. Channel utilisation budget is allocated to GAA users that belong to a single set or multiple sets to provide a transmission opportunity to all GAA users. Our proposed method allocates multiple GAA users to the same PAL channel while satisfying the FCC proposed channel allocation rules.

• Transmit power adjustment method is proposed to improve the average sum capacity of GAA users.

In a set of GAA users that can hear each other, we propose a method to adjust the interference budget of transmitting GAA users utilising the interference budget of GAA users that can hear each other.

• A method is proposed to calculate the Root Mean Square interference at the PAL protection area.

We propose a method to calculate the Root Mean Square (RMS) interference at the PAL protection area by finding the nearest point in the PAL protection area from the transmitting GAA users. Our proposed method satisfies the interference protection from all the transmitting GAA users at all the nearest points in the PAL protection area. The simulation result shows that the average sum capacity of GAA users can be maximised from our proposed method while protecting PAL users from harmful interference.

This work has been published as a conference paper "Transmit Power Allocation for General Authorized Access in Spectrum Access System using Carrier Sensing Range", and submitted as a journal paper "Interference Aware Resource Allocation Scheme for General Authorised Access User".

Chapter 5:

• We propose a joint channel and transmit power allocation to both Fixed General Authorised Access (FGAA) and Mobile General Authorised Access (MGAA) users considering the set of GAA users that are changing continually with the mobility of MGAA users.

Resource allocation is done jointly for the mobile and fixed GAA users, taking into account the consideration of the interference caused by the MGAA users to the FGAA users. We consider multiple PAL channels with multiple PAL, FGAA and MGAA users. We predict the set of FGAA users and MGAA users that can interfere with each other based on their mobility pattern.

• We propose a method to find the maximum allowed transmit power in an overlapping area for FGAA users.

To maximise the GAA network capacity while satisfying the coexistence constraint to a PAL user, we propose a conflict-free channel allocation constraint, i.e. the maximum allowed transmit power to the beams of the FGAA users that are within the carrier sensing range of the MGAA users.

• Conflict-free resource allocation algorithm is proposed, which considers not only interference protection to PAL users but also interference between GAA users.

In this work, we propose the interference angle based resource allocation method to allocate both MGAA and FGAA users with overlapping areas to the same channel at the same time. To ensure the self coexistence between GAA users, our proposed method considers interference between FGAA users, interference between FGAA user and MGAA user, and interference between MGAA users.

This work has been published as a journal paper "Resource allocation to Fixed and Mobile GAA users in the Spectrum Access System".

1.4 Organisation of the Thesis

In this chapter, the background of the thesis is discussed. The remainder of the thesis is arranged as follows:

Chapter 2 introduces the cognitive radio in section 2.1 and spectrum sharing framework in section 2.2. We provide a brief introduction on SAS and LSA. In chapter 2, we do a comprehensive review of related work in literature and differentiate our work from other relevant work. Each chapter has the relevant works part and compares the proposed method with the related works.

In Chapter 3, we investigate the transmit power and transmission time fraction allocation for GAA users considering single and multiple PAL channels. In section 3.1, we present the introduction followed by the system model in section 3.2. In section 3.3, we jointly allocate the transmit power and transmission time fraction for GAA users such that the sum capacity of the GAA network is maximised while ensuring the average aggregate interference from GAA users is below the interference threshold. In section 3.4, we define switching overhead and use it to obtain the maximum transmit power and transmission time fraction under the constraint of RMS interference. We propose a method to ensure GAA users fairness and the average capacity maximisation is achieved while satisfying the RMS interference constraint to the PAL users in section 3.5.

In Chapter 4, we present the interfering set based resource allocation, i.e. channel, transmit power and channel utilisation budget allocation to maximise the average sum capacity of GAA users. The introduction to the problem is presented in section 4.1, and in section 4.2 the system model for the interference aware resource allocation problem is introduced. In section 4.3, a problem for resource allocation considering sets of GAA users that can hear each other is formulated with the transmit power and transmission time fraction adjustment. Numerical results of the set-based resource allocation scheme are presented in section 4.4.

In Chapter 5, we propose an interfering angle based method for the joint resource, i.e. channel and transmit power allocation to the mobile and fixed GAA users considering different types of conflicts. The introduction to the problem is presented in section 5.1. System model considering the mobile GAA users is presented in section 5.2. We propose the interference angle based maximum transmit power to GAA users with overlapped coverage area and formulate the conflict-free resource allocation to fixed and mobile GAA users in section 5.3. In section 5.4, simulation results of the proposed interfering angle based method for GAA users resource allocation are presented.

Chapter 6 provides a summary of the thesis as well as discussions regarding the direction for future work.

1.5 Summary

In this chapter, we presented the background on the spectrum sharing frameworks and resource allocation schemes and discussion regarding the challenges and motivation. We summarised the contributions and organisation of this thesis in this chapter.

Chapter 2

Literature Review

In Chapter 1, we discussed the increasing spectrum demand for the new and existing services and the underutilisation of licensed user owned spectrum as the key factors to motivate the main contributions of this thesis. With the focus on these factors, we present a comprehensive literature review of the relevant works for spectrum sharing and coexistence in future wireless networks.

Section 2.1 gives an overview of spectrum sharing. In section 2.2, we review the cognitive radio. In section 2.3, we discuss spectrum sharing frameworks proposed by regulatory bodies in the US and Europe, i.e. Spectrum Access System and License Shared Access. Section 2.4 provides a general review of the vehicular communication system. Finally, we summarise the importance of spectrum sharing and coexistence in future wireless networks.

2.1 Spectrum Sharing

Spectrum sharing is an important approach that has been considered to meet the increasing spectrum demand for an increasing number of existing and new services. There are two main spectrum sharing approaches, i.e. opportunistic spectrum access and geolocation-based spectrum access [15]. In opportunistic spectrum access, the secondary user (SU) senses the spectrum band owned by the primary user (PU) and accesses the channel when it is idle [16–18]. PUs are licensed users, and SUs are unlicensed users. SUs need to sense the channel before transmission and vacate the channel when PU starts to transmit in the same channel. SUs also need to reconfigure the software and hardware parameter according to the sensing result [19]. In the geolocation-based spectrum access method, PUs need to inform the database of the spectrum usage information in space, frequency and time, and by utilising this information SUs are allocated the transmission opportunity without causing harmful interference to PUs. In the geolocation-based spectrum access method correct information regarding the spectrum availability is provided to SUs; however the complexity is high in scenarios with large numbers of users and when SUs need to detect the spectrum opportunities in real time [20]. Transmission opportunity for the SUs could be in frequency, space, time and angle [21] as shown in Table 2.1.

Dimensions	Summary
Frequency	Transmission opportunity in frequency is the part of the frequency band available for the opportunistic usage.
Time	PUs do not always utilise the spectrum band, allowing SUs the chance to use the portion of the time.
Space	Spectrum could be available in some geographical area but in use in other parts at a particular time.
Angle	Utilising the location information of PUs, the direction of PUs can be determined, and SUs can transmit in other direction of the PU beam without causing harmful interference to PUs.

Table 2.1: Transmission Opportunity in Different Dimensions

SUs need to ensure that PUs are protected from harmful interference, and the most essential requirement of the spectrum sharing approaches are:

- Determine the transmission opportunity in a PUs spectrum band.
- Ensure the PUs interference protection criteria are satisfied.
- Increase the spectrum utilisation of the underutilised spectrum band.

2.1.1 Primary Users Detection Techniques

To utilise the PUs spectrum band SUs need to detect the PUs activity pattern, and leading approaches used to identify the PUs spectrum availability are by spectrum sensing and utilising the geolocation-based database [19].

Spectrum sensing is the most challenging issue in spectrum sharing, and is used to obtain the spectrum usage information of neighbouring users. In the sensing-based spectrum sharing method SUs sense the spectrum band owned by the PUs, and based on the sensing result, the transmit powers of SUs are adjusted. If PU is sensed idle SUs can adjust the transmit power to achieve higher capacity, and when PU is sensed active SUs transmit power needs to be changed to protect the PUs from harmful interference. In opportunistic spectrum access, SUs can access the channel only when PUs are idle [22]. Spectrum sensing is used for

- Spectrum opportunity identification
- Interference protection

Spectrum sensing approaches used are energy detection, cyclostationary detection and match filter detection [21]. Energy detection is the most commonly used spectrum sensing approach. In this method, the unlicensed user calculates the energy of a received signal and compares it to the received signal threshold based on which it decides the presence or absence of a licensed user [21, 23].

Sensing information could be sometimes inaccurate due to missed detection and false alarm. Missed detection occurs when the unlicensed users do not detect licensed users when they are active, which results in interference to the licensed user. A false alarm occurs when the unlicensed user detects the primary user when they are idle, and this results in underutilisation of the spectrum.

Geolocation database is the technique used for protecting the primary users from harmful interference. Geolocation database keeps the record of spectrum usage at certain space, frequency and time, and also the transmission characteristics of users to ensure the regulatory requirements are satisfied [21].

2.1.2 Interference Mitigation Techniques

Frequency reuse is used to accommodate the growing number of new services in the limited spectrum bands. Interference mitigation is an important issue to be addressed to meet the increasing demand. The most common sources of interference are:

- Interference from SU to PU.
- Interference from PU to SU.
- Interference among SUs.

To protect PUs from harmful interference, in one approach the SUs opportunistically access the vacant spectrum band in a certain time, frequency and space. In the other approach, multiple SUs access the same spectrum while satisfying the interference threshold of the PUs [24]. Different interference mitigation schemes proposed in the literature are transmit power control schemes, channel allocation schemes and time allocation schemes [25] as shown in Table 2.2.

Transmit power control of SU can be used to mitigate the interference to PUs. In [26], transmit power allocation algorithm is presented for cognitive wireless networks, where primary and secondary users transmit at the same channel at the same time under the constraint of interference from secondary users to primary users and the QoS of secondary users. Joint channel and power allocation method is proposed in [27], where PUs and SUs can access the same channel at the same time under the constraint of the interference threshold to PU and Quality of Service (QoS) of SUs. In [28], time allocation method is proposed to maximise the throughput of the

SUs under the constraint of PUs throughput requirement. In [30, 31], zero-forcing beamforming is used to protect the PU from the harmful interference. In section 3.3, the joint transmit power and transmission time fraction allocation for maximising the GAA users capacity under the root mean square interference constraints in GAA users are discussed.

Interference Mitigation Techniques	Description
Transmit Power Control	Transmit power control technique is used to ensure that interference from transmitting users is less than the threshold.
Channel Allocation	Channel allocation techniques are used to ensure that the conflicting users are allocated a separate channel to reduce the interference.
Time Allocation	Transmission time allocation techniques are used to allocate the transmission time to reduce the interference to the victim user.
Beamforming	Aligning the direction of the beams to avoid the interference.

Table 2.2: Summary of Interference Mitigation Techniques

2.1.3 Fairness

Fairness is a critical issue that needs to be addressed on the throughput maximisation problems. In throughput maximisation problems, an unfairness issue occurs as some users are allocated more resources and some less/nill. Most commonly used qualitative fairness methods are the proportional fairness and the max-min fairness, and the quantitative fairness methods are Jain Fairness Index and entropy [29].

In the set of users that can hear each other, fairness needs to be considered to provide a fair transmission opportunity to all users in that set, and this is discussed in section 3.5.

2.2 Cognitive Radio

J. Mitola introduced the cognitive radio in 1998 to enhance the flexible use of the spectrum [32]. Cognitive radio (CR) is a leading technology for dynamic spectrum access. CR technology aims to utilise the underutilised spectrum of the primary users who are licensed users by adjusting the transmission parameters. CR users sense the channel to find availability and select the best available channel to maximise the network performance. CR users need to protect primary users from harmful interference.

Resource allocation schemes in CR can be differentiated into a centralised and distributed approach. In the centralised approach, the central entity is responsible for allocating channels to SU taking into consideration the policy and the channel state information [33, 34]. By contrast, in the distributed approach, SU decides to utilise the channel or not based on the information received from the neighbouring users [35, 36]. The centralised approach is more efficient, but it requires a large amount of information exchange. However, with the increase in new services, there is a massive increase in network overhead.

In CR resource allocation schemes, the method to share the spectrum between PUs and SUs is divided into three categories, which are underlay access method, overlay access method and interweave access method [29, 37, 38].

- Overlay mode: In this mode, CR users can access the spectrum when it is not utilised by licensed users. So in the overlay mode sensing is required as CR users need to find the spectrum holes in time and space to use the spectrum. When the licensed user starts transmission, CR users need to vacate the channel.

- Underlay mode: CR users can access the channel when the interference received by primary users is less than a certain interference threshold. Both licensed and CR users can coexist in the same channel provided the primary users received interference is less than the threshold. The PU has the priority over the SU. In the underlay paradigm, interference from SUs to PUs depends upon the transmit power, spectrum sensing results, spectrum allocation as well as transmission time.

- Interweave mode: Interweave access mode is similar to the overlay access mode. In the interweave access mode, the users utilising the frequency band at that time are considered PU and the users arriving for transmission are considered as SU [37].

CR users access the channel opportunistically by sensing, hence CR users can cause harmful interference to the licensed users. Protecting the PUs from the interference of CR users is very crucial. Resource allocation for CR users is a well-investigated topic in the literature with the primary focus to increase network performance and protecting the PUs utilising two main approaches, i.e. centralised approach and distributed approach. The centralised approach is the method in which there is a central entity that collects the radio environment information and sends the data to CR users for the channel usage decision [39, 40]. In a distributed approach, CR users sense the channel and communicate with only neighbouring users to make the channel usage decision [41–43].

Previous studies on resource allocation in cognitive radio networks (CRN) are related to this study. In SAS, GAA users are like SUs in the cognitive radio network who can access the priority user assigned channels in such a way that they do not cause harmful interference to priority users. In CRN to maximise the spectrum utilisation the efficient utilisation methods of the underutilised spectrum is proposed. In [37], resource allocation problem is divided into two main sub-problems, i.e., soectrum allocation and determining the transmission parameters. Figure 2.1 shows the main two sub-problems of resource allocation and challenges that should be considered.

Resource allocation for CR users is done with the objectives or constraints of throughput, interference, fairness and quality of service. The resource allocation schemes proposed in literature utilise radio knowledge of the neighbouring users to output bands assignment, user assignment, beamforming matrix, rate allocation, power allocation and network specific variables. Throughput maximisation for cognitive radio network has been studied with constraints of the maximum allowed

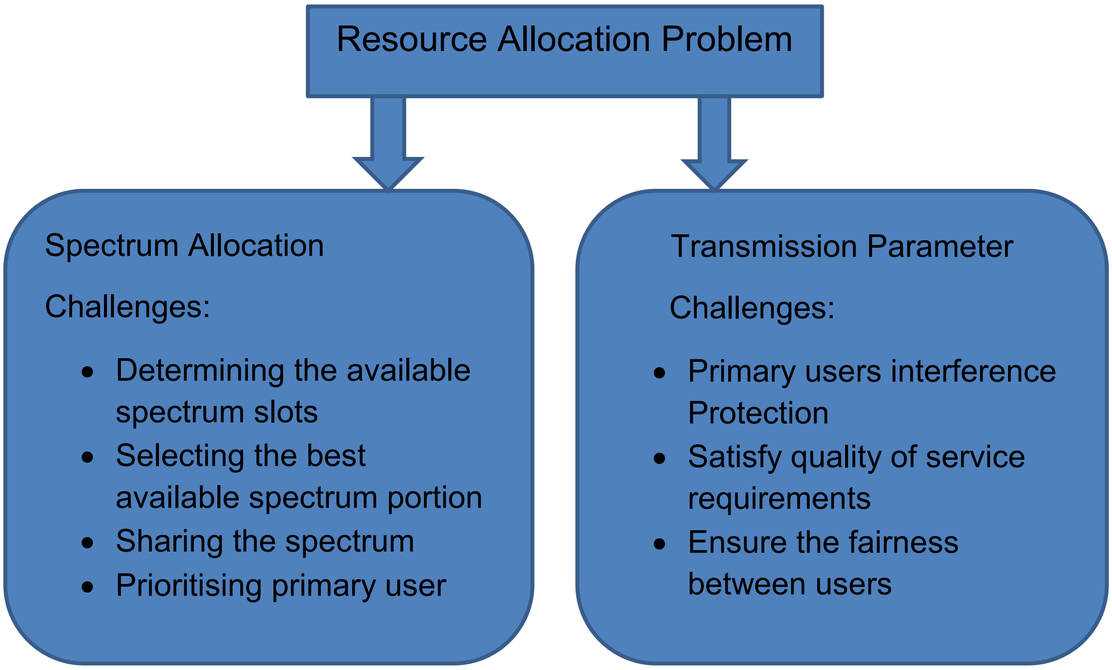


Figure 2.1: Sub-problems for the resource allocation problem and challenges

transmit power, quality of service, signal to interference plus noise ratio and interference to primary users [42, 44–46].

Interference protection of the primary user is an essential criterion for the CR users resource allocation in underlay mode. Primary users are protected from CR users harmful interference by utilising transmit power control of CR users and transmit beamforming techniques [47–50]. Interference constraints are included in resource allocation schemes as instantaneous interference from CR users at each time instant or aggregate interference from a CR users for a certain time period. Most research work focuses only on interference to primary users. Interference between CR users degrades network performance, hence more research needs to be done considering interference between CR users.

Fairness is a critical issue that arises with throughput maximisation schemes for resource allocation, due to some users not allocated any transmission time or channel. To address this max-min fairness and proportional fairness schemes have been considered. With the dense deployment of small cells, more research work needs to be done to achieve fairness between the users.

With the increasing growth of mobile data traffic, spectrum scarcity is a crucial issue to be solved in the next generation wireless communication network. Although resource allocation is studied immensely for CR users, more research work is still needed for users considering the underlay mode. Therefore the resource allocation needs to be studied further considering interference between different tiers of users using the same channel at the same time.

2.3 Spectrum Sharing Frameworks

Spectrum demand is increasing significantly with an increasing number of new services and shared spectrum access will play a vital role to solve the growing spectrum requests. Spectrum sharing happens when multiple users access the same channel taking into account multiple dimensions, i.e. frequency, time and location.

Regulatory bodies have proposed regulations that allow different tiers of users to access the same spectrum band without causing interference. Incumbent users protection can be guaranteed utilising the conditions of transmission power, exclusion zones, guard bands, locations and time.

2.3.1 Licensed Shared Access

Licensed Shared Access (LSA) is a spectrum sharing framework proposed by European telecommunication standards Institute (ETSI) in Europe in which 3GPP LTE network is operated on a licensed shared basis in the 2.3-2.4 GHz frequency band. LTE Mobile Network Operators (MNOs) will be sharing the spectrum with incumbents such as military, professional video cameras and others with a sharing contract of 10 years or more [7, 8]. LSA is a two tier system with the incumbent users having higher priority to the spectrum than the licensee. Licensee needs to vacate the spectrum when it is needed to be used by incumbent users.

Figure 2.2 shows the LSA system architecture. In the LSA system management of spectrum is done by a centralized database called LSA Repository. Incumbent users need to provide a priori information regarding their usage of LSA spectrum over the space and time. Based on the information provided by the incumbents to

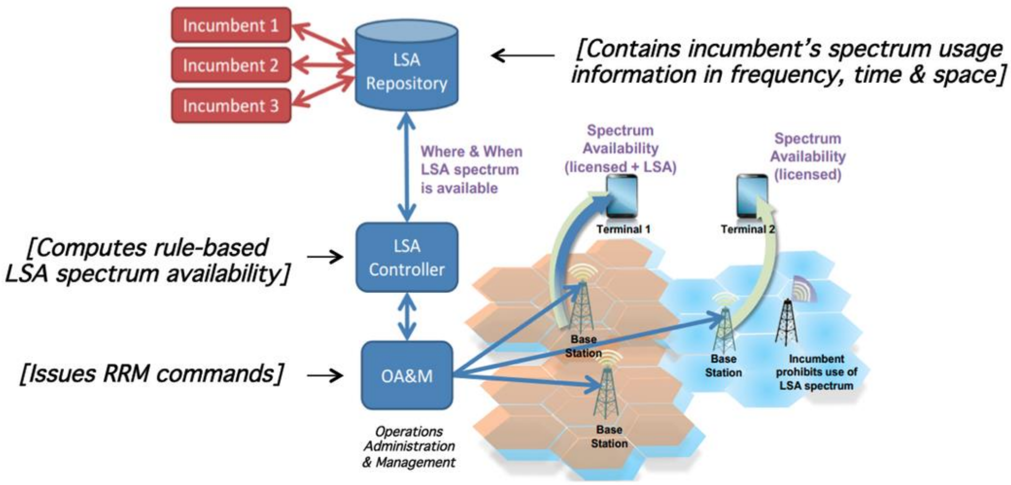


Figure 2.2: LSA architecture

the centralised database, the LSA controller controls the active and inactive period for the licensee. LSA Repository is located outside the MNO whereas LSA controller is a part of MNO [7, 8]. The MNO can only access the spectrum after it is granted access by the LSA controller, to ensure MNO does not interfere with incumbent users.

In this spectrum sharing framework either incumbents or licensees can access the frequency band at a particular location at a particular time. Two dimensions of spectrum sharing in LSA between Incumbents and LSA licensees are to share the same band at the same location in a different time period, and to share at the same time in a different geographical area. There is a location area limitation for LSA licensee which are [8]:

- Exclusion zone where a LSA licensee is not allowed to transmit.
- Restriction zone where under some restrictive conditions a LSA licensee can transmit.
- Protection zone in which incumbent receivers will not be subject to interference from a LSA licensee.

2.3.2 Spectrum Access System

Spectrum Access System (SAS) is a three tier system proposed by Federal Communications Commission (FCC) for spectrum sharing between federal and non-federal users in the frequency band 3550 to 3700 MHz as shown in Figure 2.3. The 3.5 GHz band segment was allocated for use by Department of Defense (DoD) radar systems. The National Telecommunications and Information Administration (NTIA) first proposed making the band available for shared use in its 2010 Fast Track Report. On March 24, 2015, NTIA filed a letter recommending a framework that would reduce the geographic area of the exclusion zones by approximately 77 percent. NTIAs letter also recommended the use of sensor technology to permit commercial use inside the exclusion zones, providing a roadmap to full nationwide commercial use of the band [9, 10].

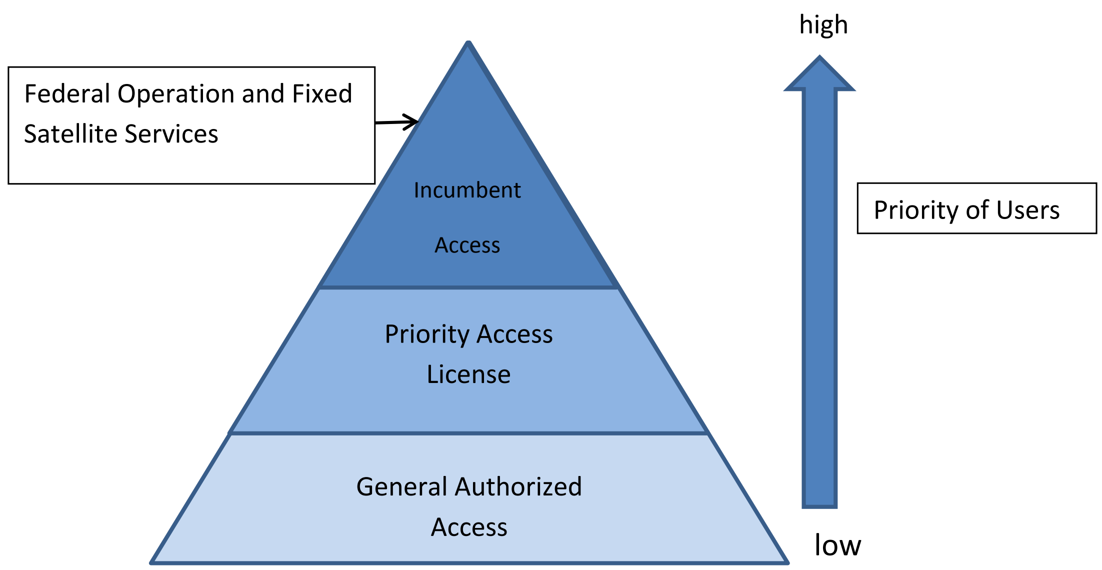


Figure 2.3: Three tier access in the 3.5 GHz band

The FCC released a Notice of Proposed Rulemaking (NPRM) in December 2012 proposing to make an additional 150 MHz for Spectrum Access System (SAS). SAS is a three-tier spectrum sharing framework recommended for use in the 3550 MHz to 3700 MHz frequency band. The three tiers are Incumbent Access (IA), Priority Access Licensee (PAL) and General authorised Access (GAA). The highest tier users are IA users, which includes federal shipborne and ground-based radar operations, Fixed Satellite Service (FSS) earth stations and grandfathered terrestrial wireless operations. NPRM proposed to create citizen broadband radio service devices (CB-SDs) for the 3.5 GHz band. CBSDs are the fixed base stations that operate on PAL and GAA basis under the authority of SAS. CBSD must register and receive authorisation from SAS before its initial service transmission. SAS is designed to ensure the coexistence of PAL and GAA users with federal users who do not provide prior information to the central database [7].

Figure 2.4 shows the SAS architecture. SAS can be operated throughout the US territory except within exclusion or protection zones close to U.S. coastal areas where military services operate. Environmental Sensing Capability (ESC) is a component in SAS architecture which performs the sensing task of military incumbents [9, 10]. Spectrum access for CBSDs depends on these sensing results. ESC can be a network of sensors, and it is a third party stand between federal users and SAS. ESC must follow the rules strictly and must have corresponding certifications to protect the confidentiality of military incumbents. If the federal system is detected by ESC, it notifies SAS and SAS must suspend or move CBSD to an unoccupied channel within 300 seconds.

IA user receives interference protection from all Citizen Broadband Radio Service (CBRS) users. CBRS consists of PAL and GAA users and both are assigned frequency resources at a given locations by SAS . The proposed CBRS is an important technology to support the increase in spectrum demand by allowing opportunistic GAA users to use the spectrum when and where it is not utilised by PAL users [9,10]. In SAS system, a PAL user receives interference protection from GAA users and a GAA user receives no protection from Incumbent Access (IA) and PAL users [9, 10].

Figure 2.5 shows the graphical representation of frequency arrangement for 3.5 GHz band. In [7]:
"A PAL is defined as a non-renewable authorization to use a 10 *megahertz channel in a single census tract for three years."* . PAL users need to vacate the spectrum when IA user needs to use it. PAL users will be assigned 70 MHz of 3.5 GHz band by competitive bidding and GAA users will be allowed throughout the 150 MHz

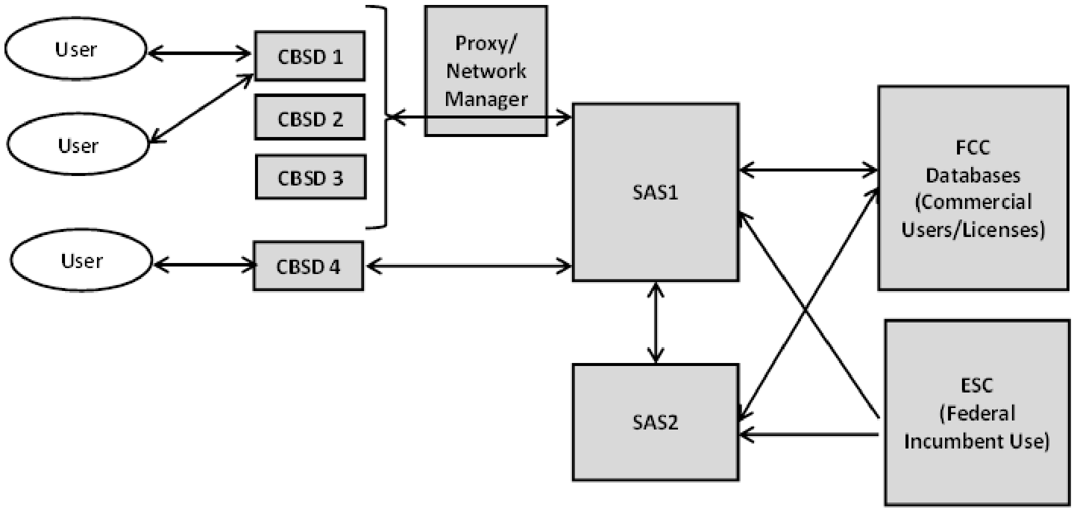


Figure 2.4: SAS architecture [7]

band. Each PAL channel is of 10 MHz bandwidth. GAA users can use spectrum opportunistically throughout 150 MHz. PAL and GAA users are authorised by SAS for a finite census tract. A census tract is defined as the minimum geographical area which can be auctioned or used for each 10 MHz band [7].

According to the FCC document [10], CBSDs must comply with the planned exclusion zones to ensure fair coexistence with incumbent users. The SAS must ensure CBSDs do not operate in exclusion zones and immediately suspend the transmission of other CBSDs causing harmful interference to incumbent users [10].

To protect the IA users CBSD must report their location coordinates of each of their antennas to within ±50 meters horizontal and ±3 meters vertical and other details to SAS. SAS then alocates the frequency channel to PAL and GAA users,

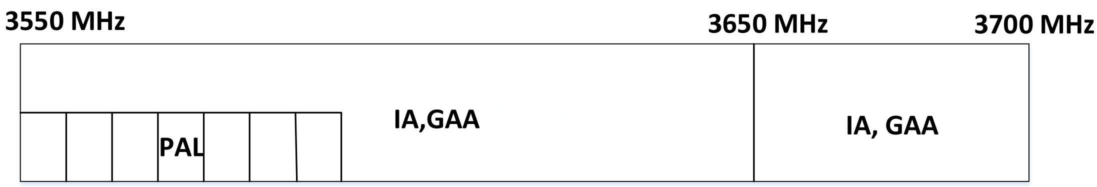


Figure 2.5: 3.5 GHz band plan

and to perform interference mitigation between tiers SAS can limit the maximum transmit power of CBSDs. FCC defines two categories of CBSDs based on maximum conducted power and deployment conditions. Category A is limited to maximum conducted transmit power of 24 dBm and a maximum EIRP of 30 dBm in 10 MHz. Category B CBSDs will be authorized to operate at higher power than Category A and maximum EIRP of 47 dBm in 10 MHz [9, 10]. Category B CBSDs will only be authorised in 3550-3650 MHz portion of the band after ESC is approved and operational [9, 10].

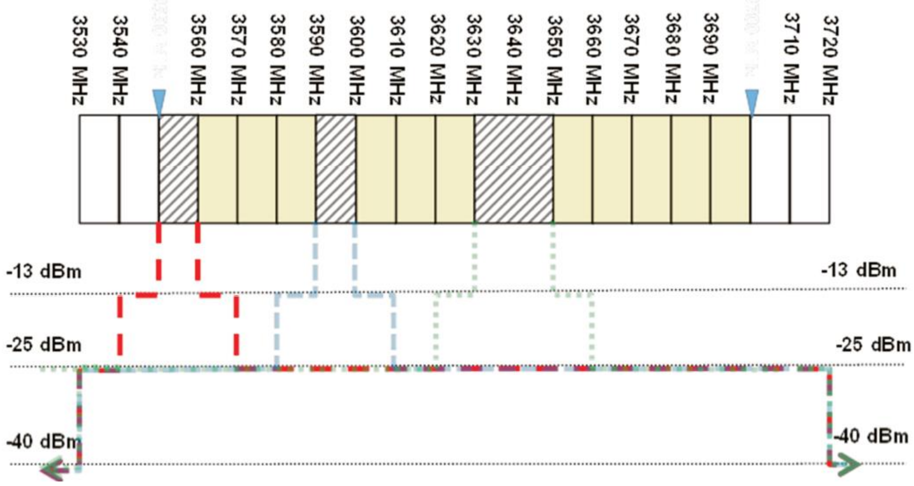


Figure 2.6: Emissions and interference limits [10]

Figure 2.6 shows the emissions and interference limits adopted by SAS to promote the coexistence of different users where Out Of Band (OOB) emissions are:

- -13 dBm/MHz from 0 to 10 MHz from the SAS assigned channel edge.
- -25 dBm/MHz beyond 10 MHz from the SAS assigned channel edge down to 3530 MHz and upto 3720 MHz.
- -40 dBm/MHz below 3530 MHz and above 3720 MHz.

To protect the authorised CBSDs for transmission in a SAS assigned channel, SAS must not allow other CBSDs in the same location at the maximum power level that will cause aggregate interference above the threshold. PAL protection criteria as defined in [10] are:

"To ensure that Priority Access operations are protected from harmful interference, an aggregate received signal level at PAL license boundaries to be at or below an average (rms) power level of -80 *dBm when integrated over a* 10 *MHz reference bandwidth with the measurement antenna placed at a height of* 1.5 *meters above ground level."*

SAS has adopted two different approaches to find out the channel assigned to PAL users in use. Firstly, PAL users must report their PAL protection area (PA) to SAS depending upon their network deployment. Secondly, to determine the maximum PAL PA, SAS uses default protection contour around CBSDs of -96 dBm/10 MHz. To increase the spectrum availability a PAL PA must be less than the default value [10].

The main function of SAS are [9, 10]:

- Determine the available frequencies at a given geographical location and assign them to CBSDs.
- Determine maximum allowed transmission power of CBSDs at a given location and communicate that information to CBSDs.
- Register and authenticate the identification information and locations of CBSDs.
- Enfore Exclusion Zones to ensure compatibility between CBSDs and IA users.
- Protect PAL users from harmful interference from GAA users.
- Ensure secure transmission of information between SAS, ESC and CBSDs.
- Communicate with ESC and ensure that CBSDs access the spectrum without causing interference to IA users.
- Facilitate the coordination between GAA users to promote a stable spectral environment.

To maximise the spectrum utilisation GAA users outside the PAL PA are allowed transmission in the PAL channel. However, careful implementation of the resource management scheme is required for the significant improvement in spectrum usage and for interference mitigation.

In SAS, PAL users are the priority users and GAA users opportunistically access the PAL channel. Hence, when the PAL users start the transmission GAA users need to stop the transmission and switch to the different available frequency. SAS does not have the PAL users spectrum usage information and switching overhead is necessary to be considered. This will be further discussed in section 3.4.

The main differences between LSA and SAS are listed below:

- LSA is a two-tier spectrum sharing framework, however, the SAS is a three tier spectrum sharing framework.
- In SAS, licensed users do not provide the prior information regarding spectrum usage to a central database; however in LSA, incumbent users spectrum usage information is known.

In our work, we consider the co-channel interference as the primary source of average aggregate interference to PAL users, as there can be multiple PAL and GAA users transmitting on the same channel in a census tract. The interference from GAA users to PAL users protection area can be controlled by controlling the transmit power such that interference is below the FCC proposed interference threshold or with careful channel allocation.

The resource allocation problem includes spectrum allocation and determining the transmission parameters allocation. Resource allocation has been widely studied in different spectrum sharing contexts, including cognitive radio networks and cellular networks. The channel and geographic contiguity, spatially varying channel availability, and coexistence awareness differentiate dynamic channel allocation in the citizen broadband radio service from the previous resource allocation work [51]. Conflict graph representation is proposed in [51] to formulate the PAL and GAA users channel allocation with binary conflicts as max-cardinality and max-reward channel allocation, respectively. However, in [51] only the conflicts between GAA users that can hear each other are considered.

A few recent studies [52, 53] are found on the resource allocation in the CBRS band. In [52] a vertical and horizontal partitioning method is proposed to partition the resource among SASs to ensure fairness. In the vertical partition method SAS is given exclusive control of the portion of the bandwith, and in the horizontal partition method SAS is given a part of the interference budget. Fairness between GAA users is an essential factor that needs to be considered to meet the FCC specified target for GAA users resource allocation while ensuring fairness. Channel allocation (CA) for PAL and GAA users are done in [53] considering the channel allocation rules proposed for CBSDs in two steps, i.e. CA for PAL user is done followed with CA for the GAA user. Conflicts between GAA users are not considered in this work, which is an important factor that needs to be dealt with in CA for GAA users. In [54], a Listen Before talk (LBT) based GAA channel access mechanism is assessed for an outdoor scenario, and the performance evaluation in this work shows that the coexistence using LBT is effective for low powered GAA users.

The incumbent usage is informed by ESC based on its sensing capability. However, SAS has no information regarding the PAL usage so GAA users needs to use a LBT mechanism to avoid harmful interference to priority access users. LBT is a process in which the radio transmitters first sense the medium (applies clear channel assesment) and transmits only if the medium is sensed to be idle. LBT scheme can be Load Based Equipment (LBE) or Frame Based Equipment (FBE) [55]. LBE is where transmit/receive structure is not fixed in time but demand driven where as FBE is not demand driven but has fixed timing.

Each chapter in this thesis has the related works section, which explains in more detail the relevant works and compares with the proposed method.

2.4 Vehicular Communications

With the increasing number of mobile users on public transport, the new and existing services need to provide mobility support in wireless communication networks. Mobile small cells is a promising technology proposed to meet the increasing demand [56]. Mobile small cells can be deployed in public transport such as buses and trains [57]. However, mobile small cells need further investigation on the communication design, resource allocation and interference. This will be further discussed in chapter 5.

FCC has proposed the deployment of mobile cells to provide an opportunity of broadband communications for public safety and emergency response [58]. Mobile small cells addresses the vehicle penetration loss issues and increases transmission reliability of the user equipment. Major challenges on the implementation of the small cells are [56]:

- Backhaul architecture

  When small cells are deployed in train and buses, many users need to be served. When mobile small cells are used, backhauling to the core network can be conducted via macrocell base stations using wireless channels [56]. Since a large number of users needs to be served the bandwidth requirement for such transmission is relatively large. Mobile small cells do not address the spectrum scarcity issue within the macrocells. Hence, backhaul architecture needs to be planned to address the spectrum scarcity issue.

- Time dependent interference

  With mobility, the interference set is time-varying. Hence it is crucial to consider the interference from mobile small cells to fixed small cells in the close proximity of the road or train track. This is further discussed in chapter 5.

- Channel allocation

  Due to the time-dependent interference set, the resource allocation method proposed in the literature will not work for mobile small cells. Resource allocation schemes for mobile small cells need to be further investigated to provide services to a large group of users.

In chapter 5, we consider two types of GAA users, i.e. fixed GAA (FGAA) users and mobile GAA (MGAA) users. FGAA users have fixed locations, and MGAA users are installed in vehicles. Resource allocation of MGAA users adds on an additional challenge as the interfering set of GAA users continually changing with time due to the movement of vehicles. In chapter 5, we present the conflict-free coexistence between PAL users, FGAA users and MGAA users.

2.5 Summary

In this chapter, we presented a literature review of the related work in spectrum sharing and coexistence for future wireless networks. We gave an overview of spectrum sharing and a brief introduction of cognitive radio and spectrum sharing studies done on cognitive radio. Next, we provided a detailed overview of spectrum sharing frameworks in the US and Europe, i.e. SAS and LSA, respectively. Lastly, the vehicular communication system is introduced. The limitations of related works are analysed to provide improvement in spectrum sharing.

Chapter 3

Coexistence between Priority Access Licensees and General Authorised Access Users in Spectrum Access System

Spectrum demand in wireless communications is increasing rapidly, and more spectrum resources are required to meet this demand. Capacity maximisation of GAA users while protecting PAL users from GAA users harmful interference is a critical issue in the SAS that needs to be addressed. In this chapter, using our proposed method, GAA users sum capacity over a single channel and multiple channels is maximised. In section 3.1, we present the introduction followed by the system model in section 3.2. In section 3.3, we find the maximum transmit power and transmission time fraction allocation for GAA users such that the sum capacity of the GAA network is maximised while ensuring the average aggregate interference from GAA users is below the interference threshold. In section 3.4, we define the switching overhead, and use it to obtain the maximum transmit power and transmission time fraction under the constraint of RMS interference. We propose a method to ensure GAA users fairness and the average capacity maximisation is achieved while satisfying the RMS interference constraint to the PAL users in section 3.5.

3.1 Introduction

Hetereogeneous networks consist of various networks using different Radio Access Technologies (RATs) and have attracted consideration to minimise the spectrum scarcity issue by increasing data rate and throughput in unlicensed spectrum [59]. According to [60], networks will be more heterogeneous as we transition to 5G and there will be more combinations among various RATs. The probability of occupying the wireless medium (which will be referred to as the transmission time fraction here onwards) varies between different RATs. This work focuses on maximising the capacity for the opportunistic spectrum access to PAL channels for GAA transmission.

Several studies have already been performed on the cognitive radio and dynamic spectrum access networks to maximise the spectrum efficiency by controlling the interference from secondary users (SU) to primary users (PU) [61–64] . However, all of these studies are based on the instantaneous interference from SU to PU without considering the transmission time of secondary users. In [65] with prior information regarding the PU idle period, authors formulate an optimisation problem to maximise the use of spectrum holes under the constraint of the probability of collision. The aggregate interference caused by secondary users was not considered in this study. For optimal power allocation in cognitive radio networks, in [66] authors considered the transmit power and instantaneous interference constraints. However, the transmit power allocation did not consider the transmit time of secondary users.

In [67], the optimal channel switching problem was studied for the average capacity maximisation considering the average transmit power and maximum transmit power. The switching delay was calculated only using the time required by a transmitter and a receiver to set their parameters in accordance with the frequency in use. In [67] authors did not consider the multiple channel switching and the interference constraint for the average capacity maximisation. Several studies have been done on switching overhead [70, 77, 78] considering hardware and software delays. Most of the studies only consider the hardware delay for the time required to switch from one channel to another and the software delay from the time required for switching algorithm implementation. However, they did not consider the time required to get the authorisation to access the channel and report the transmission characteristics to the centralised database.

Existing studies [71–74] have proposed different spectrum sharing techniques in cognitive radio networks, LTE and WiFi while protecting the PU from harmful interference. In [71] authors presented the resource allocation problem to maximise the capacity of the multiuser cognitive network considering the maximum transmit power and the cross-tier interference. The capacity of the cognitive radio network was analysed under the signal to interference model in [72]. In [73] for the coexistence between LTE and WiFi the channel switching is considered based on LBT by using the frozen period to support the channel switch decision. In [74] the optimal resource allocation scheme with equal time allocation was presented to improve fairness. Providing the transmission opportunity to all users is an important issue that needs to be addressed. However, these studies did not consider the fairness between GAA users that can hear each other.

In section 3.3, the optimal transmit power allocation problem is investigated for GAA users considering the transmission time fraction of GAA users in the SAS system. In section 3.4, we propose a method that finds the channel switching schedules for GAA users to maximise the average capacity of GAA user considering the switching overhead and the interference threshold to PAL users. In section 3.5, we propose a fair coexistence method for the set of GAA users that can hear each other.

3.2 System Model

In this study, we consider the scenario where PAL users are sharing a PAL channel with neighbouring GAA users within the same census tract. We assume that GAA users are randomly located in space. In the current SAS architecture each PAL and GAA users should always report the transmission characteristics such as the power, antenna radiation pattern and the location to the SAS [9, 10]. We consider a scenario where both PAL and GAA users report to the same SAS. Therefore, the SAS is aware of the transmission characteristics including the locations of all PAL

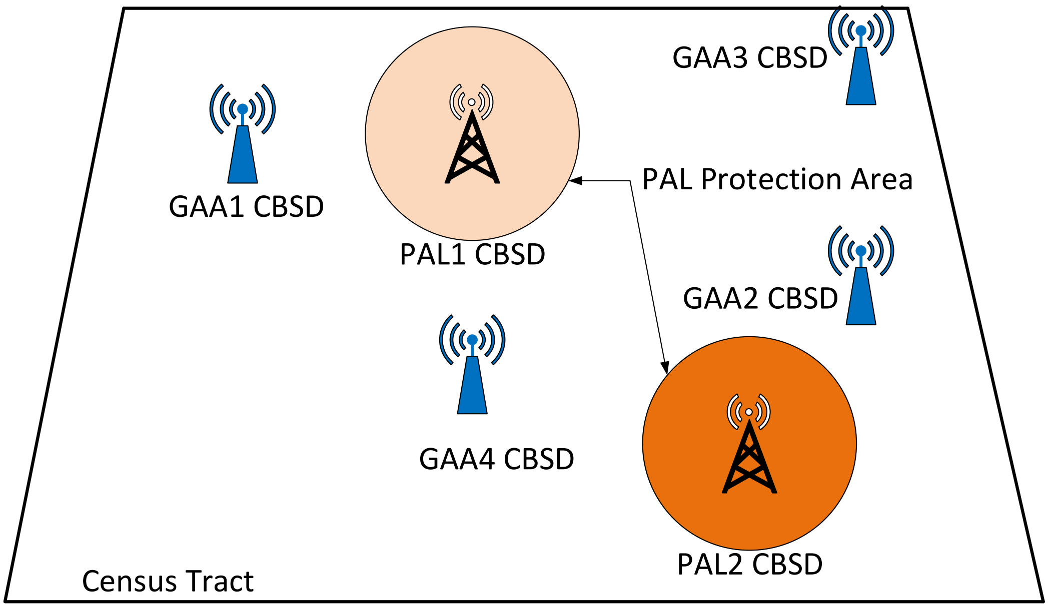


Figure 3.1: PAL and GAA users in a census tract

and GAA users.

We denote the GAA users by i, $i \in \mathcal{N} = \{1, 2, ...N\}$ and the PAL users by m, $m \in \mathcal{M} = \{1, 2, ...M\}$. The PAL channels are denoted by p, $p \in \mathcal{P} = \{1, 2, ...P\}$, with one PAL user in each PAL channel i.e. $M = P$ where P is the total number of channels.

The notation that will be used in this chapter is summarised in Table 3.1.

The GAA users could be a heterogeneous network that uses different RATs. Further the GAA users would have different network loads. Hence some GAA networks are expected to be more active than others. The transmission time fraction (μ_i) is defined as the fraction of time in which the ith GAA user is active in a certain time period [75] and is given by:

$$\mu_i = \lim_{N_t \to \infty} \frac{t_i}{N_t} \tag{3.1}$$

where t_i is the transmit time if the channel is exclusive to the ith GAA user, N_t is the total time period, and t_i depends on the RAT and number of end users in the ith GAA network.

In the SAS system GAA users can operate in the priority access channel op-

Notation	Description
i, j	GAA user index
m	PAL user index
p	Channel index
u	GAA user equipment index
$\mathcal{M}$	Set of PAL users
$\mathcal{N}$	Set of GAA users
$\mathcal{P}$	Set of PAL channels
N_{GAA}	Total number of GAA users
N_{UE}	Total number of GAA user equipments
S_k	Set of users that can hear each other
k	Set index
μ_i	ith GAA users transmission time fraction
N_t	Total time period
I_{th}	Interference Threshold
I_{rms}	RMS Interference from GAA users
Pt_i	Transmit power of ith GAA user
$Pr_{i,u}$	Received power of uth GAA UE from the ith GAA user
μ_i	Transmission time fraction of ith GAA user
v_i	Probability of transmission of ith GAA user
$g_{i,p}$	Total number of sets ith GAA users belong to in the p PAL channel.
$r_{i,p}$	Carrier sensing range of the ith GAA user in the pth PAL channel.
$\alpha_{i,p}$	Channel usage indication
$\gamma_{i,p}$	Signal to interference plus noise ratio of ith GAA in pth PAL channel
$\hat{I_{th}}$	Interference budget threshold for different sets

Table 3.1: Table of Notation and Description

portunistically in a non-interfering way. GAA users will not be authorised by SAS to operate on the same channel with aggregate interference above the interference threshold within PAL user PA i.e.

$$I_{rms} \leq I_{th} \tag{3.2}$$

where I_{rms} is the RMS interference along and inside the PAL PA and I_{th} is the interference threshold.

Winner II Path Loss (PL) model is used to calculate PL between GAA and PAL users, and is given by [76]:

$$PL_i(dB) = 46.4 + 20 \times \log_{10} d_{i,m} + 20 \times \log_{10} \frac{f}{5.0} \tag{3.3}$$

where $d_{i,m}$ is distance between the mth PAL user and the ith GAA user in meters and f is the frequency in GHz.

3.3 Opportunistic Access to PAL Channel for GAA User Transmission in SAS

In this section, we propose the capacity maximisation for GAA users by controlling the transmit power of GAA users considering different transmission time fraction in a single PAL channel. Our objective is to find the maximum transmit power and the maximum portion in time the GAA users are allowed to transmit such that the sum capacity of the GAA network is maximised while maintainting the average aggregate interference from GAA users below the interference threshold.

We consider the downlink transmission of GAA users. The received power of the uth, $u = 1, 2,...,N_{UE}$ GAA user equipment (UE) from the ith GAA user is given by:

$$Pr_{i,u}(t) = \frac{Pt_i(t)}{PL_{i,u}} \tag{3.4}$$

where Pt_i is the transmit power of the ith GAA user, $PL_{i,u}$ is the pathloss between the ith GAA user and the uth GAA UE.

The instantantaneous downlink capacity for the ith GAA network at the time t is given by:

$$C_i(t) = \sum_{u=1}^{N_{UE}^i} \log\left(1 + \frac{Pr_{i,u}(t)}{P_N + \sum_{j\in\{S_I{}^i\}\setminus\{i\}} Pr_{j,u}(t)}\right) \tag{3.5}$$

where, N_{UE}^i is the total number of GAA user equipments for the ith GAA user and ${S_I}^i$ is the subset of S_N, i.e., set of all GAA users and it includes the active GAA users when the ith GAA user is active. $Pr_{i,u}$ is the received power by the uth user equipments from transmitting GAA, i.e., the ith GAA user, and $\sum_{j\in\{S_I{}^i\}\setminus\{i\}} Pr_{j,u}(t)$ is the received power by user equipments from the other GAA users in the active subset.

It is assumed that GAA users are sufficiently far apart when transmitting and have different transmission time fraction. Probability of S_I subset doing the transmission is given by:

$$P_{S_I} = \prod_{i\in\{S_I{}^i\}} \mu_i \prod_{j\in\{S_N\}\setminus\{S_I{}^i\}} (1-\mu_j) \tag{3.6}$$

where μ_j is the transmission time fraction of inactive GAA users, and μ_i is the transmission time fraction of the active GAA users.

The average capacity over time for the ith GAA user in ${S_I}^i$ set is given by:

$$C_{S_I} = P_{S_I} \sum_{u=1}^{N_{UE}^i} \log\left(1 + \frac{Pr_{i,u}}{P_N + \sum_{j\in\{S_I{}^i\}\setminus\{i\}} Pr_{j,u}}\right) \tag{3.7}$$

where P_{S_I} is from equation (3.6)

The average downlink capacity when the ith GAA user is transmitting considering different combination of ${S_I}^i$ is given by:

$$C_i = \sum^{\{S_I{}^i\}\in\{S_S{}^i\}} \left(\prod_{j\in\{S_I{}^i\}} \mu_j \prod_{i\in\{S_N\}\setminus\{S_I{}^i\}} (1-\mu_i) \sum_{k=1}^{N_{UE}^i} \log\left(1 + \frac{Pr_{i,u}}{P_N + \sum_{j\in\{S_I{}^i\}\setminus\{i\}} Pr_{j,u}}\right)\right) \tag{3.8}$$

where S_S is all the possible combination of S_I that includes ith GAA.

In our work, we assume GAA users perform LBT to sense other GAA users, and GAA users will not transmit in the same channel if they sense other PAL or GAA users. The average downlink capacity of the ith GAA user is given by:

$$C_{GAA} = \mu_i \sum_{u=1}^{N_{UE}} \log_2 \left(1 + \frac{Pr_{i,u}}{P_N}\right) \tag{3.9}$$

We consider $|\mathcal{N}|$ number of GAA users transmit in the PAL channel opportunistically over the time period N_t.The average aggregated downlink capacity of all GAA users is given by:

$$C_{agg} = \sum_{i=1}^{|\mathcal{N}|} \mu_i \sum_{u=1}^{N_{UE}} \log_2 \left(1 + \frac{Pr_{i,u}}{P_N}\right) \tag{3.10}$$

3.3.1 Average Aggregate Interference

The interference from the ith GAA user to the mth PAL user is given by:

$$I_i = \frac{Pt_i}{PL_{i,m}} \tag{3.11}$$

where, I_i is the interference from the ith GAA user to the mth PAL user, Pt_i is the transmit power of the ith GAA user and $PL_{i,m}$ is the path loss (as a ratio-not dB) from the ith GAA user to the mth PAL user.

The instantantaneous aggregate interference from GAA users to PAL users at the certain time is given by:

$$I_{agg} = \sum_{i=1}^{|\mathcal{N}|} \frac{Pt_i}{PL_{i,m}} \tag{3.12}$$

With GAA users transmitting with different transmission time fraction, the RMS interference from all GAA users to the mth PAL user for time period N_t is given by:

$$I_{rms,m} = \sum_{i=1}^{|\mathcal{N}|} \frac{Pt_i}{PL_{i,m}} \times \mu_i \tag{3.13}$$

3.3.2 GAA Users Transmit Power and Transmission Time Fraction Allocation Considering Single PAL Channel

The optimisation problem is to find the optimal power and the maximum portion in time the GAA users are allowed to transmit. The average sum capacity of GAA users is maximised subject to transmit power, transmission time fraction of GAA users and average aggregated interference constraints. The sum of transmission time fraction allocated to all the GAA users should be less than or equal to 1. Using this proposed method in the current SAS architecture where users need to report their locations to SAS, GAA users can be allocated optimal transmit power and transmission time fraction. The optimisation problem can be formulated as:

$$\begin{aligned}
\text{maximize} \quad & \sum_{i=1}^{|\mathcal{N}|} \log_2\left(1 + \frac{Pt_i}{P_N}\right) \times \mu_i \\
\text{subject to} \quad & 0 < Pt_i <= P_{max} \\
& \sum_{i=1}^{|\mathcal{N}|} \frac{Pt_i}{PL_{i,PAL}} \times \mu_i \leq I_{th} \\
& \sum_{i=1}^{|\mathcal{N}|} \mu_i \leq 1
\end{aligned} \tag{3.14}$$

where P_N is the noise power, and μ_i is the transmission time fraction of the ith GAA user.

The optimisation problem (3.14) is a convex optimisation problem as it satisfies the proof in [80] for Problem 2.

3.4 Considering Switching Overhead for Transmit Power Allocation for GAA User in Spectrum Access System

In this section, we propose a method for GAA users to switch to different channels considering the transmission time fraction of GAA user. We proposed the method to calculate switching overhead and maximised average capacity of GAA users considering the optimal channel switching schedule. Switching overhead is the time delay when switching the channel from one to another. In this work, we define switching overhead as the time required for the GAA users to sense the channel, set the transmission characteristics of GAA users and user equipments according to

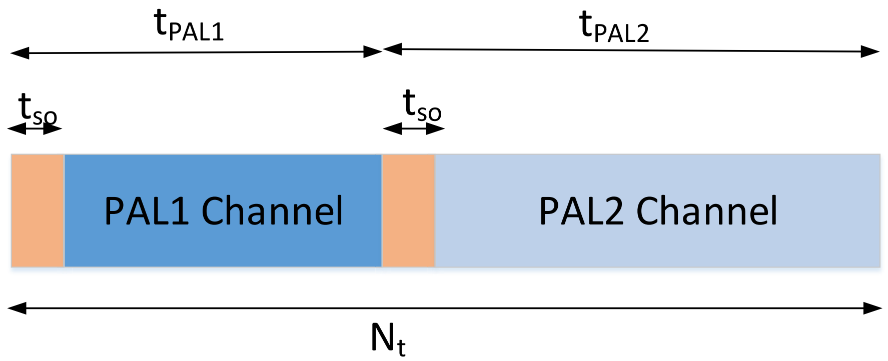


Figure 3.2: Illustration of channel switch for GAA users

channel bandwidth considered for the transmission and time required to switch from one channel to another. For the GAA users who share the spectrum with priority access users, switching overhead could be from switching to multiple PAL channels when their transmission time fraction is low.

We consider a scenario in which there is no PAL1 user transmission in the channel assigned to PAL1 user initially and there is a PAL2 transmission. When there is no PAL1 transmission all GAA users can access the PAL1 channel with the maximum allowed transmit power. When PAL1 starts the transmission GAA users needs to transmit on PAL1 channel without causing harmful interference to PAL1 user. In this work, we consider that the GAA users who receives a low transmission time fraction switch to a different channel. Figure. 3.2 shows a sample time structure in which a GAA user switch over 2 channels during the total time period of N_t with the time required for switching given by t_{so}. In N_t time the channel switching schedule is to use PAL channel 1 and 2, i.e. $t_{PAL1} + t_{PAL2} = N_t$ where t_{PAL1} and t_{PAL2} is the time allocated for PAL1 ans PAL2 channels respectively.

3.4.1 Switching Overhead

Switching overhead of the ith GAA user (δ) is given by:

$$\delta = \frac{t_{so}}{N_t} \tag{3.15}$$

where t_{so} is the time required to switch to the channel.

Time required to switch to the channel depends on the time for clear channel assessment i.e. t_{CCA}, the time to switch from one channel to another which is also known as hardware switching delay i.e. t_{hd} and the time required by GAA user to report to SAS their transmission characteristics and get access to PAL channel i.e. t_{tc}. As the number of GAA users accessing the channel at a given location and time increases the switching overhead also increases.

$$\delta = \frac{t_{CCA} + t_{hd} + t_{tc}}{N_t} \tag{3.16}$$

Switching overhead is a period where there is no transmission. The probability of transmission of the ith GAA user considering switching overhead and transmission time fraction is given by:

$$v_{i,p} = \mu_{i,p} - \delta \tag{3.17}$$

3.4.2 GAA Users Transmit Power and Transmission Time Fraction Allocation Considering Multiple PAL Channels

The optimisation problem is to maximise the average aggregate capacity of GAA users under the constraint of maximum transmit power, root mean square interference, switching overhead and transmission time fraction of GAA users. Some GAA users might switch to different channels when a PAL user starts the transmission due to the transmission time fraction for GAA user being low or because they are within the PAL PA. In this problem, we consider root mean square interference at the boundary of the PA of both PAL1 and PAL2 users and transmission time fraction of GAA users transmitting at PAL1 and PAL2 channel. The optimisation problem can be formulated as:

$$\begin{aligned}
\text{maximize} \quad & \sum_{i=1}^{|\mathcal{N}|} \log_2 \left(1 + \frac{Pt_{i,p}}{P_N}\right) \times (\mu_{i,p} - \delta) \\
\text{subject to} \quad & C1 : 0 < Pt_{i,p} <= P_{max} \\
& C2 : I^{p}_{rms,m} \leq I_{th}, \forall\ p = 1, 2 \\
& C3 : \sum_{i=1}^{|\mathcal{N}|} \mu_{i,p} \leq 1, \forall\ p = 1, 2 \\
& C4 : \sum_{p=1}^{|\mathcal{P}|} \mu_{i,p} \leq 1, \forall\ i \in \mathcal{N}
\end{aligned} \tag{3.18}$$

where, $I^{p}_{rms,m}$ is the RMS interference at the boundary of PAL1 and PAL2 PA allocated in PAL1 and PAL2 channel respectively , $\mu_{i,p}$ is the transmission time fraction for GAA users transmitting in PAL1 and PAL2 channel.

From the optimisation equation (3.18) we can find $Pt_{i,p}$ and $\mu_{i,p}$ for all GAA users, i.e. ,$\forall\ i \in \mathcal{N}$ in all PAL channels, i.e. ,$\forall\ p \in \mathcal{P}$. In this work, to maximise the average aggregate capacity of GAA users channel switching is proposed in which GAA users can switch to the different channel based on the transmission time fraction allocation. Transmission time fraction is allocated under the constraint of RMS interference to PAL PA when a PAL user is active. In the proposed algorithm, i.e., Algorithm 1, we propose the method for GAA users to switch to a different channel when the transmission time fraction is below a certain threshold μ_{th}.

Algorithm 1 Channel Switch for GAA

1: **Input**: P_{max}, I_{th}, μ_{th}
2: From Optimisation equation (3.18) calculate transmit power ($Pt_{i,p}$) and transmission time fraction ($\mu_{i,p}$) of GAA users
3: **if** $\mu_{i,p} \leq \mu_{th}$ **then**
4: GAA stop transmission and switch to other channel
5: **else**
6: GAA transmit in same channel while satisfying the RMS interference threshold

3.5 Fairness Aware Resource Allocation for General Authorized Access Users

Coexistence among GAA users is an important problem to be solved to enhance the system capacity to meet the increasing traffic demand. In this section, we propose a method for fair and efficient spectrum utilisation for GAA users. To achieve the fairness among GAA users, an equal interference budget allocation scheme is proposed for each set of GAA users that can hear each other. In this work, we propose a method to ensure GAA users fairness and find the optimal channel switching schedule that maximises the average capacity of GAA users while satisfying the interference constraint at the PAL PA.

In the dense area, there could be many GAA users that can hear each other. In these scenarios, GAA users may need to share the same frequency channel with multiple GAA users in the set that can hear each other. Transmission time fraction allocation restrains GAA users from using a particular channel for a long time. To ensure the fairness between GAA users, we provide an opportunity to each GAA users to access the PAL channel by allocating a transmission time fraction threshold to operate on a particular PAL channel. This strategy gives the opportunity to other GAA users to access the PAL channel and avoid interference to PAL users which is caused by GAA users using the same channel for a long time (RMS Interference).

3.5.1 Carrier Sensing Range

According to the FCC standards [81,82], the nodes can hear each other if the received signal strength is at least 6 dB above the noise floor, i.e.

$$Pr(dBm) = N_{Fl} + 6 \tag{3.19}$$

where N_{Fl} is the noise floor in dBm, and Pr is the received power threshold for the nodes to hear each other.

Let $r_{i,p}$ denote the carrier sensing range for the ith GAA user on the pth channel and $r_{i,p}$ is determined using (3.3) and (3.19). The carrier sensing range of GAA users depends on the transmit power of the GAA users and can be expressed as:

$$r_{i,p} = 10^{\left(\frac{10\log_{10}\left(\frac{Pt_{i,p}}{Pr}\right)-46.4-20\times\log_{10}\frac{f}{5.0}}{20}\right)} \tag{3.20}$$

where $r_{i,p}$ is the carrier sensing range of the ith GAA user in the pth PAL channel.

For each PAL channel, GAA users have different carrier sensing ranges as the transmit power allocation for GAA users is different in a different channel. The number of sets of GAA users that can hear each other is different for each PAL channel, i.e. G_p, $\forall p \in \mathcal{P}$. Channel allocation of GAA users considering the carrier sensing range has a higher computational complexity as the sets of GAA users that can hear each other differ for different PAL channels.

For simplicity to solve the problem, we find the carrier sensing range of GAA users using the maximum allowed transmit power. With the optimum transmit power allocation the set of GAA users that can hear each other is the same for all PAL channels. In this study, the worst case scenario of GAA users transmitting with maximum power is considered to calculate the optimal carrier sensing range for the ith GAA user (r_i^*) and is given by:

$$r_i^* = 10^{\left(\frac{10\log_{10}\left(\frac{P_{max}}{Pr}\right)-46.4-20\times\log_{10}\frac{f}{5.0}}{20}\right)} \tag{3.21}$$

Let S_k denote the set of the GAA users that can hear each other. The GAA users in set S_k cannot transmit at the same time. The GAA users can hear each other if the distance between the GAA users is less than the carrier sensing range, i.e.

$$d_{ij} \leq \min\{r_i^*, r_j^*\} \tag{3.22}$$

where d_{ij} is the distance between the ith and jth GAA user, and r_j is the carrier sensing range for the jth GAA user.

3.5.2 GAA Users Transmit Power and Transmission Time Fraction Allocation Considering Fairness

The GAA users in S_k set cannot transmit at the same time, and in this work to provide each GAA user an opportunity to access the channel we do the transmission time fraction allocation in set S_k. The transmission time fraction for the ith GAA user from S_k set in the pth PAL channel is denoted as $\mu^p_{i,k}$, and $\mu^p_{i,k} = 1$ when $|S_k| = 1$. The transmission time fraction of the mth GAA user in a set S_k can be calculated using

$$\sum_{i \in S_k} \mu^p_{i,k} \leq 1, \forall\ k = 1, .., R \tag{3.23}$$

where R is the total number of sets of GAA users that can hear each other when transmitting in the pth channel.

GAA users may belong to multiple sets of GAA users that can hear each other, and this is an important factor to solve the transmission time fraction allocation for GAA users. We define $g_{i,p}$ as the total number of sets the ith GAA user belongs to in the pth PAL channel, and this can be calculated using:

$$g_{i,p} = \sum_{k=1}^{R} \mathbb{I}^k_i \tag{3.24}$$

$$\mathbb{I}^k_i = \begin{cases} 1, & \text{if } i \in S_k \\ 0, & \text{if } i \notin S_k \end{cases} \tag{3.25}$$

RMS interference from $|\mathcal{N}|$ GAA users to the mth PAL user is given by:

$$I_{rms,m} = \sum_{i=1}^{|\mathcal{N}|} \alpha_{i,p} \times I_{i,m} \times (\mu^p_{i,k} - \delta) \tag{3.26}$$

where $\alpha_{i,p}$ is used to indicate if the pth channel is used by the ith GAA user, i.e. if the ith GAA user uses the pth channel then $\alpha_{i,p} = 1$. $I_{i,m}$ is the instantaneous interference from the ith GAA user to the mth PAL user and is given by $I_{i,m} = \frac{Pt_{i,p}}{PL_{i,m}}$, where $Pt_{i,p}$ is the transmit power of the ith GAA user at the pth PAL channel, and $PL_{i,m}$ is the path loss between the ith GAA user and the mth PAL user (as a ratio-not dB).

Different combinations of GAA users could transmit at a particular time at a particular channel. We define $\mathbb{Z}^k_p$ as an indication function to check if the kth set belongs to the pth channel. We define $\hat{R}_p$ as the total number of active sets in the

pth PAL channel where $\hat{R}_p \leq R$, and this can be calculated using:

$$\mathbb{Z}_p^k = \begin{cases} 1, & \text{if } k \in p \\ 0, & \text{if } k \notin p \end{cases} \tag{3.27}$$

$$\hat{R}_p = \sum_{k=1}^{R} \mathbb{Z}_p^k \tag{3.28}$$

In this work, to achieve the fairness between GAA users we allocate the interference budget threshold based on active sets in a particular channel. Interference budget threshold for different sets of GAA users is given by:

$$\hat{I_{th}} = \frac{I_{th}}{\hat{R}_p} \tag{3.29}$$

where $\frac{I_{th}}{R} \leq \frac{I_{th}}{\hat{R}_p}$.

λ_p is one combination of GAA users transmitting at the same time in the pth channel. The signal to interference plus noise ratio of the ith GAA user in the pth PAL channel is given by:

$$\gamma_{i,p} = \frac{\alpha_{i,p} \frac{Pt_{i,p}}{PL_{i,m}}}{P_N + \sum_{j \in \{\lambda_p\} \setminus \{i\}} \alpha_{j,p} \frac{Pt_{j,p}}{PL_{i,j}}} \tag{3.30}$$

where P_N is the noise power, and $PL_{i,j}$ is the PL between the ith GAA user and the jth GAA user.

Average capacity of the ith GAA user considering the interference from other GAA users in λ_p set is given by:

$$C_{i,k}^p = (\mu_{i,k}^p - \delta) \times (\log_2(1 + \gamma_{i,p})) \tag{3.31}$$

When number of elements in the set S_k is greater than 1, i.e. $|S_k| > 1$, GAA users do not receive the optimal transmission time fraction, i.e. $\mu_{i,k}^p = 1$ to give a chance to other GAA users to access the channel. In this work, we propose the method to achieve fairness and average capacity maximisation of GAA users, in a set $S_k, \forall k = 1, .., R,$. In a certain time period GAA users might use one PAL channel for $\mu_{i,k}^p$, and then switch to another PAL channel for a certain period and so on.

The optimisation problem for average capacity maximisation can be formulated as:

$$\begin{aligned} \underset{\mu_{i,k}^{p}, Pt_{i}^{p}}{\text{maximize}} \quad & \sum_{p=1}^{|\mathcal{P}|} \sum_{i=1}^{|\mathcal{N}|} C_{i,k}^{p} \\ \text{subject to} \quad & 0 < Pt_{i,p} \leq P_{max} \\ & \sum_{i=1}^{|\mathcal{N}|} \mathbb{I}_{i}^{k} \times I_{i,m} \times (\mu_{m,l}^{k} - \delta) \leq \hat{I_{th}} \\ & \sum_{i \in S_k} \mu_{i,k}^{p} \leq 1, \forall\ k = 1, .., R \end{aligned} \tag{3.32}$$

The function $(\mu_{m,l}^{k} - \delta) \times (\log_2(1 + \gamma_{m,k}))$ is concave, and the sum of concave functions is also concave. In (3.32) the optimisation equation is concave, and the constraints are convex. The optimisation problem (3.32) is a convex optimisation problem as it satisfies the proof in [80] for Problem 2. Thus the problem (3.32) is convex.

GAA users with $g_{i,p} > 1$ belong to multiple sets of nodes that can hear each other, and they will have a different transmission time fraction for set $S_k, \forall\ k = 1, .., R$. To obtain the fairness between GAA users and to protect PAL user from GAA users interference we find the transmission time fraction and transmit power using not only the $|S_k|$ but also on the $g_{i,p}$. The adjusted transmission time fraction of the ith GAA user considering all the sets of GAA users that can hear each other is denoted as $\hat{\mu_i^p}$, and is given by:

$$\hat{\mu_i^p} = \min\{\mu_{i,k}^{p}\}, \forall\ k = 1, .., R \tag{3.33}$$

The adjusted transmit power of the ith GAA user considering all the sets of GAA users that can hear each other is denoted as $\hat{Pt_i^p}$, and is given by:

$$\hat{Pt_i^p} = \min\{Pt_{i,k}^{p}\}, \forall\ k = 1, .., R \tag{3.34}$$

3.6 Numerical Results

In this section, we present simulations results for our problem which is presented in the above sections. To solve our optimisation problem we used convex optimisation

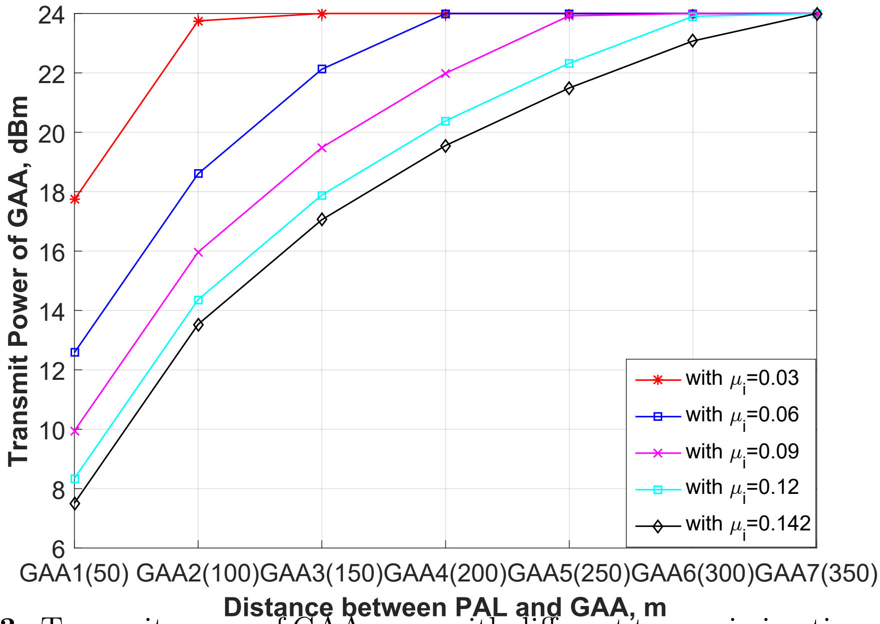


Figure 3.3: Transmit power of GAA users with different transmission time fractions and particular locations, results of convex optimisation for transmit power allocation when transmission time fraction is known

in MATLAB. For each GAA user we considered a cell of radius 50 m with 6 GAA UE randomly located within the cell. In MATLAB simulation we used the maximum allowed interference at the PAL PA as -80 dBm, maximum transmit power as 24 dBm, and the carrier frequency is 3.6 GHz [9, 10].

3.6.1 Numerical Results Considering Single PAL Channel

We consider a scenario with a single PAL users and 7 GAA users at different locations sufficiently far apart.

Figure 3.3 shows the transmit power allocation to GAA users based on our optimisation results. We considered different scenarios with different transmission time fractions, in which GAA users are transmitting with the same transmission time fraction. Results show that greater the transmission time fraction, the lower the transmit power of the GAA user gets which alligns with the target of our method. Results also show that when the distance is more than 350 m from the PAL, then the GAA user can transmit with maximum transmit power with any transmission time fraction.

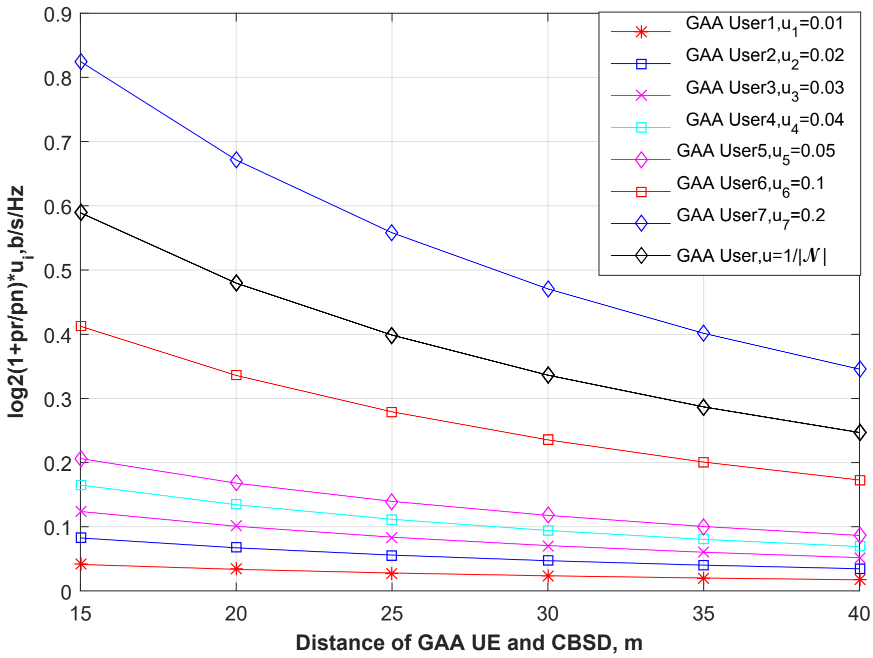


Figure 3.4: Downlink capacity of GAA users

Figure 3.4 shows the capacity of a GAA receiver at different transmission time fractions and distance for different GAA users. GAA users have different transmission probability with an average transmission time fraction less than one. It is seen from the results that the average capacity can be maximised by controlling the transmission time fraction of GAA users. The black plot shows the average capacity when the channel is fully used for the time period i.e. all GAA users are transmitting with the same transmission time fraction.

Figure 3.5 shows the transmit power allocation for GAA users which are transmitting at different distances from PAL when considering the constraint as instantaneous aggregated interference and average aggregated interference with the same transmission time fraction for all GAA users. Results from the optimisation show that we can maximise the transmit power allocation for GAA users by considering the average aggregate interference.

Figure 3.6 shows the result of optimisation for transmit power allocations for GAA users from equation (3.14) and transmit power allocations for GAA users when the transmission time fraction is $\mu_i = 1/|\mathcal{N}|$. The results show that more transmit power is allocated to GAA users using this method when compared to

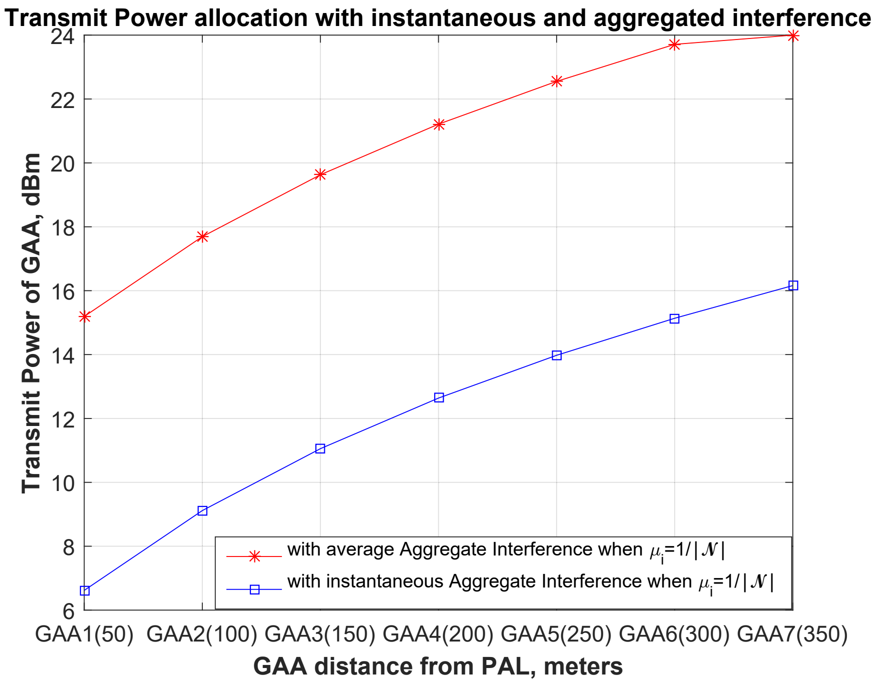


Figure 3.5: Transmit power allocation for GAA users with average and instantanenous aggregate interference with transmission time fraction $\mu_i = 1/|\mathcal{N}|$

GAA users transmiting with the same transmission time fraction.

Figure 3.7 shows the comparision between transmission time fraction allocation for GAA users i.e. results from equation (3.14) and $u_i = 1/|\mathcal{N}|$ i.e. all GAA users are transmitting with the same probability. Results from equation (3.14) show that the transmission time fraction for GAA users increases with distance.

3.6.2 Numerical Results Considering Multiple PAL Channels

To solve our problem we consider a scenario with two PAL users and seven GAA users which are randomly located in space. There are two channels, with one PAL user assigned to PAL1 and another to PAL2 channel. When there is no PAL1 transmission all seven GAA users use the channel assigned to PAL1. When PAL1 starts the transmission GAA users who receive less probability of transmission switch to the different unoccupied channel. We consider that PAL1 user starts the transmission at $0.5T_{total}$ and the transmission time fraction threshold for GAA users is taken as 0.1 in this work.

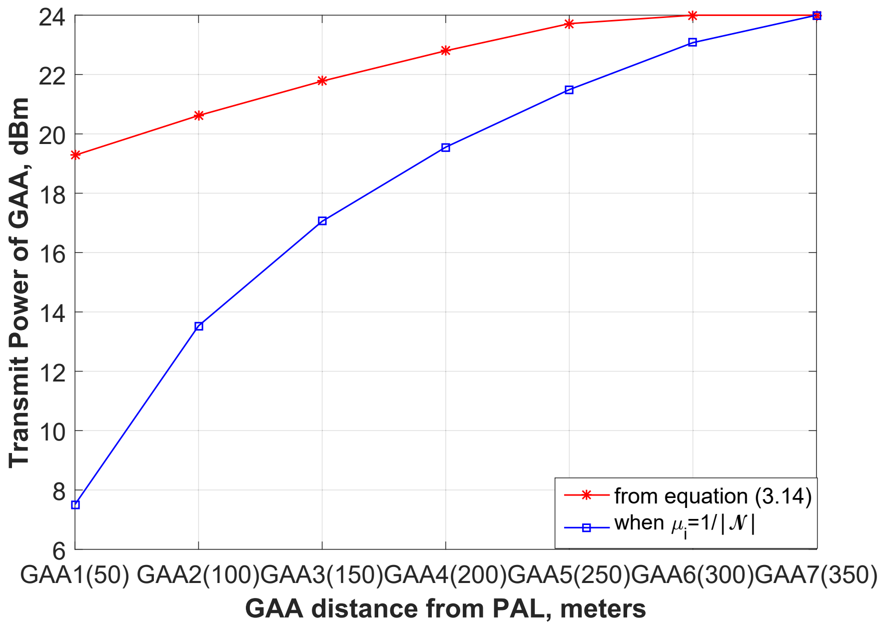


Figure 3.6: Transmit power allocation for GAA users from equation (3.14) and when $\mu_i = 1/|\mathcal{N}|$

Figure 3.8 shows the transmit power allocation of GAA users at PAL1 and PAL2 channels with switching. 0 to $0.1T_{total}$ shows the initial channel selection for GAA users which are selecting the channel assigned to PAL1 user which is not transmitting at that time. When there is no PAL1 transmission all GAA users are transmitting with the maximum allowed transmit power with transmission time fraction $1/|\mathcal{N}|$. PAL1 user starts transmission after $0.5T_{total}$ and after the PAL1 starts transmission GAA1 and GAA2 users switch to the channel assigned to PAL2. From $0.5T_{total}$ to $0.6T_{total}$ they perform switching , and other GAA users reduce the transmit power to ensure RMS interference at the boundary of the PAL PA is below the threshold.

Figure 3.9 shows the instantaneous aggregate interference at PAL1 and RMS interference threshold at the PAL PA. From $0.1T_{total}$ to $0.5T_{total}$ PAL1 is not transmitting and all seven GAA users transmit with the maximum allowed transmit power and instantaneous aggregate interference is in the range of -49 dBm to -81 dBm. Next, when PAL1 user starts transmission after $0.5T_{total}$ GAA users transmitting at that time i.e. GAA3, GAA4, GAA5, GAA6, GAA7 reduces the transmit power and transmission time fraction so that the interference to the PAL PA is below the RMS interference.

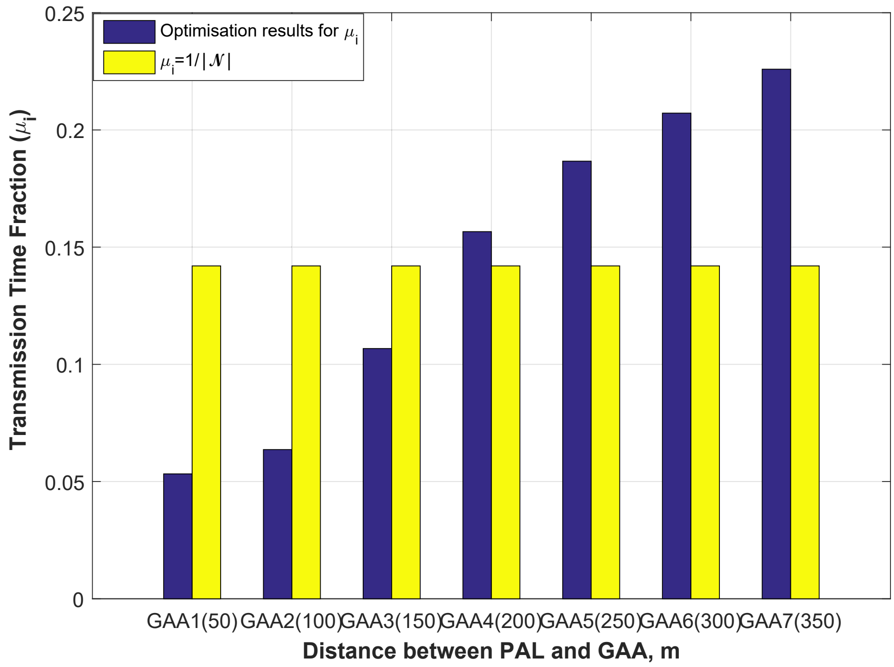


Figure 3.7: Transmission time fraction allocation for GAA users, results of convex optimisation from equation (3.14)

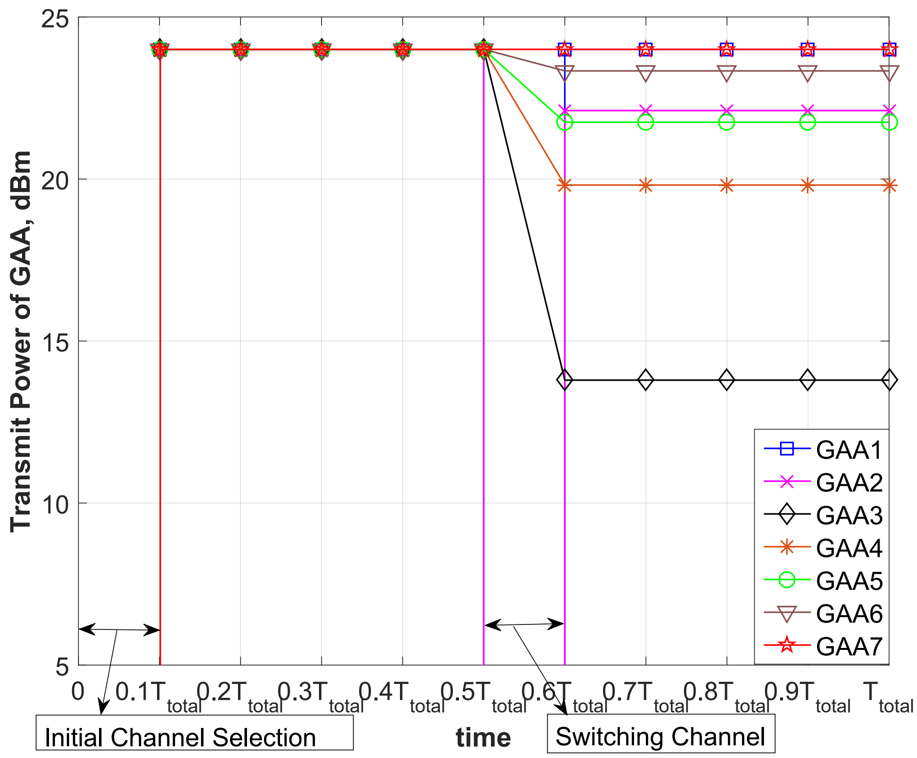


Figure 3.8: Transmit power allocation of GAA users at PAL1 channel with and without PAL1 transmission

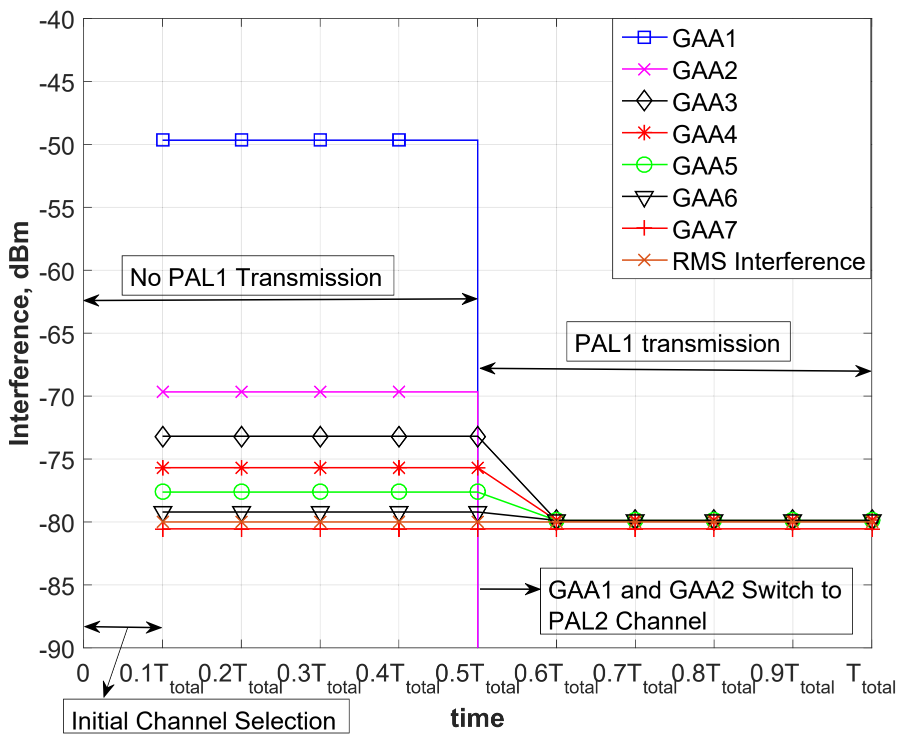


Figure 3.9: Instantaneous aggregate interference at PAL1 user

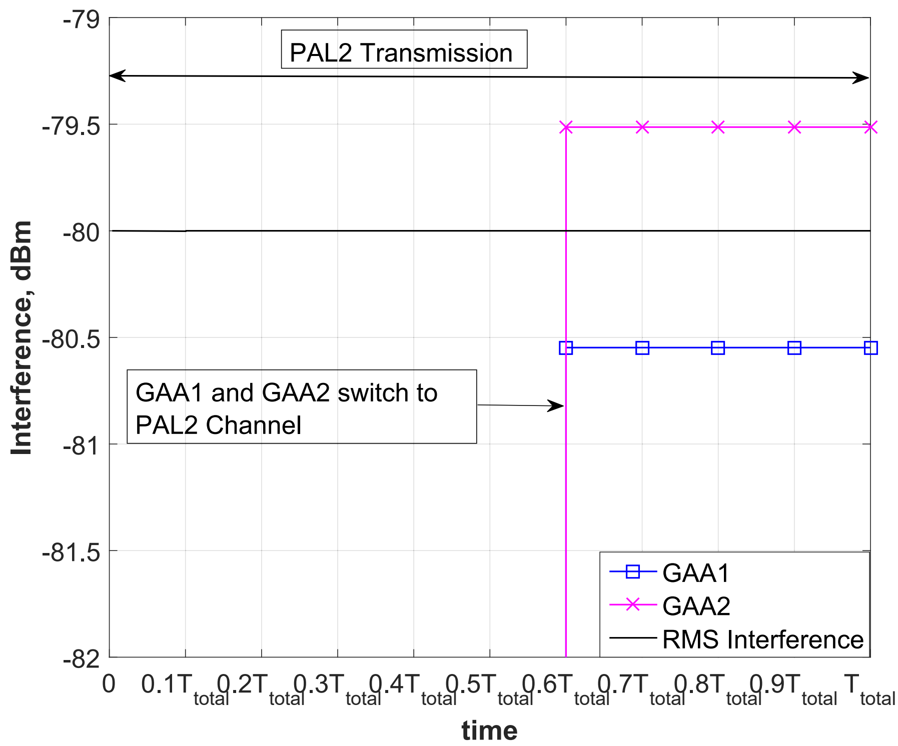


Figure 3.10: Instantaneous aggregate interference at PAL2 user

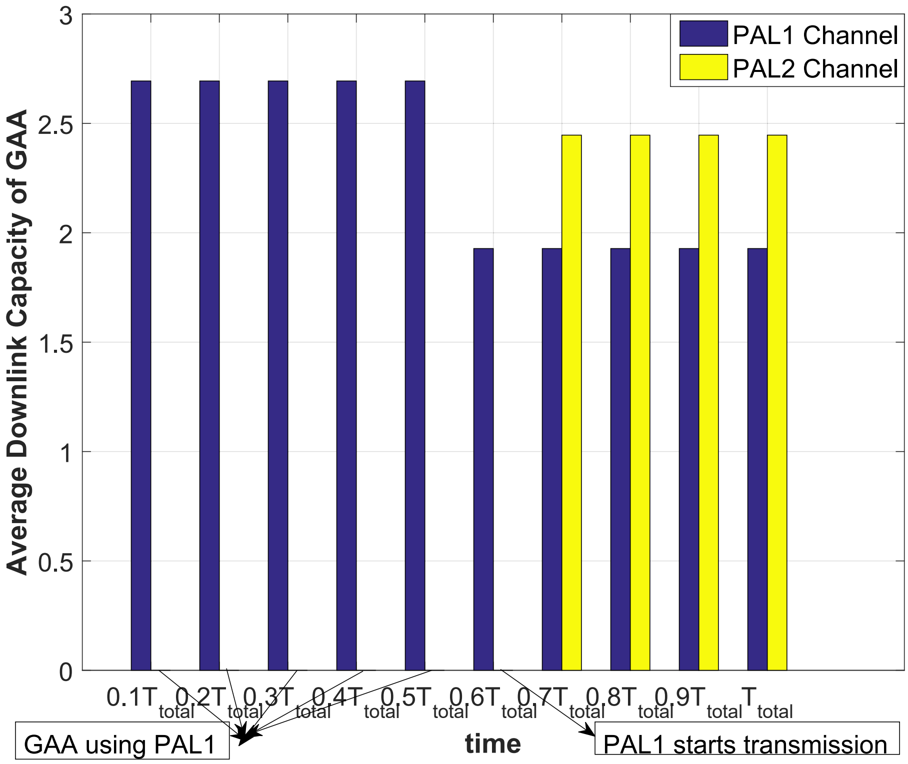


Figure 3.11: Average downlink capacity of GAA users

Figure 3.10 shows the instantaneous aggregate interference on the boundary of the PAL2 user PA and RMS interference threshold at the PAL PA. When PAL1 user starts transmission GAA1 and GAA2 users switch to PAL2 channel. The RMS interference from GAA1 and GAA2 to the PAL2 user PA is −80 dBm.

Figure 3.11 shows the average downlink capacity of GAA users transmitting at the channel assigned to PAL1 and PAL2 users. PAL1 channel is used over the time period T_{total} with all seven GAA users utilising the channel from $0.1T_{total}$ to $0.5T_{total}$ and five GAA users transmitting after $0.5T_{total}$. GAA1 and GAA2 users switch to PAL2 channel and from the results we can see that more power is allocated considering switching.

3.6.3 Numerical Results Considering Fairness between GAA Users

In the simulation, 15 GAA users and 2 PAL users were randomly located within a range of 300 meters in both x and y coordinates. For the channel switching, we

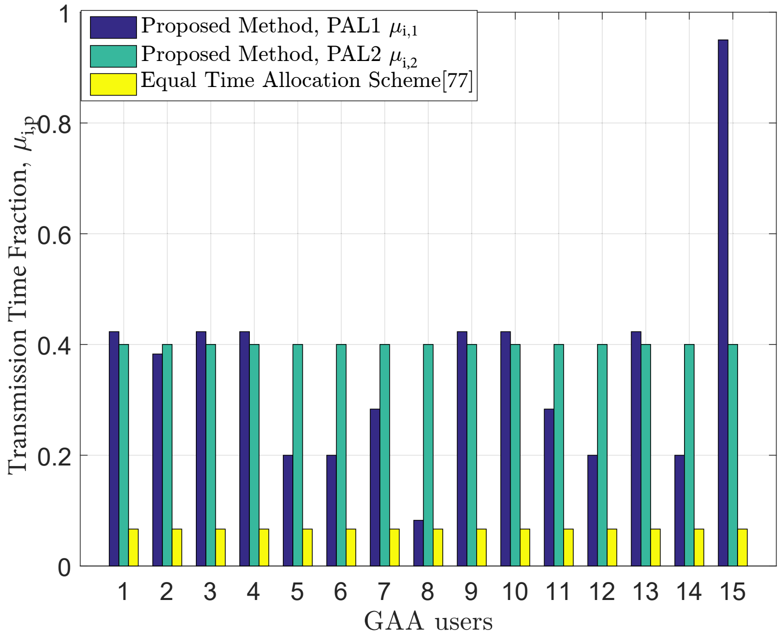


Figure 3.12: GAA users transmission time fraction threshold at different PAL channels

consider the switching overhead as 0.05.

Figure 3.12 shows the transmission time fraction for GAA users at PAL1 and PAL2 channels from our proposed method and an equal time allocation scheme to enhance the fairness in [77] for optimal SUs resource allocation. The results show that the transmission time fraction allocation from our method is more than an equal distribution of the transmission time fraction to GAA users in all cases except when the GAA user is too close to PAL. The results show that when $|S_k| = 1$, i.e. GAA user cannot hear other GAA users, GAA users receive the optimal transmission time fraction and our proposed method also depends on the distance from the PAL user.

Figure 3.13 shows the transmit power allocation for GAA users from our proposed method and an equal time allocation scheme [77]. In SAS for PAL users, FCC has proposed the RMS interference threshold which also depends on the spectrum utilisation time. The results show that the transmit power allocation is more when $\hat{\mu_i^p}$ is less.

Figure 3.14 shows the interference from GAA users to PAL1 and PAL2. In SAS GAA users can opportunistically transmit while ensuring the RMS interference threshold is satisfied. The result shows that our proposed method satisfies the RMS

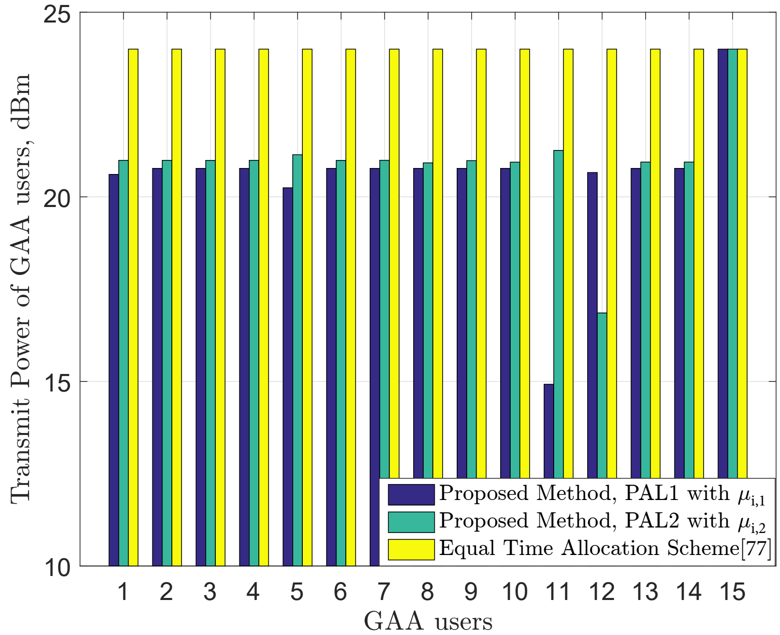


Figure 3.13: Transmit power of GAA users from the proposed method and equal time allocation scheme [77]

interference constraint with RMS interference from GAA users at PAL1 and PAL2 below -80 dBm.

Figure 3.15 shows the comparison between average capacity of GAA users from the proposed method and the sum throughput maximisation scheme with equal time allocation to enhance the fairness presented in [77]. We can see from the results that the average capacity is increased from our proposed method, as it considers the sets that can hear each other for the transmission time fraction threshold, except when GAA user is too close to PAL users to protect PAL users from harmful interference.

To ensure the fairness between GAA users in a set that can hear each other, the interference threshold is divided between the sets of GAA users. We use Jains Fairness Index (JFI) rate to assess the fairness of the RMS interference to PAL users and transmission time fraction allocation between GAA users in a set of nodes that can hear each other. JFI equation for RMS interference budget is given by: $\mathcal{J}2(I^k_{RMS,i,m}) = \frac{(\sum_i^{|S_k|} I^k_{RMS,i,m})^2}{|S_k|\sum_i^{|S_k|}(I^k_{RMS,i,m})^2}$. The result shows that the JFI score for $I^k_{RMS,i,m}$ and $\hat{\mu_{i,p}}$ for different sets of GAA users that can hear each other at PAL1 channel is 1. Larger the $\mathcal{J}$ resembles fair RMS interference and transmission time fraction of GAA users according to JFI index [78].

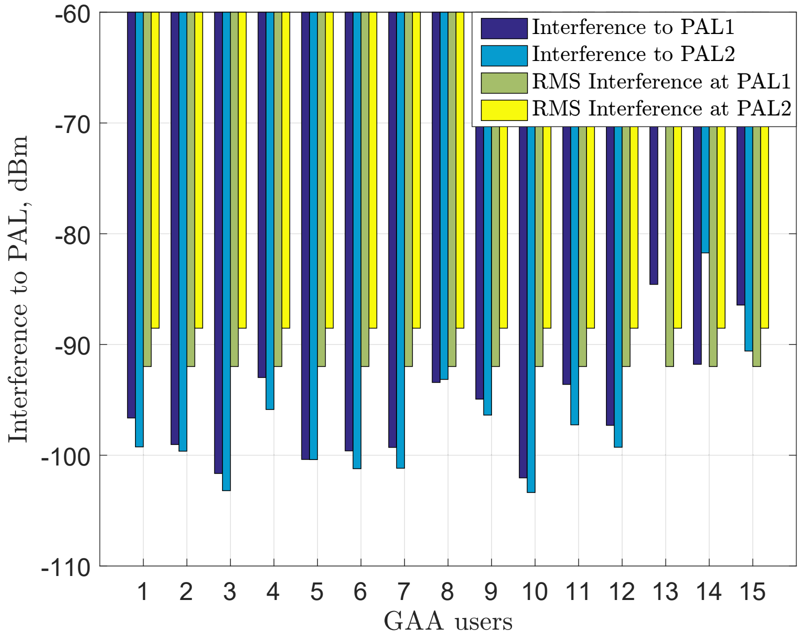


Figure 3.14: Interference from GAA users to PAL users

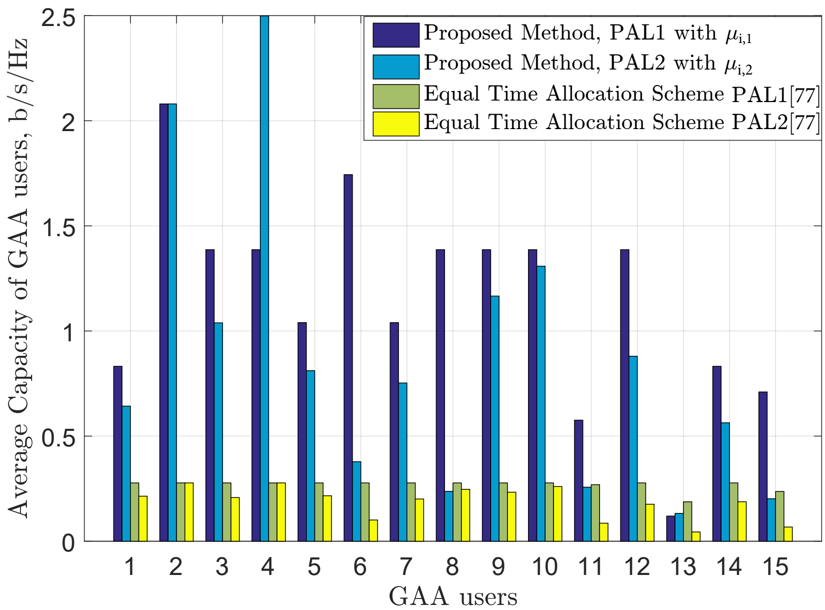


Figure 3.15: Average capacity of GAA users at different PAL channels.

3.7 Summary

In this chapter, we propose an optimum transmit power allocation and transmission time fraction allocation scheme for GAA users when only locations of PAL and GAA users are known. In the SAS, GAA users can opportunistically transmit in a PAL channel when the RMS interference at the boundary of the PAL PA is below

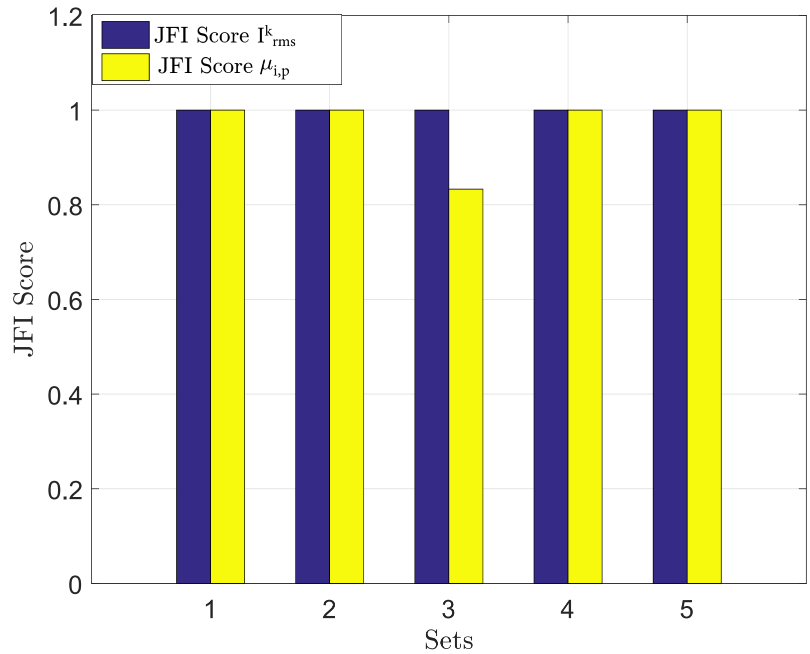


Figure 3.16: JFI score for $I^l_{RMS,m,j}$ and $\mu^{\hat{k}}_{m,l}$ at different PAL channel for different sets of GAA users

the threshold. With the optimisation equation, we can ensure that the transmit power and transmission time fraction is allocated to GAA users without causing any harmful interference to PAL users. We compare our approach of average aggregate interference considering the transmission time fraction with the instantaneous aggregate interference without considering the transmission time fraction allocation. Numerical results show that our joint transmit power and transmission time allocation for GAA users is effective in maximising the capacity of GAA users. From our proposed method, the average aggregate interference is -88.1 dBm which is much less than the maximum allowable interference threshold, i.e. -80 dBm. Second, we propose a method for GAA users to switch to the different channel when the transmission time fraction is below a certain threshold. From the simulation results, we can see that the average downlink capacity of GAA users can be maximised by switching the GAA users with low transmission time fraction to a different channel. For the efficient use of spectrum, fairness is a crucial performance metric to be addressed and we have proposed a method for the transmission time fraction and transmit power allocation for GAA users at different PAL channels for ensuring each GAA user gets the transmission opportunity in the dense area. Our proposed method maximises the average capacity of GAA users using the equal interference threshold allocation to the sets that can hear each other rather than using an equal time allocation scheme to maximise fairness. Simulation results show that fairness and average capacity maximisation of GAA users can be achieved by our proposed method.

Chapter 4

Interference Aware Resource Allocation Scheme for General Authorised Access Users

Facilitating harmonious coexistence among GAA users is another challenge in SAS. Compared to PU and SU coexistence, SU and SU coexistence has drawn less interest from the regulatory bodies and researchers. In this chapter, we discuss an equally important problem, techniques for assuring harmonious sharing between GAA users. We propose a transmit power adjustment method using the knowledge of sets that can hear each other which leads to a significant increase in the GAA network capacity.

4.1 Introduction

In this chapter, we propose an interference aware resource allocation for GAA users, i.e. channel, transmit power and channel utilisation budget allocation for GAA users while satisfying the interference constraint from all the GAA users to the PAL protection. Our proposed resource allocation method ensures a conflict-free channel allocation for GAA users, utilising the information of the sets of GAA users that can hear each other. Our proposed interference aware resource allocation method ensures a conflict-free resource allocation to GAA users considering the following co-channel interferences.

1. Interference to PAL Users:- All GAA users resource allocation is done satisfying the interference constraint proposed by FCC to PAL PAs.

2. Interference among GAA Users:- In a set of GAA users that can hear each other to avoid co-channel interference separate channel or a separate channel utilisation time is allocated to GAA users.

4.1.1 Related Works

Resource allocation for capacity maximisation is a well-investigated topic in cognitive radio networks. However, in these studies [83–86] the sets of secondary users (SUs) that can listen to each other are not considered for the transmit power allocation adjustment. In [83] SU changes the transmit power based on the activity pattern of the primary users (PUs) with the maximum allowed transmit power constraint. To maximise the spectrum utilisation when the channel utilisation information of PU is known an optimisation problem was formulated in [84] with the probability of a collision constraint. In [85, 86] the optimal transmit power allocation is done to cognitive radio users under the limitations on a maximum allowed transmit power and instantaneous interference.

Channel allocation is done in [88–91] considering interference from secondary users to primary users; however, conflicts between secondary users are not considered. In [88] channel allocation is done for cognitive radio networks to maximise the network capacity using binary integer linear programming and the radix tree. Channel allocation for cellular users is done in [89, 90] to maximise the weighted sum rate considering the rate requirement. The resource allocation problem is investigated in [91] considering both the perfect and the statistical channel state information.

Several studies [92–97] on the rate maximisation, interference coordination and fair resource allocation are related to this work. In [92] a channel assignment to maximise the sum rate is proposed subject to the interference, power and signal to interference noise ratio constraints. In [93] for heterogeneous cellular networks, using an interference graph and proportional fair algorithm resource blocks are assigned.

For multichannel cognitive vehicular networks channel allocation is done to maximise the network throughput in [94]. In [95] channel allocation is done to cellular users and power control for D2D users to maximise the sum rate of D2D users by utilising all the channels. In [96] resource allocation for GAA users to ensure fairness was proposed using resource sharing among SASs. In [97] for the SUs resource allocation, to minimise collisions among SUs, only one SU is allocated to one channel. In [97] the authors have considered only the scenario where the number of available channels is greater than or equal to the number of SUs. In a real scenario, it is practical for the number of available channels to be less than the number of the SUs which is not considered in this study.

In all these studies, SUs use spectrum access methods, i.e. hybrid, overlay or underlay depending upon the distance between PU and SU. In a scenario where an SU is close to a PU, SU uses an overlay to access the channel. Whereas, when a PU is far from a SU, a PU channel can be used by SU using the underlay mode. In SAS GAA users are like SU in the cognitive radio network who can access the priority user assigned channels in such a way that they do not cause harmful interference to priority users. In this work, we propose a resource allocation for GAA users based on the number of sets GAA users belong to and the number of GAA users in the set that can hear each other.

In this chapter, the interference-aware resource allocation method for GAA users is proposed that uses the information of a set of GAA users that can hear each other. The GAA users that belong to multiple sets makes the resource allocation problem more challenging. Although the resource allocation method has been studied considering the various constraints for interference protection to the primary user and secondary user, resource allocation is not done considering the users that belong to a single set and multiple sets which differentiate the interference aware resource allocation method from previous works.

TABLE OF NOTATION AND MEANING	
i	GAA users index
i^*	GAA users that belong to single set index
$\hat{i}$	GAA users that belong to multiple set index
m	PAL users index
p	PAL Channel index
k	Set that can hear each other index
$\mathcal{N}$	Set of GAA users
$\mathcal{M}$	Set of PAL users
$\mathcal{P}$	Set of PAL Channel
N	Total number of GAA users
P	Total number of PAL channels
$\beta_{i,p}$	The indicator function for the ith GAA users channel allocation
r_i^*	The optimal carrier sensing range for the ith GAA user
$\mathbb{I}_i^k$	The indicator function to find if the ith GAA user belong to S_k set
$T_{i,p}$	The number of sets the ith GAA user belongs to
$\hat{G}_p$	The total number of active sets in the pth PAL channel
$\mu_{i^*,k}^p$	The channel utilisation budget of the i^*th GAA user in the pth PAL channel
$I_{i,inc}^{p,k}$	The interference budget increment received by the ith GAA user from the other GAA users
$P\hat{t}_{i,p}$	Adjusted transmit power for the ith GAA user

Table 4.1: Table of Notation and Meaning

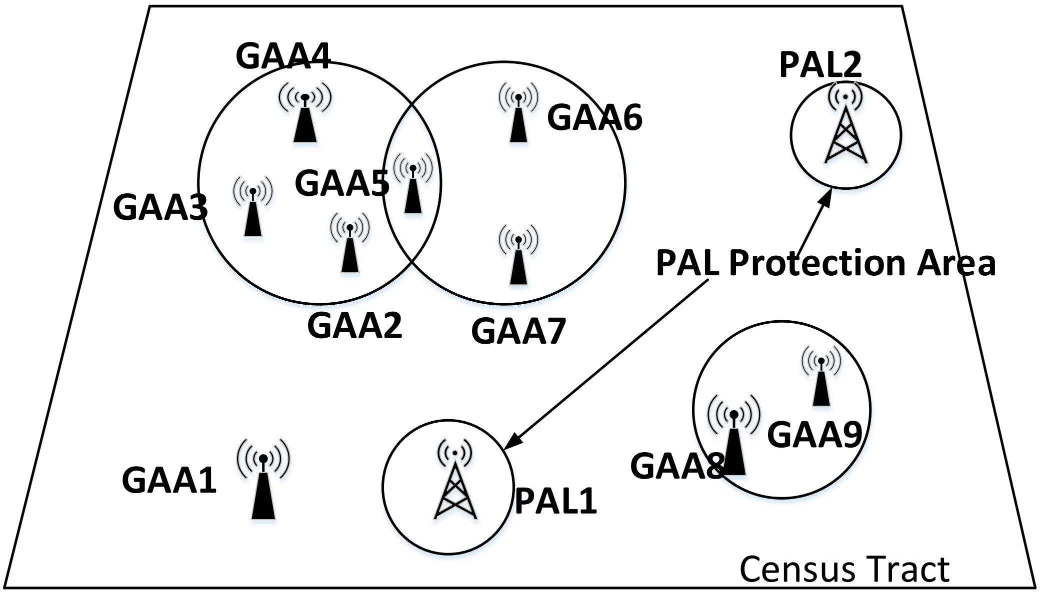


Figure 4.1: Multiple PAL and multiple GAA users in different sets in a census tract.

4.2 System Model

We consider a scenario in which M PAL users and N GAA users are randomly located in the same census tract reporting to the same SAS. We denote the GAA users by i, $i \in \mathcal{N} = \{1, 2, ...N\}$ and the PAL users by m, $m \in \mathcal{M} = \{1, 2, ...M\}$. The PAL channel is denoted by p, $p \in \mathcal{P} = \{1, 2, ...P\}$, with one PAL user in each PAL channel i.e. $M = P$ where P is the total number of channels. In this work, we consider that the number of GAA users is much greater than the available channels, i.e. $N >> P$. Figure 4.1 shows different sets of GAA users that can hear each other with some GAA users in multiple sets. The notation that will be used in this paper is shown in Table 4.1.

To ensure protection of incumbents from PAL and GAA users, CBSDs must inform SAS about their location coordinates and other details [98, 99]. FCC has proposed two categories of CBSDs, i.e. Category A and B based on the maximum allowed transmit power [98, 99]. CBSDs must ensure they transmit at or below the maximum allowed transmit power.

$$0 < Pt_{i,p} \le P_{max} \tag{4.1}$$

where $Pt_{i,p}$ is the transmit power of the ith GAA user when transmitting on the pth channel, and P_{max} is the maximum allowed transmit power for CBSDs.

Let $(x_i,\, y_i)$ be the location coordinates of the ith GAA user and $(x_m,\, y_m)$ be the location coordinates of the mth PAL user. The distance between the mth PAL user and the ith GAA user is given by $d_{i,m} = \sqrt{(x_m - x_i)^2 + (y_m - y_i)^2}$. In this work, we assume that the path loss from PAL user to GAA user and from GAA user to PAL user is the same. The channel gain between the ith GAA user and the uth UE is given by:

$$G_{u,i} = 10^{-\frac{L_{i,u}^{dB}}{10}} \times \zeta_{u,i} \times \Gamma_{u,i}, , \forall u = 1, 2, .., U \tag{4.2}$$

where $L_{i,u}$ is the pathloss between the ith GAA user and the uth GAA end user, $\zeta_{u,i}$ is the shadowing coefficient and is modeled as a correlated lognormal distribution, and $\Gamma_{u,i}$ is the Rayleigh distributed fading coefficient.

4.3 Problem Formulation

In this section, we propose a new resource allocation method for GAA users to maximise the average sum capacity of GAA users. The main focus is to allocate transmit power and channel to GAA users while ensuring the RMS interference at the PAL PA is below the predefined threshold. We use the set based method for the resource allocation of GAA users to mitigate the co-channel interference between GAA users while guaranteeing the interference protection to the PAL user.

Let $\beta_{i,p}$ denote the indicator function for the GAA users channel allocation for all $i \in \mathcal{N}$ and $p \in \mathcal{P}$.

$$\beta_{i,p} = \begin{cases} 1, & \text{if } i\text{th GAA is allocated to the } p\text{th channel} \\ 0, & \text{Otherwise} \end{cases} \tag{4.3}$$

We consider the downlink transmission of the GAA users. The downlink capacity for the ith GAA network when transmitting on the pth channel is given by:

$$C_{i,p} = \sum_{u=1}^{U_i} \log_2 \left(1 + \frac{Pt_{i,p} G^p_{u,i}}{P_N + \sum_{j \in \{SS\} \backslash \{S^i_k\}} Pt_{j,p} G^p_{u,j}} \right) \tag{4.4}$$

where U_i is the total number of GAA user equipment, $Pt_{i,p}G^p_{u,i}$ is the received power of the uth GAA receiver from the ith GAA user transmitting in the pth channel, P_N is the noise power, and $\sum_{j \in \{SS\} \backslash \{S^i_k\}} Pt_{j,p} G^p_{u,j}$ is the received power by the uth GAA receiver from the jth GAA user in the set $\{SS\}\backslash\{S^i_k\}$, and $j \neq i$.

To maximise the GAA network capacity, we use the channel allocation matrix (H) for all the PAL channels.

$$H = \begin{bmatrix} \beta_{1,1} & \beta_{2,2} & \dots & \beta_{N,1} \\ \beta_{1,2} & \beta_{2,2} & \dots & \beta_{N,2} \\ \dots & \dots & \dots & \dots \\ \beta_{1,P} & \beta_{2,P} & \dots & \beta_{N,P} \end{bmatrix} \tag{4.5}$$

$R = \{C_{i,p} | C_{i,p} \geq 0\}$ contains the capacity of each GAA users on the pth PAL channel, i.e.

$$R = \begin{bmatrix} C_{1,1} & C_{2,1} & \dots & C_{N,1} \\ C_{1,2} & C_{2,2} & \dots & C_{N,2} \\ \dots & \dots & \dots & \dots \\ C_{1,P} & C_{2,P} & \dots & C_{N,P} \end{bmatrix} \tag{4.6}$$

for $p = 1, ..., P$.

We use the Hadamard product to multiply two matrices H and R of the same size to get another matrix of the same size, i.e.

$$H \circ R = \begin{bmatrix} \beta_{1,1}C_{1,1} & \beta_{2,1}C_{2,1} & \dots & \beta_{N,1}C_{N,1} \\ \beta_{1,2}C_{1,2} & \beta_{2,2}C_{2,2} & \dots & \beta_{N,2}C_{N,2} \\ \dots & \dots & \dots & \dots \\ \beta_{1,P}C_{1,P} & \beta_{2,P}C_{2,P} & \dots & \beta_{N,P}C_{N,P} \end{bmatrix} \tag{4.7}$$

H and R are matrices of size $P \times N$. $\left(H \circ R\right)$ will be a matrix of the same size as H and R.

Using the channel allocation matrix (H) for all the PAL channels and the capacity of each GAA users on each PAL channel we calculate the average sum capacity of GAA user over P PAL channels as:

$$\sum_{p=1}^{P}\sum_{i=1}^{N}\frac{1}{N}\left(H \circ R\right) \tag{4.8}$$

Using $\left(r_i^* = 10^{\left(\frac{10\log_{10}\left(\frac{P_{max}}{Pr}\right)-46.4-20\times\log_{10}\frac{f}{5.0}}{20}\right)}\right)$ from equation (3.21) and ($d_{ij} \leq \min\{r_i^*, r_j^*\}$) from equation (3.22) we can find the sets of GAA users that can hear each other. We define SS_p as the superset of all the interfering sets of GAA users, i.e. $S_k \subset SS$

$$SS_p = \{S_1, S_2, .., S_k, .., S_{G_p}\} \tag{4.9}$$

where G_p is the total number of the set on the pth channel that can hear each other.

In the set S_k, only one GAA user can transmit at a particular time in a particular channel. The number of sets the ith GAA user belongs to can be calculated using:

$$\mathbb{I}_i^k = \begin{cases} 1, & \text{if } i \in S_k \\ 0, & \text{if } i \notin S_k \end{cases} \tag{4.10}$$

$$T_{i,p} = \sum_{k=1}^{G_p}\mathbb{I}_i^k, \forall i = 1, .., N \tag{4.11}$$

where $T_{i,p}$ is the number of sets the ith GAA user belongs in the pth channel.

4.3.1 Channel Utilisation Budget for GAA Users that Belong to a Single Set and Multiple Sets

When a GAA user that belongs to multiple sets transmits, all other GAA users from the sets that the transmitting GAA user belongs to cannot transmit at the same time on the same channel. To give the transmission opportunity to all GAA users, and to mitigate the co-tier interference between GAA users we allocate the channel utilisation budget to GAA users. In this work, we define the channel utilisation budget as the fraction of time in which a GAA user is active in a certain period.

The channel utilisation budget of the ith GAA user in the pth PAL channel is denoted as μ_i^p and is given by:

$$\mu_i^p = \lim_{T \to \infty} \frac{t_i^p}{T} \tag{4.12}$$

where t_i^p is the transmission time of the ith GAA user in the pth PAL channel, T is the total time period.

To provide an opportunity to all GAA users to access the PAL channel we initially allocate an equal channel utilisation budget, i.e. $\mu_{i,k}^p = \frac{1}{|S_k^i|}$ to GAA users in the set of GAA users that can hear each other taking into consideration the cardinality of the set.

We denote a GAA user that belongs to multiple sets as $\hat{i}$ and a GAA user that belongs to a single set by i^*. When $T_i > 1, \forall i \in S_k$, the $\hat{i}$th GAA user will have different channel utilisation budgets for different sets; for a conflict-free channel utilisation budget allocation to GAA users in multiple sets we find the set with the minimum channel utilisation budget, i.e.

$$\mu_{\hat{i},\hat{k}}^p = \min\{\mu_{i,k}^p\}, \forall k = 1, 2, ...N_s \tag{4.13}$$

where $\hat{k}$ is the set with the minimum channel utilisation budget which the $\hat{i}$th GAA user belongs to.

In our proposed method, GAA users with $T_i = 1$ use the channel utilisation budget from GAA users with $T_i > 1$ from the same set that can hear each other. The channel utilisation budget increment of the i^*th GAA user depends upon the difference between the channel utilisation budget of the $\hat{i}$th GAA user in the kth and the $\hat{k}$th set, i.e. $(\mu_{\hat{i},k}^p - \mu_{\hat{i},\hat{k}}^p)$. The channel utilisation budget increment received by the i^*th GAA user from other GAA users in a set S_k is $\sum_{\hat{i} \in S_k} \frac{\mu_{\hat{i},k}^p - \mu_{\hat{i},\hat{k}}^p}{\mathbb{E}_k}$, where $\mathbb{E}_k$ is the total number of GAA users that only belong to a single set, i.e. S_k set.

For the i^*th GAA user that satisfies the condition $T_i = 1$, the i^*th GAA will receive the channel utilisation budget difference from the GAA users that are in multiple sets. The channel utilisation budget of the i^*th GAA user is given by:

$$\mu_{i^*,k}^p = \mu_{i,k}^p + \sum_{\hat{i} \in S_k} \frac{\mu_{\hat{i},k}^p - \mu_{\hat{i},\hat{k}}^p}{\mathbb{E}_k}, \forall k = 1, 2, ...N_s \tag{4.14}$$

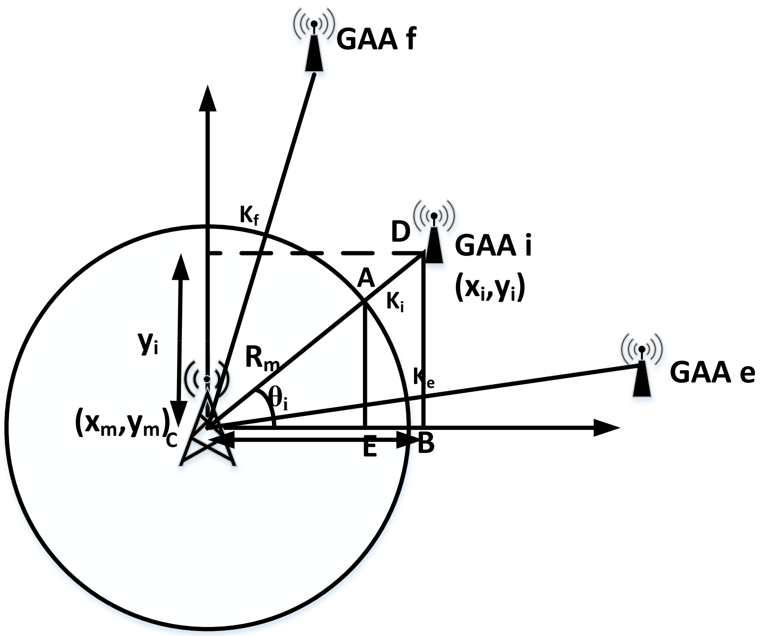


Figure 4.2: RMS interference from multiple GAA users to the PAL user protection area

4.3.2 PAL Users Protection from Multiple GAA Users

In SAS, location coordinates of PAL and GAA users, i.e. (x_m, y_m) ,$\forall m \in \mathcal{M}$ and (x_i, y_i), $\forall i \in \mathcal{N}$ and the radius of PAL PA, i.e. R_m are known to SAS. To calculate the RMS interference at the PAL PA we first need to find the points at the PAL PA with the worst RMS interference from GAA users. Figure 4.2 shows the nearest points from GAA users to the PAL PA, i.e. K_i, $\forall i \in \mathcal{N}$. From the figure, we can see that $BC = x_m - x_i$ and $BD = y_m - y_i$. In SAS the location coordinates of GAA users are known, however to find RMS interference from GAA users to the point (K_i) at the PAL PA with the worst interference we need to find the location coordinates of the point K_i, $\forall i \in \mathcal{N}$. Let (x_{m,K_i}, y_{m,K_i}) be the location coordinates of the point K_i.

To find the coordinates (x_{m,K_i}, y_{m,K_i}) we first need to find the angle θ_i.

$$\cos\theta_i = \frac{BC}{CD} = \frac{\sqrt{(x_m - x_i)^2}}{d_{i,m}} \tag{4.15}$$

where the location coordinates at point B are (x_i, y_m)

$$\theta_i = \cos^{-1}\left(\frac{\sqrt{(x_m - x_i)^2}}{d_{i,m}}\right) \tag{4.16}$$

Using θ_i we can find the x and y coordinates at point A, i.e.

$$x_{m,K_i} = x_m + R_m \cos\theta_i \tag{4.17}$$

$$y_{m,K_i} = y_m + R_m \sin\theta_i \tag{4.18}$$

Using the same method, we can find the location coordinates of point K_i, $\forall i \in \mathcal{N}$ and we can calculate the distance between the ith GAA user and point K_i at PAL PA $\left(d_{K_i,m}\right)$ $\forall i \in \mathcal{N}$ using:

$$d_{K_i,m} = \sqrt{(x_{m,K_i} - x_i)^2 + (y_{m,K_i} - y_i)^2}, \forall i = 1, 2, ...N \tag{4.19}$$

RMS interference at the mth PAL PA from N number of GAA users at point K_i is given by

$$I^{rms}_{m,K_i} = \sum_{i=1}^{N} I_{i,m,K_i}\mu^p_{i,k},\ \forall i = 1, 2, ...N \tag{4.20}$$

where I_{i,m,K_i} is the interference from the ith GAA user to the K_i point in the PAL user PA .

Multiple GAA users can be allocated to the same PAL channel if the RMS interference is below the SAS assigned threshold, i.e.

$$I^{rms}_{m,K_i} \leq I_{th} \tag{4.21}$$

where I_{th} is the FCC proposed interference threshold to protect PAL from harmful interference.

Proposition 1. *RMS interference from GAA users at point K_i at PAL PA boundary $\forall i \in \mathcal{N}$ should be below the interference threshold.*

In Figure 4.2 the shortest distance between the ith GAA user and the mth PAL user is d^i_{m,K_i}, i.e. point K_i in the PAL PA is the shortest point from the ith GAA user to the mth PAL PA. At point K_i in the PAL user PA, the mth PAL user receives maximum RMS interference from the ith GAA users. Point K_i is the point with the worst interference from the ith GAA users. Hence, to protect the PAL from harmful interference RMS interference at point $K_i, \forall i \in \mathcal{N}$ should be below the FCC proposed interference threshold.

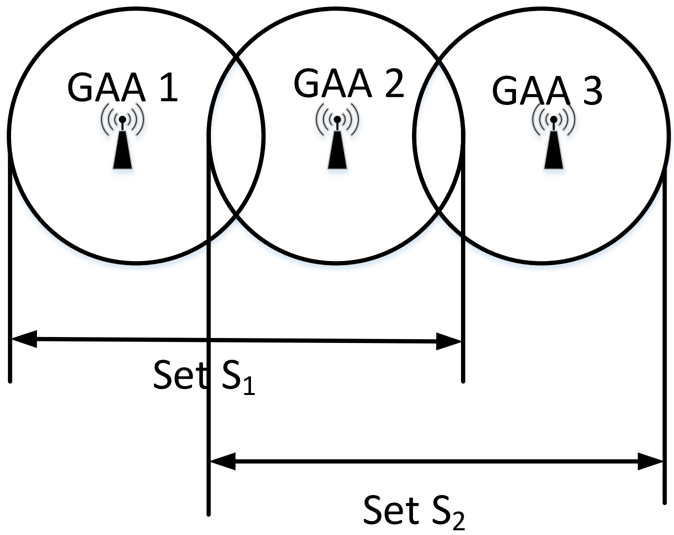


Figure 4.3: GAA users in multiple sets

4.3.3 GAA Users Channel Assignment Condition

In SAS, a PAL channel is considered in use within the PAL PA, and the channel allocation differs considerably based on the location of GAA users. To protect the mth PAL user from harmful interference, GAA users inside of the PAL PA (i.e., $d_{i,m} < R_m$) should not be allocated to the same channel with the PAL user. Let $\chi^c_{i,m}$ denote the indicator function for GAA users inside or outside the mth PAL user PA.

$$\chi^p_{i,m} = \begin{cases} 1, & \text{if } i\text{th GAA is inside the } m\text{th PAL PA} \\ 0, & \text{Otherwise} \end{cases} \tag{4.22}$$

4.3.4 Conflict-free Channel Allocation for GAA Users

In this work, we present a channel allocation scheme to mitigate the interference between GAA users in the same channel using the set based resource allocation. We first find the set S_k, and to mitigate the co-channel interference between GAA users in the set only one GAA user from the set S_k should be allocated to the same channel at the same time, i.e.

$$\sum_{i \in S_k} \beta_{i,p} \mathbb{I}^k_i \leq 1, \ \forall k = 1, 2, ...G_p \tag{4.23}$$

In this work, we divide the GAA users based on the number of sets they belong to. GAA users that belong to multiple sets make the resource allocation problem more challenging. For a conflict-free channel allocation in a scenario as shown in Figure 4.3 if the pth PAL channel is allocated to GAA1 user from set S_1, then GAA2 user cannot be assigned to the same channel from the set S_2, i.e.

$$\sum_{\hat{i}\in S_k} \beta_{\hat{i},p}\mathbb{I}_{\hat{i}}^{k} + \sum_{i^*\in S_k} \beta_{i^*,p}\mathbb{I}_{i^*}^{k} \leq 1, i^* \neq \hat{i} \;\forall k = 1,2,....G_p \tag{4.24}$$

Using (4.24) we can ensure that a GAA user that belongs to multiple sets does not interfere with a GAA user that belongs to single set.

4.3.5 Resource Allocation for GAA Users

In this section, we present the channel allocation and transmit power allocation of GAA users to maximise the average GAA sum capacity. The optimisation problem can be formulated as:

$$\begin{aligned}
\underset{\beta_{i,p},Pt_{i,p}}{\text{maximize}} \quad & \sum_{p=1}^{|\mathcal{P}|}\sum_{i=1}^{|\mathcal{N}|} \beta_{i,p}\mu_{i,k}^{p}C_{i,p} \\
\text{subject to} \quad & C1 : 0 < Pt_{i,p} \leq P_{max} \\
& C2 : I_{m,K_i}^{rms} \leq I_{th}, \forall i \in \hat{\mathcal{N}} \\
& C3 : \beta_{i,p} \in \{0,1\}, \forall p \in \mathcal{P}, \forall i \in \mathcal{N} \\
& C4 : \sum_{i\in\mathcal{N}} \beta_{i,p} \leq 1 \\
& C5 : \sum_{i\in S_k} \beta_{i,p}\mathbb{I}_{j}^{\hat{k}} \leq 1, \forall \hat{k} = 1,2,....\hat{G}_p, \forall p \in \mathcal{P} \\
& C6 : \sum_{\hat{i}\in S_{\hat{k}}} \beta_{\hat{i},p}\mathbb{I}_{\hat{i}}^{\hat{k}} + \sum_{i^*\in S_{\hat{k}}} \beta_{i^*,p}\mathbb{I}_{i^*}^{\hat{k}} \leq 1, i^* \neq \hat{i} \\
& C7 : \chi_{i,m}^{p} = 0, \forall m \in \mathcal{M}
\end{aligned} \tag{4.25}$$

where $\hat{N}$ is the total number of transmitting GAA users, $C1$ is the constraint for the maximum allowed transmit power for the GAA users. The RMS interference from the GAA users to the PAL PA should be below the FCC proposed threshold which is shown in constraint $C2$. Constraint $C4$ denotes that one GAA user can be assigned a single channel at the particular time. Constraint $C5$ ensures that only one GAA user from the set of GAA users that can hear each can be assigned to one channel at a particular time. Constraint $C6$ ensures that a GAA user that belongs to multiple sets does not interfere with a GAA user that belongs to a single set. Constraint $C7$ is to ensure that the GAA users within the PAL user PA should not be allocated to the same frequency channel as the PAL user.

The optimisation problem (4.25) is a mixed integer linear programming (MILP) problem with integer $\beta_{i,p}$ that is used for channel allocation and the continuous variables of transmit power and aggregate interference. The MILP problem in (4.25) has high computational complexity, and the complexity increases with the number of PAL channels and the number of GAA users [107]. To solve this resource allocation problem with low computational complexity, we divide the problem into two subproblems: channel and transmit power allocation of GAA users.

4.3.6 Transmit Power Allocation for GAA Users

In this section, we investigate the optimal tansmit power allocation for GAA users to maximise the average sum capacity of the GAA users subject to the transmit power, and RMS interference constraints to the PAL PA. To ensure the interference to the PAL PA from the different sets is below the interference threshold, the sets of GAA users are allocated an interference budget threshold which is given by $\hat{I_{th}} = \frac{I_{th}}{G_p}$.

Considering all GAA users are transmitting at the same time in the same (pth) channel, the optimisation problem to find the optimum transmit power allocation that maximises the average sum capacity of GAA users can be formulated as:

$$\begin{aligned} \max_{Pt_{i,p}} \quad & \sum_{i=1}^{|S_k|} \frac{1}{|S_k|} \log_2 \left(1 + \frac{Pt_{i,p} G_{u,i}^p}{P_N + \sum_{j \in \{S_k^i\} \setminus \{i\}} Pt_{j,p} G_{u,j}^p} \right) \\ \text{s.t.} \quad & 0 < Pt_{i,p} \leq P_{max} \\ & I_{m,K_i}^{rms} \leq \hat{I_{th}}, \forall i \in S_k \end{aligned} \tag{4.26}$$

Lemma 1. *The optimisation equation (4.26) is a convex optimisation problem.*

Proof. To prove that the optimisation equation (4.26) is a convex optimisation problem, we need to prove that the objective equation is concave or convex and the constraints are convex.

The objective function for the set of GAA users allocated to the pth channel is:

$$f(\mu_{i,k}^{p}, Pt_{i,p}) = \mu_{i,k}^{p} C_{i,p} \tag{4.27}$$

The Hessian matrix of the above objective function with respect to $\mu_{i,k}^{p}$ and $Pt_{i,p}$ can be obtained as:

$$H(f) = \begin{bmatrix} -\frac{1}{\ln 2}\frac{\mu_{i,k}^{p}(G_{u,i})^2}{\left(P_N+\sum_{j\in\{S_k^i\}\backslash\{i\}} Pt_{j,p}G_{u,j}+Pt_{i,p}G_{u,i}\right)^2} & 0 \\ 0 & 0 \end{bmatrix} \tag{4.28}$$

The eigen value of the first element of Hessian matrix (4.28) is negative. Hence we can determine that the hessian matrix is negative semidefinite and the objective function is concave. The inequality constraint in optimisation equation (4.26) is convex, so the feasible set of the objective equation is convex and the optimization equation (4.26) is a convex problem. □

Based on the convexity proof for the optimisation equation (4.26) we obtain the optimal solution of (4.26) by using the Karush-Kuhn-Tucker (KKT) conditions. Using the interference constraint, the optimal transmit power can be allocated to the ith GAA user when transmitting on the pth channel. The Lagrangian can be written as :

$$\mathcal{L} = \sum_{i=1}^{|S_k|} \frac{1}{|S_k|} \log_2\left(1 + \frac{Pt_{i,p}G_{u,i}^{p}}{P_N + \sum_{j\in\{S_k^i\}\backslash\{i\}} Pt_{j,p}G_{u,j}^{p}}\right) + \lambda_p\left(\hat{I_{th}} - \frac{1}{N}\sum_{i=1}^{N} Pt_{i,p}G_{i,K_i}^{p}\mu_{i,k}^{p}\right) \tag{4.29}$$

where λ_p is the non-negative Lagrange multiplier. The Karush Kuhn Tucker condition can be described as follows:

$$\lambda_p \geq 0;\; Pt_{i,p} > 0 \tag{4.30}$$

$$\lambda_p\left(\frac{1}{N}\sum_{i=1}^{N} Pt_{i,p}G_{i,K_i}^{p}\mu_{i,k}^{p} - \hat{I_{th}}\right) = 0,\; \forall p, \forall i \in S_k \tag{4.31}$$

$$\frac{\partial \mathcal{L}}{\partial Pt_{i,p}} = \frac{G^p_{u,i}}{\ln_2\left(P_N + \sum_{j\in\{S^i_k\}\setminus\{i\}} Pt_{j,p}G^p_{u,j} + G^p_{u,i}Pt_{i,p}\right)} - \frac{\lambda_p}{N}\sum_{i=1}^{N}\mu^p_{i,k}G^p_{i,K_i} = 0 \quad (4.32)$$

Solving (4.32) we get the optimal transmit power of the ith GAA user ($Pt^*_{i,p}$) to maximise the GAA network capacity , i.e.

$$Pt^*_{i,p} = \left[\frac{N}{\lambda_p \ln_2 \sum_{i=1}^{N}\mu^p_{i,k}G^p_{i,K_i}} - \frac{P_N + \sum_{j\in\{S^i_k\}\setminus\{i\}} Pt_{j,p}G^p_{u,j}}{G^p_{u,i}}\right]^+ \quad (4.33)$$

The Lagrange multiplier is calculated using (4.31) and (4.33)

$$\lambda_p = \frac{N}{\sum_{i=1}^{N}\mu^p_{i,k}G^p_{i,K_i}\left(\hat{I_{th}} + \frac{P_N + \sum_{j\in\{S^i_k\}\setminus\{i\}} Pt_{j,p}G^p_{u,j}}{G^p_{u,i}}\right)} \quad (4.34)$$

Transmit Power Adjustment

In this work, we define the interference budget increment as the additional interference budget that can be used by the transmitting GAA user from other GAA users in the same set that can hear each other. Interference budget increment depends upon the number of sets GAA users belong to and the number of GAA users in the set. The interference budget increment received by the ith GAA user from the other GAA users is

$$I^{p,k}_{i,inc} = \sum_{k=1}^{G_p}\mathbb{I}^k_j \sum_{\substack{j\in S_k \\ j\neq i}} \frac{I^j_{m,K_j}}{T_j} \quad (4.35)$$

where I^j_{m,K_j} is the interference from the jth GAA user on the point K_j of the mth PAL user PA when transmitting with transmit power calculated using (4.33).

The adjusted interference budget of the ith GAA user can be calculated using:

$$I^{i\,\hat{}}_{m,K_i} = I^i_{m,K_i} + I^{p,k}_{i,inc} \quad (4.36)$$

where $I^{i\,\hat{}}_{m,K_i}$ is the adjusted interference budget for the ith GAA user in the set S_k.

We can use (4.35) and (4.36) to calculate the adjusted transmit power for the ith GAA user using the adjusted interference budget.

$$P\hat{t}_{i,p} = \frac{I^{i\,\hat{}}_{m,K_i}}{L_{i,K_i}} \quad (4.37)$$

4.3.7 Channel Allocation for GAA Users

In the proposed method single or sets of GAA users are allocated the channel in a scenario when $N >> P$ to maximise the average GAA sum capacity considering the interference to the PAL user PA and the collision avoidance among GAA users in a single set. The optimisation equation for GAA users channel allocation can be formulated as:

$$\begin{aligned} \underset{\beta_i^p}{\text{maximize}} \quad & \sum_{p=1}^{|\mathcal{P}|}\sum_{i=1}^{|\mathcal{N}|} \beta_{i,p}\mu_{i,k}^{p} C_{i,p} \\ \text{subject to} \quad & C3 : \beta_i^p \in \{0,1\}, \forall i \in \mathcal{N}, \forall p \in \mathcal{P} \\ & C4 : \sum_{i\in\mathcal{N}} \beta_i^p \leq 1, \forall i \in \mathcal{N} \\ & C5 : \sum_{i\in S_k} \beta_i^p \mathbb{I}_u^k \leq 1, \forall k = 1,2,....N_s, \forall p \in \mathcal{P} \\ & C6 : \sum_{\hat{i}\in S_k} \beta_{\hat{i},p}\mathbb{I}_{\hat{i}}^k + \sum_{i^*\in S_k} \beta_{i^*,p}\mathbb{I}_{i^*}^k \leq 1, i^* \neq \hat{i} \end{aligned} \tag{4.38}$$

In this work, using (4.38) the set of non-conflicting GAA users is allocated to the same channel at the same time to maximise the GAA network capacity. The optimisation equation (4.38) considers the GAA users in a single and multiple sets.

Lemma 2. *To maximise the GAA network capacity optimal channel allocation can be achieved when the channels are allocated to GAA users that have the highest signal to interference plus noise ratio.*

Proof. The Lagrangian can be written as :

$$\begin{aligned} \mathcal{L} = & \sum_{p=1}^{|\mathcal{P}|}\sum_{i=1}^{|\mathcal{N}|} \frac{\beta_i^p}{N} \log_2\left(1 + \frac{Pt_{i,p}G_{u,i}^p}{P_N + \sum_{j\in\{S_k^i\}\setminus\{i\}} Pt_{j,p}G_{u,j}^p}\right) \\ & + \alpha_p\left(1 - \sum_{i\in S_k}\beta_i^p\right) + \delta_p\left(1 - \sum_{\hat{i}\in S_k}\beta_{\hat{i},p}\mathbb{I}_{\hat{i}}^k - \sum_{i^*\in S_k}\beta_{i^*,p}\mathbb{I}_{i^*}^k\right) \end{aligned} \tag{4.39}$$

where α_p and δ_p are the non-negative Lagrangian multipliers.

If the pth channel is allocated to the ith GAA users, according to the Karush Kuhn Tucker condition the following condition should be satisfied:

$$\log_2\left(1 + \frac{Pt_{i,p}G_{u,i}^p}{P_N + \sum_{j\in\{S_k^i\}\setminus\{i\}} Pt_{j,p}G_{u,j}^p}\right) - \alpha_p - \delta_p = 0 \tag{4.40}$$

Our objective is to allocate the ith GAA user to the pth channel that maximises the GAA network capacity, the necessary condition for $\beta_i^p = 1$ is given by:

$$\begin{aligned}\hat{\beta_{i,p}} &= \max_{\beta_i^p} \log_2 \left(1 + \frac{Pt_{i,p}G_{u,i}^p}{P_N + \sum_{j\in\{S_k^i\}\setminus\{i\}} Pt_{j,p}G_{u,j}^p}\right) \\ &= \max_{\beta_i^p} \left(\frac{Pt_{i,p}G_{u,i}^p}{P_N + \sum_{j\in\{S_k^i\}\setminus\{i\}} Pt_{j,p}G_{u,j}^p}\right)\end{aligned} \tag{4.41}$$

which means that the pth channel is allocated to the GAA user with highest signal to interference plus noise ratio.

□

4.3.8 GAA Users Resource Allocation Algorithm

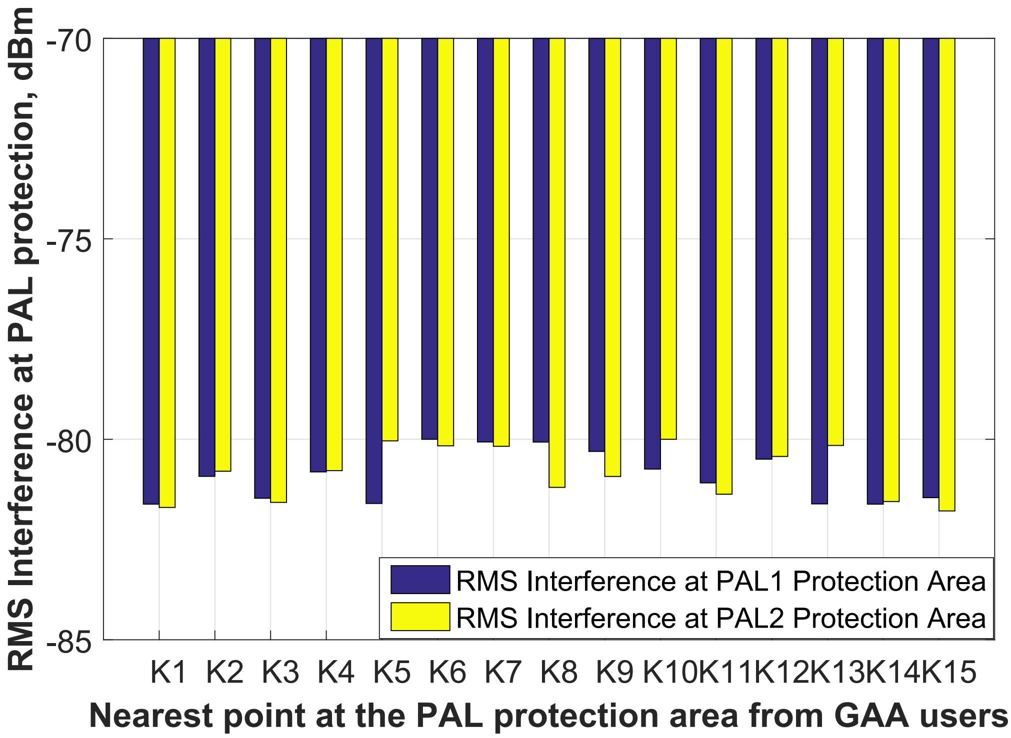
In the proposed algorithm, i.e. Algorithm 2 transmit power, channel and channel utilisation budget is allocated to GAA users using our proposed set based resource allocation. Transmit power and channel utilisation adjustment is proposed to maximise the average GAA sum capacity. ur proposed interference aware resource allocation method considers the GAA users that can hear each other in a single set and/or multiple sets. Algorithm 2 has a lower computational complexity of $N(G_pP|\mathcal{M}|)$.

4.4 Numerical Results

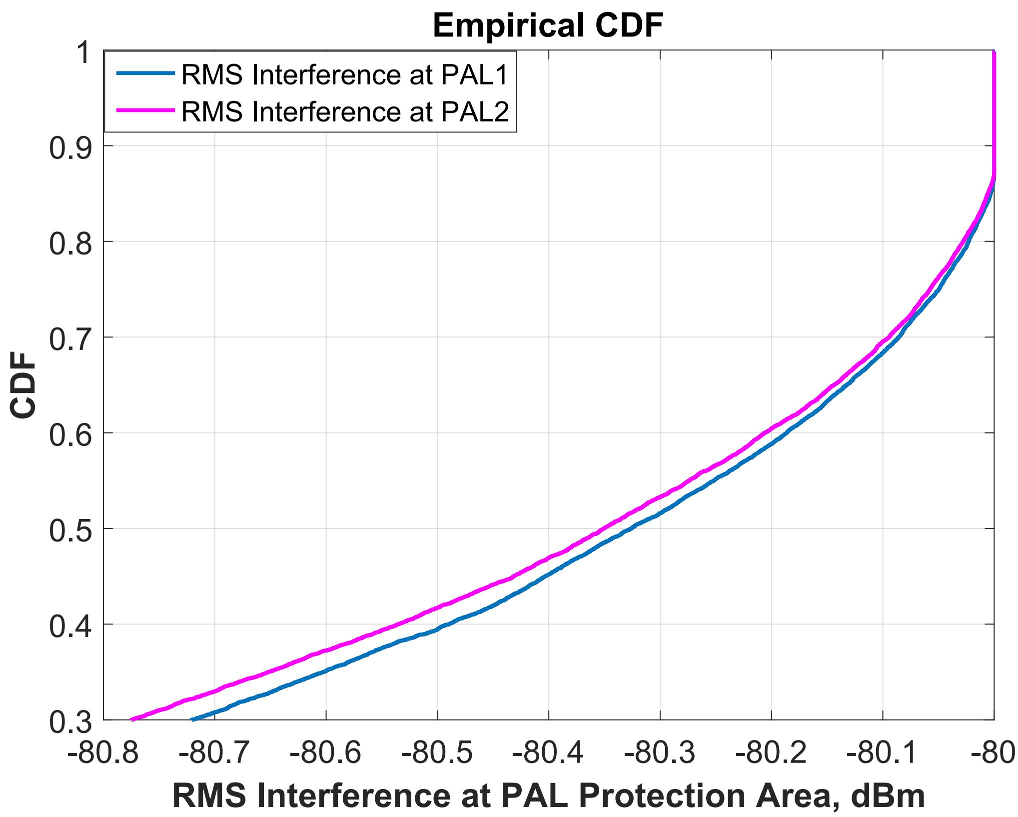
This section presents simulation results for our problem formulation which is presented in Section III. We consider the scenario in which there are 2 PAL channels with 2 PAL users and 15 GAA users randomly located within a range of 400 meters in both x and y coordinates. To calculate the downlink capacity of a GAA user, we randomly allocate 6 GAA user equipments per GAA user. This problem can be easily extended to multiple PAL users allocated to the same channel by considering maximum interference from GAA users to PAL PA. In SAS GAA users can access a PAL channel when the RMS interference from transmitting GAA user is below the −80dBm threshold at the PAL PA when integrated over a 10 MHz reference bandwidth [98,99]. In the simulation, we used the maximum allowed transmit power for users as 30 dBm [99] and central frequency 3.6 GHz.

Algorithm 2 Resource Allocation of GAA users considering the CS range

Input: P_{max}, I_{th}
for GAA i, $i = \{1, ..., N\}$ **do**
  $r_i^* = 10^{\left(\frac{10\log_{10}\left(\frac{P_{max}}{Pr}\right) - 46.4 - 20\times\log_{10}\frac{f}{5.0}}{20}\right)}$.
  Find set S_k, using $d_{ij} \leq \min\{r_i^*, r_j^*\}$.
  Calculate the number of sets the jth GAA belongs to using $T_j = \sum_{k=1}^{N_s} \mathbb{I}_j^k$.
  for PAL Channel p, $p = \{1, ..., P\}$ **do**
    Find $\mu_{i,k}^p$ using the sets information.
    Find GAA users that satisfy $T_i = 1$ and $T_i > 1$ condition.
    if $T_i > 1$ **then**
      Find the $\hat{k}$th set and calculate $\mu_{i,\hat{k}}^p$ using (4.13)
    else
      Calculate $\mu_{i^*,k}^p$ using (4.14)
    end if
    for PAL m, $m = \{1, ..., M\}$ **do**
      Find the points in the mth PAL protection area with the worst interference from GAA users using (4.17) and (4.18).
      $I_{m,K_i}^{rms} = \sum_{i=1}^{N} I_{i,m,K_i}\mu_{i,k}^p, \ \forall i = 1, 2, ...N.$
    end for
    Find the initial interference budget of the ith GAA users using (4.33).
    $I_{i,inc}^{p,k} = \sum_{k=1}^{N} \mathbb{I}_j^k \sum_{\substack{j\in S_k \\ j\neq i}} \frac{I_{m,K_j}^j}{T_j}$.
    $\hat{I}_{m,K_i}^{i} = I_{m,K_i}^i + I_{i,inc}^{p,k}$.
    Calculate adjusted transmit power for the ith GAA user using (5.22).
    for set k, $k = \{1, ..., G_p\}$ **do**
      Find β_i^p using (4.41).
      Repeat for all GAA users in the set $S_k, \forall\ k = 1, .., G_p$ to find H.
    end for
  end for
end for
Output:β_i^p, $\mu_{i,k}^p$, $\hat{Pt}_{i,p}$



(a) RMS interference at different points in the PAL1 and PAL2 users protection



(b) CDF of RMS interference at PAL1 and PAL2 users protection area.

Figure 4.4: RMS interference at the PAL users protection area from the GAA users

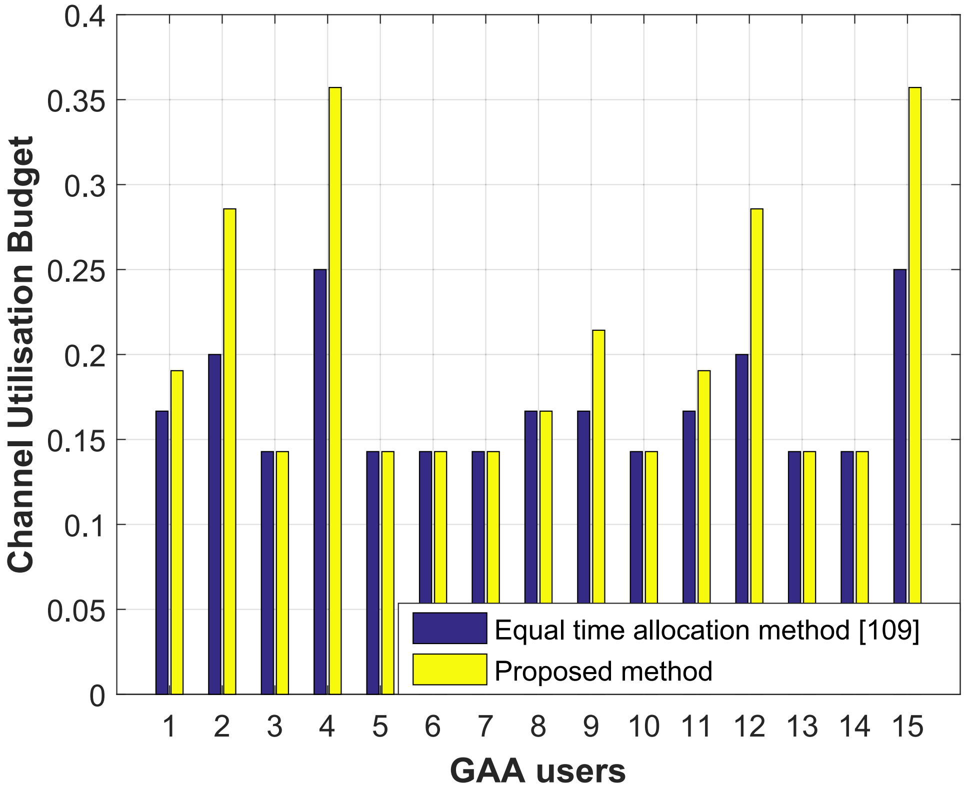


Figure 4.5: CDF of channel utilisation budget from our proposed adjustment method using similar method as in [109].

Figure. 4.4 shows that the RMS interference constraint is satisfied by our proposed method in the PAL PA. Figure. 4.4a shows the RMS interference at the points K_i, in the PAL1 and PAL2 PAs, i.e. the nearest point in the PAL PA from the ith GAA user. Figure. 4.4b shows a CDF of RMS interference at the PAL1 user and the PAL2 users protection area. RMS interference at the PAL protection area from our proposed method is equal to or less than -80 dBm. CDF function has the vertical jump of height 1/n at each of the n data values. Figure 4.4 shows a vertical jump at the RMS interference value of -80 dBm, i.e., the FCC proposed RMS interference threshold. The number of occurrences of -80 dBm is high, as in our proposed method the interference budget of the other users in the set S_k is allocated to the transmitting GAA user. Similar jumps can be obseved in Figures 4.8, 4.9, 4.10 and 4.13.

Figure 4.5 shows the channel utilisation budget from our proposed method compared to equal time allocation [109]. In this work, first we allocate equal time to GAA users in a set that can hear each other. Then, the channel utilisation budget

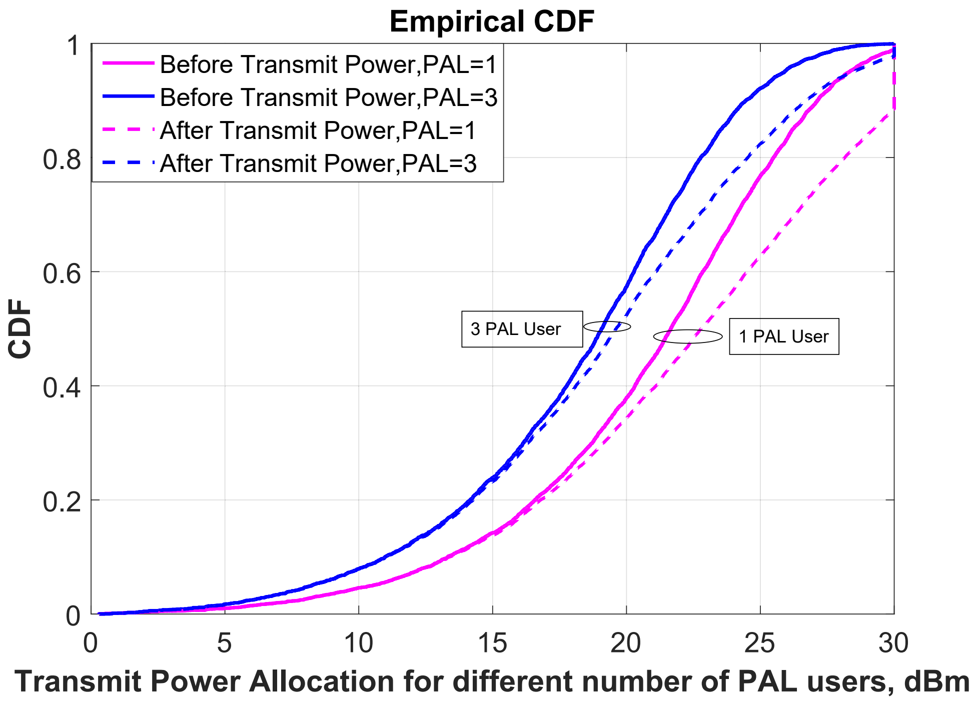


Figure 4.6: CDF of transmit power allocation for 15 GAA users for the different number of PAL users in a single channel.

adjustment is done considering GAA users in the single set and multiple sets. The results show the channel utilisation budget increment for GAA users from the GAA users that belong to multiple sets.

Figure 4.6 shows the cdfplot for transmit power allocation for GAA users for the different number of PAL users i.e. 1, 3, from optimisation equation (4.26), i.e. before and with our proposed algorithm, i.e. after. The results show that there is more transmit power allocation to GAA users from our proposed method, and when the number of PAL users is less. When there is a single PAL user, GAA users need to satisfy the interference protection to only one PAL PA and GAA users have more interference budget compared to multiple PAL users. In a scenario, with multiple PAL users, the interference from GAA users to all PAL PAs should be below the predetermined threshold.

Fig. 4.7 shows the cumulative distribution function (CDF) of instantaneous aggregate interference from GAA users to PAL users for different number of PAL users from optimisation equation (4.26) and our proposed algorithm. The results show that the instantaneous aggregate interference from the proposed method is

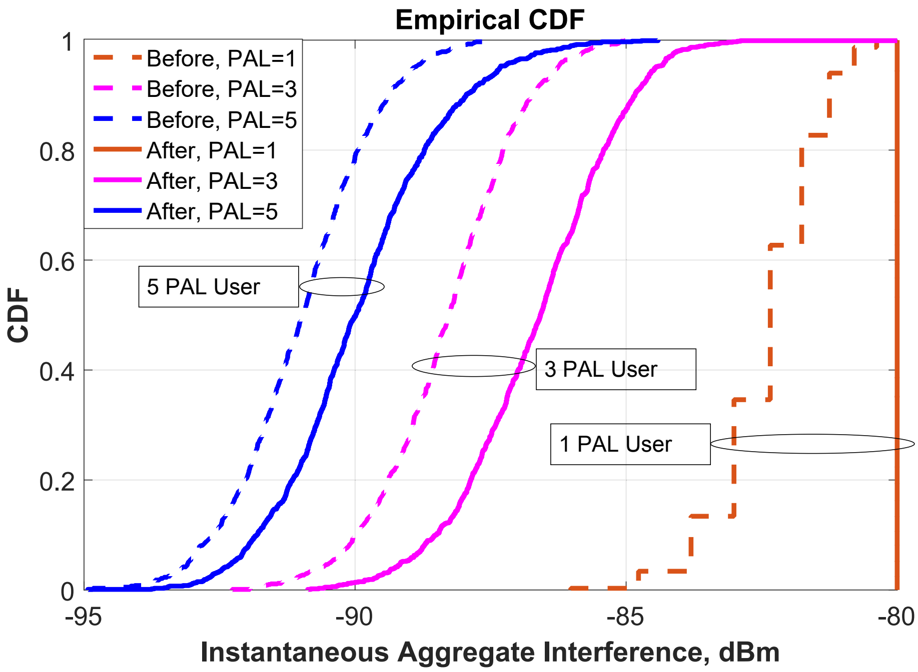


Figure 4.7: CDF of instantaneous aggregate interference for 15 GAA users for the different number of PAL users.

more than the optimisation equation (4.26) and the results satisfy the interference constraint at multiple PAL protection areas. For 1 PAL user the results from optimisation equation (4.26) show steps as there are many combinations with the same instantaneous aggregate interference.

Figure. 4.8 shows the CDF for the average GAA users capacity from optimisation equation (4.25) and our proposed sub-optimal method from optimisation equation (4.25) and our proposed sub-optimal method using the transmit power adjustment method. The results show that our proposed sub-optimal method with the transmit power adjustment can further maximise the average GAA users capacity. We can observe an average decrease of 4.22% in our proposed method as compared to the optimal solution.

Figure. 4.9 shows the CDF for the transmit power allocation for GAA in a single set and multiple sets. The results show that the transmit power allocation for the GAA users in multiple sets is much higher than in the single set. In our proposed method the transmit power adjustment is done for a transmitting GAA user utilising the interference budget from other GAA users in the same set. GAA users that belong to multiple sets receive more transmit power adjustment from

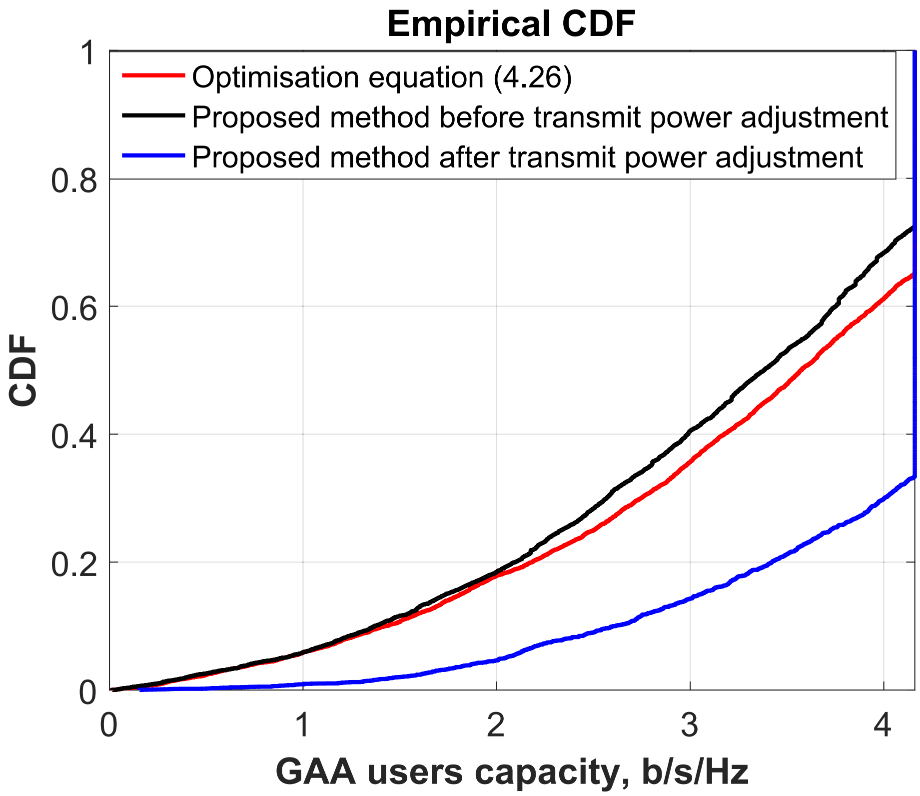


Figure 4.8: CDF of average GAA users capacity from optimisation equation (4.25) and our proposed sub-optimal method

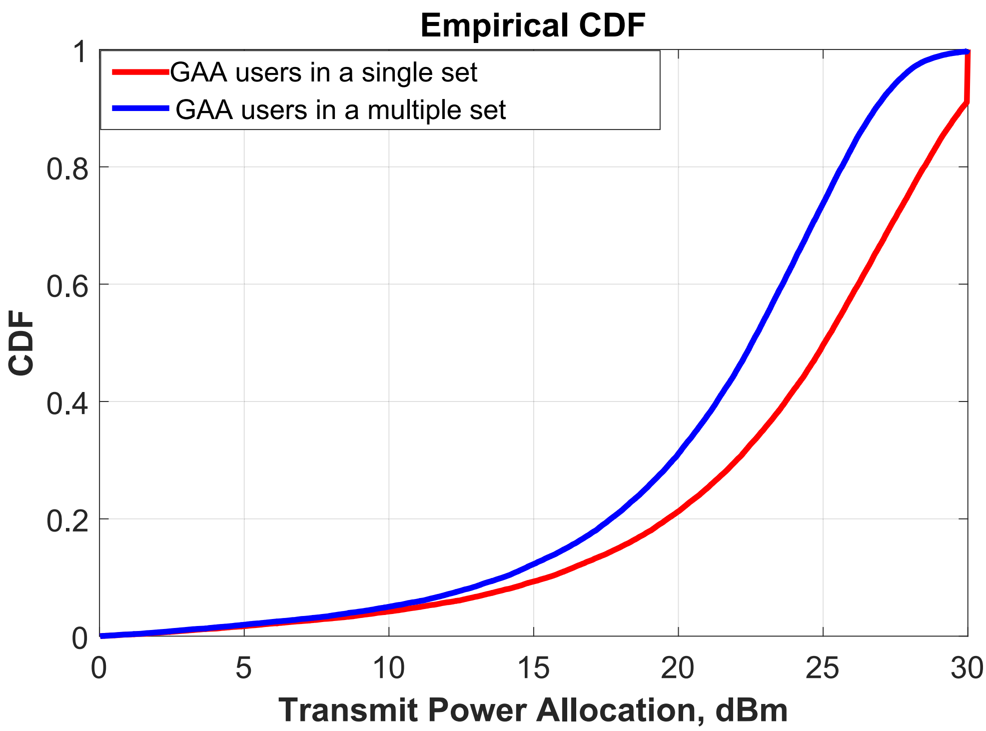


Figure 4.9: CDF of transmit power allocation for GAA users in a single set and multiple sets from our proposed method

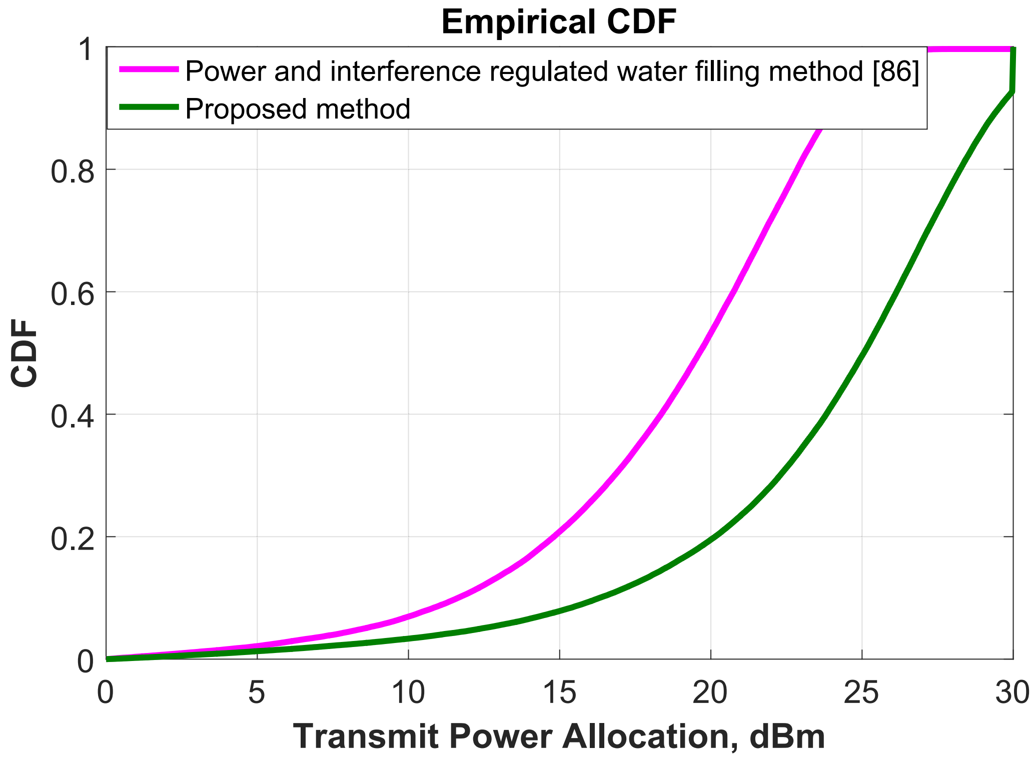


Figure 4.10: CDF of transmit power allocation comparison between [86] and our proposed method.

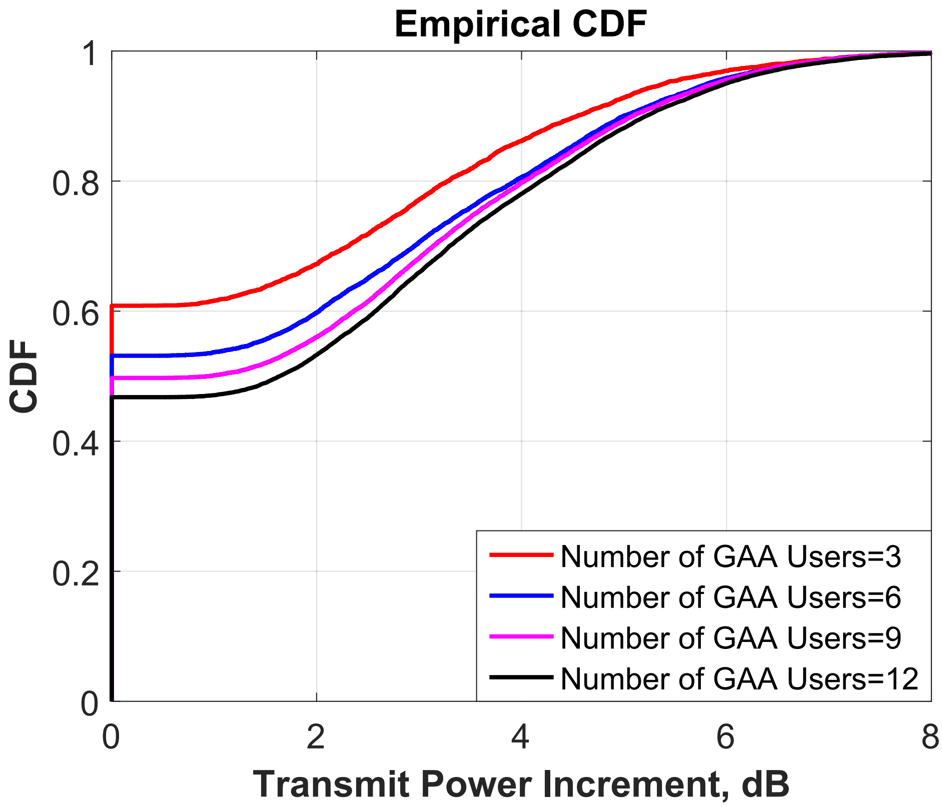


Figure 4.11: CDF of transmit power increment for different numbers of GAA Users

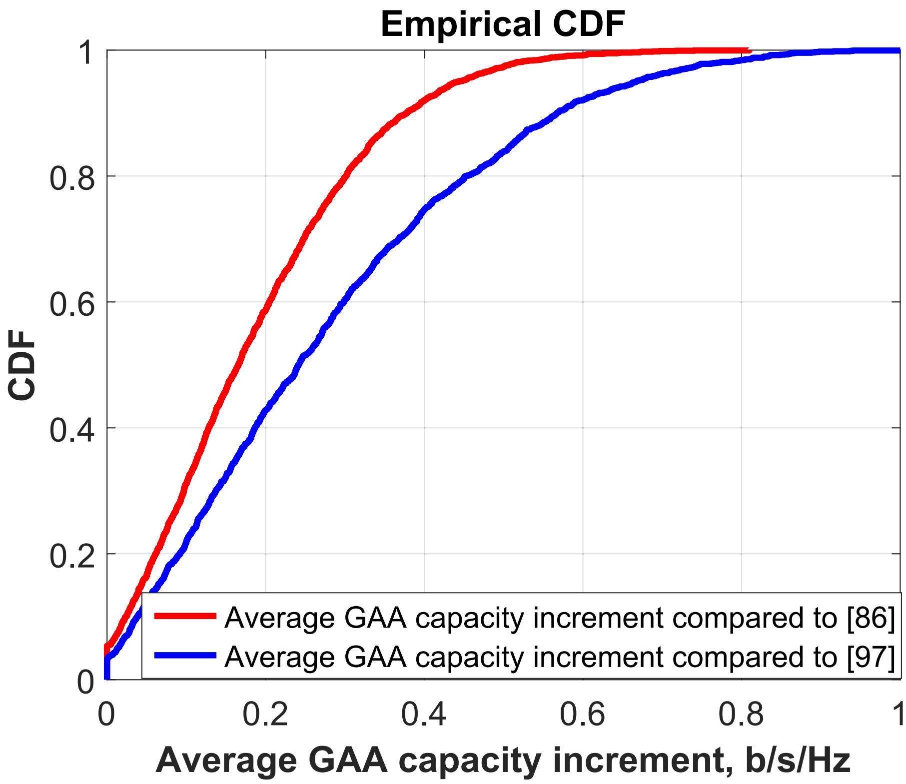


Figure 4.12: Average GAA network capacity increment from our proposed channel and transmit power allocation method compared to [86] and [97]

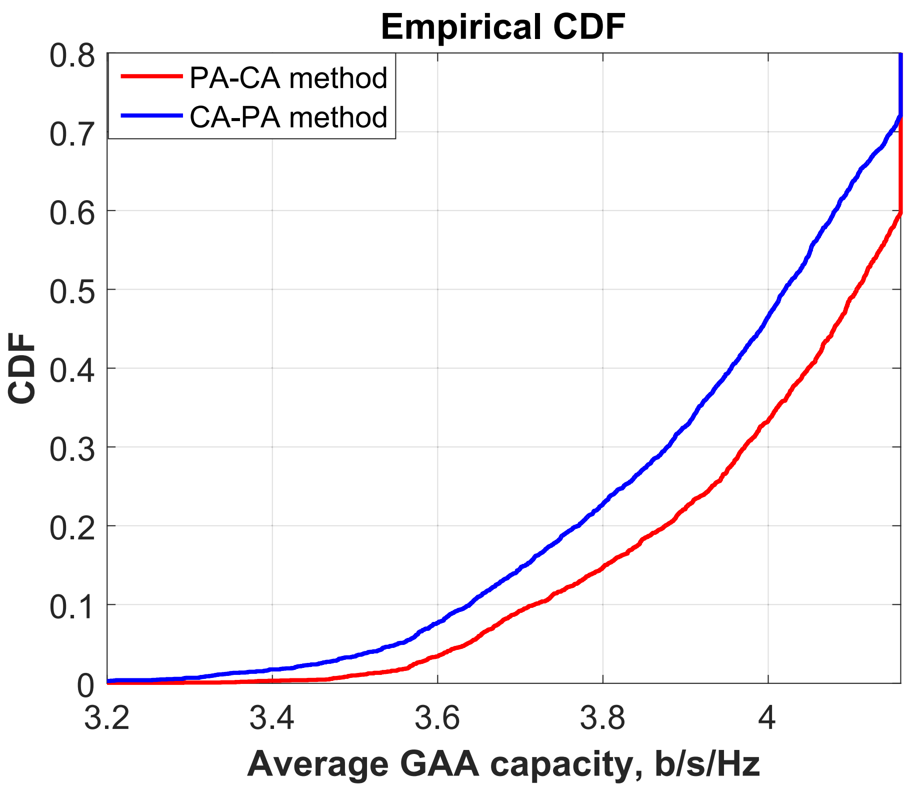


Figure 4.13: Average capacity comparison from transmit power allocation done first followed with channel allocation and vice-versa

GAA	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PAL1	0	1	1	0	0	1	0	0	0	0	0	0	1	0	1
PAL2	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0

Table 4.2: The Channel Allocation for GAA Users

our proposed method, as the GAA users that belong to multiple sets receives more interference budget increment from GAA users in multiple sets they belong to.

Figure. 4.10 shows the CDF of transmit power allocation for GAA users comparison between our proposed method and power and interference regulated water filling method in [86]. Transmit power allocation from our proposed method is higher as we use the adjusted interference budget for power allocation considering the sets of GAA users that can hear each other.

Figure. 4.11 shows the CDF of the transmit power increment when considering a scenario of different numbers of GAA users, i.e. 3, 6, 9 and 12 GAA users. Transmit power increment is the difference between the transmit power from our proposed method and power and interference regulated water filling method in [86]. The results show that this transmit power increment is high as the number of GAA users increases. With the increase in the number of GAA users the interference budget increment received by the transmitting GAA user is high.

Figure. 4.12 shows the CDF of average GAA capacity increments from our proposed method compared to [86] and [97]. Average GAA capacity increment is the capacity increment received from our proposed method, i.e. the difference between average capacity from our proposed method and [86] or [97]. Figure. 4.12 shows that our proposed method receives average capacity increment compared to the power and interference regulated water filling method [86] in a particular PAL channel. In [97] to avoid the co-channel interference among SUs, only one SU is allocated to one channel. The results show that our proposed method can maximise the average GAA network capacity by allocating a set of GAA users to the same PAL channel.

Figure. 4.13 shows a comparison between the two methods of dividing the MILP resource allocation problem into two sub-problems. In the first method transmit power allocation is done first followed with channel allocation for GAA users, i.e. PA-CA method and in the second method, the channel allocation is done first followed with transmit power allocation for GAA users, i.e. CA-PA method. The results show the increment in average capacity from our proposed method, i.e. PA-CA method. In CA-PA method channel allocation is done using the set information and maximum transmit power, and then the transmit power allocation is done for GAA users while satisfying the interference constraint at the PAL PA.

Table 5.1 shows the channel allocation for GAA users at a particular time. In our proposed method conflict-free channel allocation is done for GAA users, i.e. GAA users that can hear each other are not allocated to the same channel at the same time. In this case the sets of GAA users that can hear each other are five i.e. GAA users in a set are $\{1, 2, 5\}$,$\{1, 3, 4, 7\}$,$\{4, 6, 7, 8\}$,$\{9, 10, 12, 13\}$ and $\{11, 14, 15\}$. From Table 5.1 we can see that conflict-free channel allocation is done for GAA users $\{2, 3, 6, 13, 15\}$ which are allocated to PAL1 channel and the GAA users $\{5, 8, 12, 14\}$ which are allocated to PAL2 channel.

4.5 Summary

In this chapter, we proposed the set based interference aware resource allocation for GAA users in the Spectrum Access System to maximise the average GAA sum capacity. Using the location information of the GAA users we find GAA users that belong to a single set and multiple sets. GAA users in multiple sets require careful planning for the conflict-free resource allocation. In this work, we propose a conflict-free channel allocation to GAA users using the set information as shown in the simulation results. Our proposed method allocates multiple GAA users to the same channel at the same time in the dense area, i.e. when there are more GAA users. We propose a method to calculate the adjusted interference budget for GAA users with GAA individual interference budget and increment received from the other GAA users in a set that cannot transmit at the same time. Transmit power allocation is done using the adjusted interference budget while satisfying the interference constraint proposed by FCC to PAL users allocated to the same channel. Simulation results show that our proposed method maximises the GAA network capacity by around 19.62%, and mitigates interference between both GAA and PAL users as well as between GAA users.

Chapter 5

Conflict-free Resource Allocation to Fixed and Mobile GAA Users

There is a significant increase in the mobile data traffic and to accommodate the growing moving data traffic moving small cells have been proposed in the literature. We consider two types of GAA users in this study, i.e. fixed GAA (FGAA) users and mobile GAA (MGAA) users. FGAA users have fixed locations, and MGAA users are installed in vehicles. In this study, we consider MGAA users are installed in trains and they move in known fixed paths, i.e. train tracks. We define the carrier sensing range as the range in which other GAA users can hear a transmitting GAA user. Dense deployment of GAA users may result in overlapped carrier sensing ranges with neighbouring GAA users. GAA user equipments in the overlapped area can interfere with each other when they transmit in the same channel at the same time.

5.1 Introduction

In this work, we present conflict-free coexistence between PAL users, FGAA users and MGAA users. For the conflict-free co-channel coexistence we consider four different categories of interference which are listed below:

- Interference between PAL users and FGAA /MGAA users.

- Interference between FGAA users and FGAA users.
- Interference between FGAA users and MGAA users.
- Interference between MGAA users and MGAA users.

With a large number of small cells deployment, there is a significant increase in the overlapped carrier sensing ranges. The user equipment (UE) in the overlapped area receives interference which affects network performance. A conflict-free resource management scheme is essential since interference would reduce network performance.

5.1.1 Related Works

Resource allocation is a well-investigated topic in a fixed small cell [100–106] . In [100], an iterative approach for the joint subchannel and transmit power allocation was proposed for the femtocells. In [101] the subchannel and power allocation problem for the cognitive small cells was studied using cooperative Nash bargaining game theory, where the cross-tier interference mitigation, minimum outage probability requirement, imperfect channel state information (CSI) and fairness in terms of minimum rate requirement are considered. Capacity aware channel allocation was presented in [102] for cognitive radios with only one interfering secondary user from the interfering set allocated to the same channel at the same time. In [103] to improve spectrum utilisation, interference alignment along with frequency clustering was proposed for the cognitive radio system. Resource allocation was done in a cognitive radio network in [104] with primary users cooperation by allowing only one secondary user to access the channel at a time. In [105] the authors provide an overview of the FCC regulation for citizen broadband radio services and utilise the listen before talk for the coexistence of GAA users. A super radio formation algorithm has been proposed in [106] for citizen broadband radio services utilising a Wi-Fi like carrier sensing mechanism.

Resource allocation in moving small cells has been investigated in [107–109]. In [107,108] resource blocks and power are allocated to moving small cells to enhance the network service quality restricting one resource block to only one user at a certain

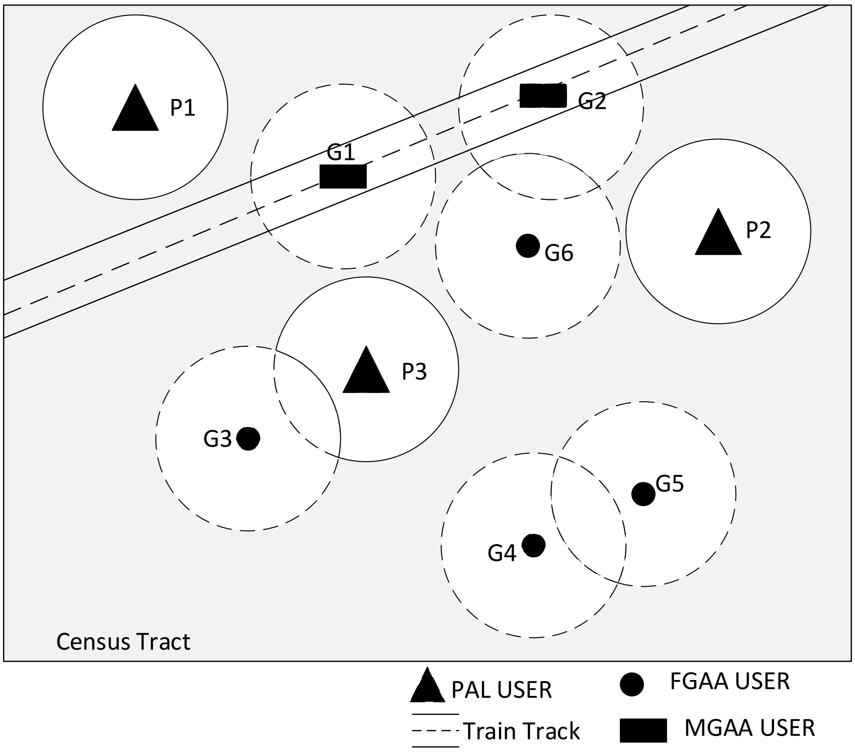


Figure 5.1: Illustration of PAL, FGAA, MGAA users interference scenarios in a census tract

time. However, in these studies, interference to fixed small cells is not considered for the resource allocation; conflicts between fixed and mobile small cells need to be addressed properly for the conflict-free resource allocation. In [109] resource allocation schemes for the fixed and mobile small cell users are reviewed, and their studies show that further studies need to be done to avoid interference to nearby fixed cells from the moving cells.

Traditional channel allocation schemes [100–106] avoid allocating the same channel to users that can interfere with each other. In this work, we consider the three types of conflicts between GAA users to ensure conflict-free resource allocation to GAA users. To reduce the interference between GAA users and to allocate multiple GAA users to the same channel in case of spectrum scarcity we propose a novel resource allocation scheme that considers the overlapping coverage area.

5.2 System Model

The notation that will be used in this chapter are summarized in Table 5.1.

In this work, we consider a GAA network that consists of F FGAA users, and M MGAA users, and P PAL users as shown in Figure 5.1. We denote FGAA users by i, $i \in \mathcal{F} = \{1, ..., F\}$, MGAA users by j, $j \in \mathcal{M} = \{1, ..., M\}$ and PAL users by m, $m \in \mathcal{C} = \{1, ..., C\}$. In SAS, PAL users use dedicated PAL channels denoted as p, $p \in \mathcal{P} = \{1, ..., P\}$. We consider a scenario in which $(F + M) >> P$.

In this study, we considered that the MGAA users are located in the trains. Trains move on a fixed track with a uniform speed; hence the mobility is deterministic [107]. We estimate the position of the MGAA users using the information of the MGAA user's velocity. We assume that MGAA users are equipped with omnidirectional antennas and the FGAA users are equipped with smart antennas with switch beam systems with multiple beams to maximise the spectrum reuse in the GAA network [112–114]. We denote the beam of the ith FGAA user as b_i, $b_i \in \mathcal{B}_i = \{1, ..., B_i\}$ where B_i is the number of beams of the ith FGAA user.

In SAS, a PAL channel is considered busy inside of the PAL PA, i.e. GAA users outside the PAL user PA can utilise the channel while satisfying the interference constraint at the PAL PA. For example, in Figure 5.1, MGAA user G1 can use all the PAL channels while satisfying the interference constraint to PAL users. FGAA user G3 and PAL user P3 cannot transmit on the same channel at the same time to protect the PAL user from harmful interference. Also, FGAA users G4 and G5 would cause harmful interference to each other when transmitting on the same channel. Similarly, user equipments associated with MGAA user G2 and FGAA user G6 interfere with each other in the overlapped area.

The interference between FGAA users is constant. However, the other three possible interferences involving MGAA users vary over time due to the mobility.

The channel gain from the ith GAA user to the uth user equipment (UE) on the pth PAL channel is given by:

$$h^p_{u,i} = 10^{-\frac{L^{dB}_{i,u}}{10}} \times \zeta_{u,i} \times \Gamma_{u,i}, , \forall u = 1, 2, .., U \tag{5.1}$$

where $L_{i,u}$ is the pathloss between the ith GAA user and the uth GAA end user, $\zeta_{u,i}$

Symbol	Definition
$\mathcal{C}$	Set of PAL users
$\mathcal{P}$	Set of PAL channels
$\mathcal{F}$	Set of FGAA users
$\mathcal{M}$	Set of MGAA users
B_i	Total number of beams of the ith FGAA user
i	FGAA user index
j	MGAA user index
m	PAL user index
p	PAL channel user index
$\hat{\mathcal{U}}_i$	Set of UEs that lie in the overlapped area
$\mathcal{U}_i^*$	Set of UEs that do not lie in the overlapped area
T	Total number of time slots
S	Superset of all the FGAA users that can hear each other
S^*	Superset of all the MGAA users that can hear each other
r_i^p	Carrier sensing range of the ith FGAA user when transmitting on the pth channel
$d_{i,j}(t)$	Distance between the ith FGAA user and the jth MGAA user at a certain time t
$Pt_{i,b}^p$	Transmit power for set of beams that lies in the interfering angle
Pt_{i,b^*}^p	Transmit power for set of beams that does not lie in the interfering angle
α_i^p	Indication function for the ith FGAA user channel allocation
β_j^p	Indication function for the jth MGAA user channel allocation
$\mathcal{S}_{\mathcal{N}}(t)$	Set of FGAA user and MGAA user that can hear each other at certain time

Table 5.1: Symbols and Definitions.

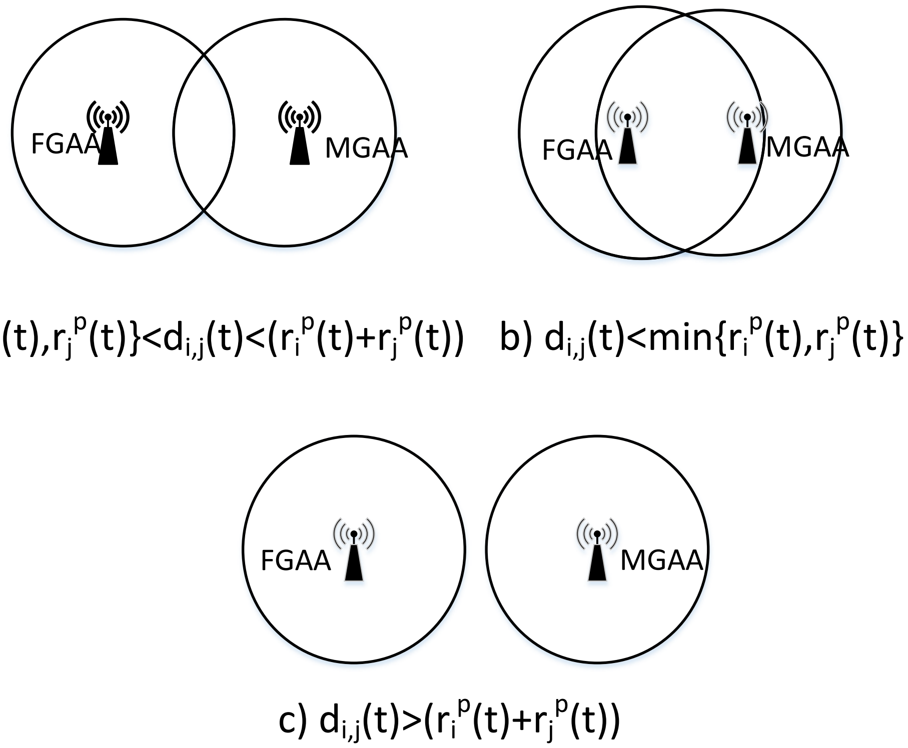


Figure 5.2: Impact of MGAA users interference to FGAA users a) MGAA users and FGAA users cannot hear each other, but user equipment in overlapped area are interfered b) MGAA users and FGAA users can hear each other, i.e. they are within the carrier sensing range c) MGAA user and FGAA user do not interfere with each other.

is the shadowing coefficient and is modeled as a correlated lognormal distribution, and $\Gamma_{u,i}$ is the Rayleigh distributed fading coefficient.

5.3 Resource Allocation for FGAA Users and MGAA Users

Interference pattern between FGAA users and MGAA users is time-dependent due to the mobility of the MGAA users. The Signal to Interference plus Noise Ratio (SINR) at uth user equipment of the ith FGAA user over the pth channel in time t is given by:

$$\gamma_u^p(t) = \frac{Pt_i^p(t)h_{u,i}^p(t)}{P_N + \sum_{o\in\mathcal{F}\setminus\{i\}} Pt_o^p(t)h_{u,o}^p(t) + \sum_{j\in\mathcal{M}} Pt_j^p(t)h_{u,j}^c(t)} \tag{5.2}$$

where $Pt_i^p(t)$ is the transmit power of the ith FGAA users on the pth channel in time t, $\sum_{o\in\mathcal{F}\setminus\{i\}} Pt_o^p(t)h_{o,u}^p$ is the interference on the uth user equipment from other transmitting FGAA users and $\sum_{j\in\mathcal{M}} Pt_j^p(t)h_{j,u}^p(t)$ is the interference on the uth user equipment from the jth transmitting MGAA user.

Similarly, $\gamma_v^p(t)$ is defined for user equipment v_j of the jth MGAA user.

$$\gamma_v^p(t) = \frac{Pt_j^p(t)h_{v,j}^p(t)}{P_N + \sum_{i\in\mathcal{F}} Pt_i^p(t)h_{v,i}^p(t) + \sum_{k\in\mathcal{M}\setminus\{j\}} Pt_k^p(t)h_{v,k}^p(t)} \tag{5.3}$$

The downlink capacity per GAA UE for the jth MGAA user when transmitting on the pth channel at a certain time t is given by

$$C_j^p(t) = \frac{1}{|\mathcal{V}_j|}\sum_{v=1}^{|\mathcal{V}_j|} \log_2\left(1+\gamma_v^p(t)\right) \tag{5.4}$$

where $|\mathcal{V}_j|$ is the total number of user equipments in the jth MGAA user. Similarly, for the ith FGAA user $C_i^p(t) = \frac{1}{|\mathcal{U}_i|}\sum_{u=1}^{|\mathcal{U}_i|} \log_2\left(1+\gamma_u^p(t)\right)$, where $|\mathcal{U}_i|$ is the total number of user equipment in the ith FGAA user.

According to the FCC documents, the nodes can hear each other if the received signal strength is 6 dB above the noise floor [115,116]. Considering that GAA users are transmitting with the maximum allowed transmit power we find the carrier sensing range of both FGAA users and MGAA users as:

$$r_i^p = 10^{\left(\left(10\log_{10}\left(\frac{P_{max}}{Pr}\right) - 46.4 - 20\times\log_{10}0.2f\right)/20\right)} \tag{5.5}$$

where r_i^p is the carrier sensing range of the ith FGAA user when transmitting on the pth channel, P_{max} is the FCC allowed maximum transmit power, $Pr(dB) = (N_{fl}+6)$ is the received power threshold for GAA users to hear each other, and N_{fl} is the noise floor in dBm.

The impact of MGAA users interference to the FGAA users is shown in Figure 5.2. The first type of conflict is the one in which MGAA user is hidden from FGAA user, i.e. FGAA user and MGAA user cannot hear each other as shown in Figure 5.2(a). MGAA users are hidden if the distance between the ith FGAA user and the jth MGAA user at a certain time t, i.e. $d_{i,j}(t)$ is smaller than $(r_i^p(t) + r_j^p(t))$ but larger than $\min\{r_i^p(t), r_j^p(t)\}$. In the overlapped area, the user equipments that are associated with the ith FGAA user and the jth MGAA user are interfered with.

In this work, for the first type of conflict where FGAA users and MGAA users are hidden from each other we propose an interfering angle based resource allocation to ensure self coexistence between mobile and fixed GAA users. The second type of conflict as shown in Figure 5.2(b) is the one in which MGAA user and FGAA user can hear each other, i.e. $d_{i,j}(t) \leq \min\{r_i^p(t), r_j^p(t)\}$. Similarly, in a scenario as shown in Figure 5.2(c) FGAA users and MGAA users do not interfere with each other. When $d_{i,j}(t) > (r_i^p(t) + r_j^p(t))$ both FGAA users and MGAA users can use the same channel at the same time while satisfying the FCC proposed interference threshold.

5.3.1 Interfering Angle Based Maximum Allowed FGAA Transmit Power Constraint

Due to the mobility, MGAA users can be in the interference range of FGAA users for a certain time. $\theta_{i,p}(t)$ is the interfering angle on the ith FGAA user from the jth MGAA user at time t as shown in Figure 5.3, and is given by

$$\theta_i^p(t) = 2\cos^{-1}\left(\frac{d_{i,j}^2(t) + r_i^p(t)^2 - r_j^p(t)^2}{2r_i^p(t)d_{i,j}(t)}\right) \tag{5.6}$$

where $d_{i,j}(t)$ is the distance between the ith FGAA user and the jth MGAA user at a certain time t.

In this work, we propose an interfering angle based resource allocation to the ith FGAA user, $\forall i \in \mathcal{F}$ during the time the ith and jth GAA users are in the carrier sensing range. For the conflict-free channel allocation to FGAA users and MGAA users, the carrier sensing range threshold of the ith FGAA user in $\theta_i^p(t)$ angle should be:

$$\epsilon_{i,th}^{\theta_i^p}(t) = d_{i,j}(t) - r_j^p(t) \tag{5.7}$$

To ensure self-coexistence between the FGAA users and MGAA users, FGAA users need to satisfy the following constraint in $\theta_i^p(t)$ angle.

$$10^{\left(\left(10\log_{10}\left(\frac{Pt_i^{\theta_i^p}(t)}{Pr}\right) - 46.4 - 20\times\log_{10}\frac{f}{5.0}\right)/20\right)} \leq \epsilon_{i,th}^{\theta_i^p}(t) \tag{5.8}$$

where the left-hand side of equation (5.8) is the carrier sensing range of the ith FGAA user, and $Pt_i^{\theta_i^p}(t)$ is the transmit power of the ith FGAA user in $\theta_i^p(t)$ angle.

Let $\hat{\mathcal{B}_i^p}(t)$ be the set of beams that lie in the interfering angle $\theta_i^p(t)$ when $\min\{r_i^p(t), r_j^p(t)\} < d_{i,j}(t) < (r_i^p(t) + r_j^p(t))$. For the conflict-free resource allocation to FGAA users and MGAA users, we propose a method to find the maximum allowed transmit power to the $\hat{\mathcal{B}_i^p}(t)$ set of beams. The maximum allowed transmit power for the bth beam, $\forall b \in \hat{\mathcal{B}_i^p}(t)$ of the ith FGAA user can be determined by solving equation (5.8) which is given by :

$$P_{max}^{\theta_{i,b}^p}(t) = Pr \times 10^{\frac{L^{dB}\left(\epsilon_{i,th}^{\theta_i^p}(t)\right)}{10}} \tag{5.9}$$

where $L^{dB}(\epsilon_{i,th}^{\theta_i^p}(t))$ is the path loss for the ith GAA for the $\epsilon_{i,th}^{\theta_i^p}(t)$ distance.

The maximum allowed transmit power for the $\hat{\mathcal{B}_i^p}(t)$ set of beams that lie in the interfering angle $\theta_{i,p}(t)$ for the ith FGAA user is given by:

$$0 \leq Pt_{i,b}^p \leq P_{max}^{\theta_i^p}, \forall b \in \hat{\mathcal{B}_i^p}(t) \tag{5.10}$$

The maximum allowed transmit power constraint for the jth MGAA user and the b^*th beam of the ith FGAA user that does not lie in $\theta_{i,p}(t)$ angle is given by:

$$0 < Pt_{i,b^*}^p, Pt_j^p \leq P_{max}, \forall b^* \in \mathcal{B}_i \backslash \hat{\mathcal{B}_i^p}(t) \tag{5.11}$$

Using the interfering angle based maximum allowed transmit power constraint for FGAA users, both FGAA users and MGAAs user can transmit at the same time on the same channel. With our proposed method the FGAA user coverage area will be divided into three parts, one part where the beams transmit power is unchanged, the other part with reduced transmit power for the beams in the presence of MGAA users and a small area with no coverage. The downlink capacity per user for FGAA users from our proposed method is

$$C_i^p(t) = \frac{1}{\mathcal{U}_i^*} \sum_{u^*=1}^{|\mathcal{U}_i^*|} \log_2\left(1 + \gamma_{u^*}^p(t)\right) + \frac{1}{\hat{\mathcal{U}}_i} \sum_{\hat{u}=1}^{|\hat{\mathcal{U}}_i|} \log_2\left(1 + \gamma_{\hat{u}}^p(t)\right) \tag{5.12}$$

where $\mathcal{U}_i^*$ are the UEs that lie in the area with no transmit power changes, $\hat{\mathcal{U}}_i$ are the UEs that lie in the area with changed transmit power, and $\left(\mathcal{U}_i^* + \hat{\mathcal{U}}_i\right) \leq \mathcal{U}_i$. Similarly, $\gamma_{u^*}^p(t)$ and $\gamma_{\hat{u}}^p(t)$ are the SINR at u^*th and $\hat{u}$th UE of the ith FGAA user over the pth channel in time t.

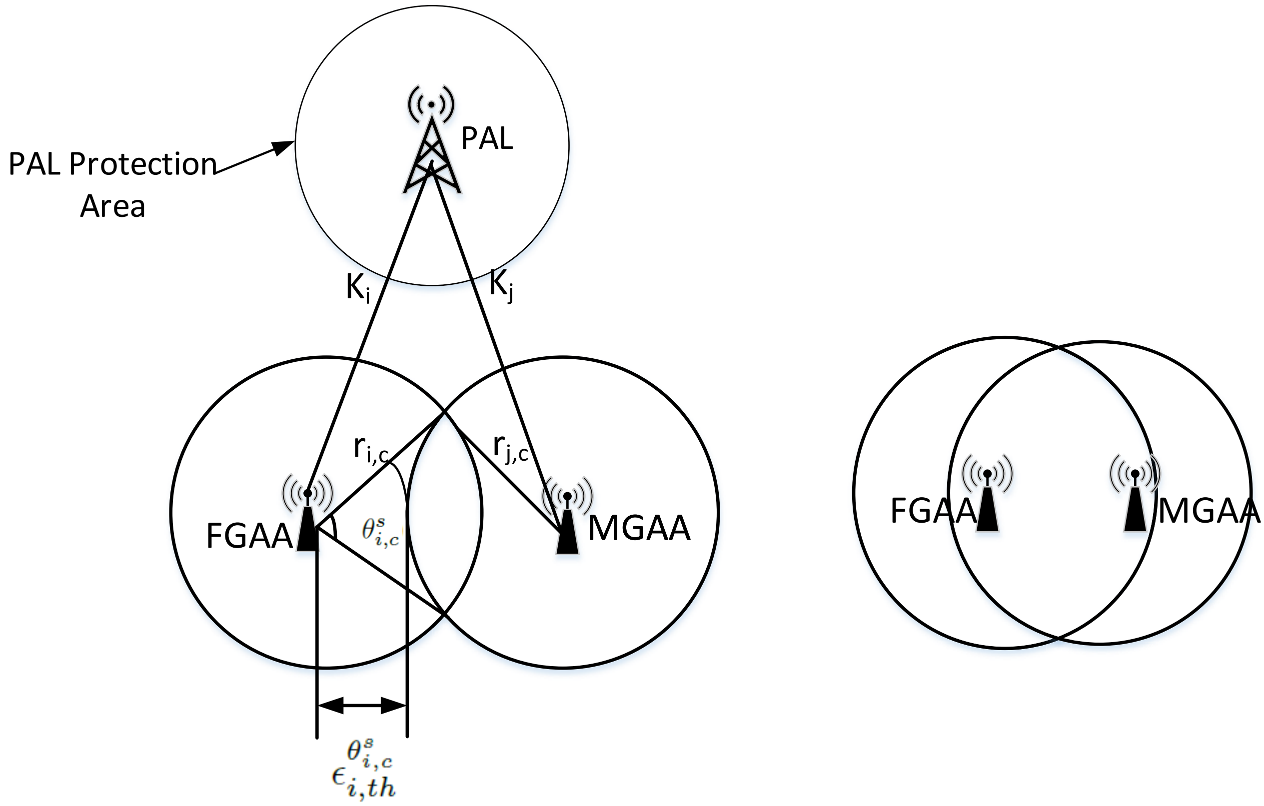


Figure 5.3: Illustration of FGAA user and MGAA user with overlapped area and PAL user protection area to find the RMS interference from GAA users at point K_i

Lemma 3. *Our proposed method of resource allocation for FGAA users and MGAA users is conflict free.*

FGAA users and MGAA users interfere with each other if the coverage area overlaps, i.e. $d_{i,j} < r_i^p(t) + r_j^p(t)$. *In our proposed method to ensure conflict-free channel allocation, the maximum allowed transmit power is allocated to the beams of FGAA users that lie in interfering angle such that* $\epsilon_{i,th}^{\theta_i^p}(t) = d_{i,j}(t) - r_j^p(t)$.

5.3.2 Interference Protection to PAL Users

In SAS, to ensure that PAL protection criteria are satisfied, a channel is considered as busy for GAA users inside the PAL PA, however a PAL channel can be utilised by GAA users beyond the PAL PA, i.e.

$$d_{i,m} > R_m \tag{5.13}$$

where R_m is the radius of the mth PAL user PA.

To satisfy the above conditions, we find the set of FGAA users, i.e. $\hat{\mathcal{F}}$ and the set of MGAA users, i.e. $\hat{\mathcal{M}}$ that satisfy the condition $d_{i,m} > R_m$ and $d_{j,m}(t) > R_m$.

To protect PAL users from harmful interference RMS interference from GAA users $\forall i \in \mathcal{F},\ j \in \mathcal{M}$ at the PAL PA should be less than the FCC proposed interference threshold. Let K_i, is the nearest point at the mth PAL PA from the ith GAA user as shown in Figure 5.3. The point in the PAL PA with the shortest distance from the GAA user receives maximum interference. RMS interference at the mth PAL PA is given by:

$$I^m_{K_{i,j}} = \frac{1}{T}\int_0^T \left(\sum_{i=1}^{F^*(t)} Pt^p_{i,b^*}(t)h_{i,m}(t) + \sum_{j=1}^{M^*(t)} Pt^p_j(t)h_{j,m}(t)\right)dt \tag{5.14}$$

where b^* is the beam in the direction of the mth PAL user, $F^*(t)$ is the total number of transmitting FGAA users at a certain time, and $M^*(t)$ is the total number of transmitting MGAA users at the certain time. $\frac{1}{T}\int_0^T \left(\sum_{i=1}^{F^*(t)} Pt^p_{i,b^*}(t)h_{i,m}(t)\right)dt$ is the RMS interference to the mth PAL user from transmitting FGAA users, and $\frac{1}{T}\int_0^T \left(\sum_{j=1}^{M^*(t)} Pt^p_j(t)h_{j,m}(t)\right)dt$ is the RMS interference to the mth PAL user from transmitting MGAA users.

To protect the mth PAL user from the GAA users harmful interference RMS interference at the PAL user PA should be less than the FCC predetermined interference threshold, i.e. I_{th}.

$$I^m_{K_{i,j}} \leq I_{th}, \forall j \in \mathcal{M}, \forall i \in \mathcal{N} \tag{5.15}$$

In this work, we have considered multiple PAL users allocated to the same channel. To ensure FCC proposed interference criteria are satisfied the RMS interference from GAA users should be less than the interference threshold at all the PAL PA allocated to the same channel.

5.3.3 Self Coexistence Between GAA Users Constraint

In this work, to ensure self coexistence between GAA users that can hear each other we consider three different types of coexistence, i.e. coexistence between FGAA users, coexistence between MGAA users and the coexistence between FGAA users and MGAA users.

Let $\alpha_i^p(t)$ denotes the indication function for FGAA users channel allocation.

$$\alpha_i^p(t) = \begin{cases} 1, & \text{if the } i\text{th FGAA user is allocated to the } p\text{th channel} \\ 0, & \text{Otherwise} \end{cases} \tag{5.16}$$

Let $\beta_j^p(t)$ denotes the indication function for MGAA users channel allocation at certain time.

$$\beta_j^p(t) = \begin{cases} 1, & \text{if the } j\text{th MGAA users is allocated to the } p\text{th channel} \\ 0, & \text{Otherwise} \end{cases} \tag{5.17}$$

FGAA users do not interfere with each other if $d_{i,o}(t) > \max\{r_i^p, r_o^p\}, \forall i, o \in \mathcal{F}, i \neq o$. Let $\mathcal{S}_{\mathcal{F}}$ denotes the set of FGAA users that satisfy the carrier sensing range condition $d_{i,o}(t) \leq \min\{r_i^p, r_o^p\}$, $\forall i, o \in \mathcal{F}, i \neq o$, where $d_{i,o}$ is the distance between the ith and oth FGAA user. To ensure self coexistence between FGAA users that can hear each other only one user from set $\mathcal{S}_{\mathcal{F}}$ can transmit at a particular time in the same channel, i.e.

$$\sum_{i=1}^{|\mathcal{S}_{\mathcal{F}}|} \alpha_i^p(t) \leq 1, \alpha_i^p(t) \in \{0, 1\}, \forall i \in \mathcal{S}_{\mathcal{F}} \tag{5.18}$$

For MGAA users their position and distance between the MGAA users can be determined due to the deterministic mobility. MGAA users do not interfere with each other if $d_{j,k}(t) > \max\{r_j^p, r_k^p\}, \forall j, k \in \mathcal{M}, j \neq k$. With mobility the interfering set of MGAA users changes rapidly, let $\mathcal{S}_{\mathcal{M}}(t)$ denotes the set of MGAA users that satisfy the carrier sensing range condition $d_{j,k} \leq \min\{r_j^p, r_k^p\}$, $\forall j, k \in \mathcal{M}, j \neq k$. Similarly, to ensure self coexistence between MGAA users they must satisfy the following constraint:

$$\sum_{j=1}^{|\mathcal{S}_{\mathcal{M}}(t)|} \beta_j^p(t) \leq 1, \beta_j^p(t) \in \{0, 1\}, \forall j \in \mathcal{S}_{\mathcal{M}}(t) \tag{5.19}$$

Let $\mathcal{S}_{\mathcal{N}}(t)$ denotes the set of FGAA users and MGAA users that satisfy the carrier sensing range condition $d_{i,j}(t) \leq \min\{r_i^p, r_j^p\}$, $\forall i, j \in \mathcal{N}$, where $\mathcal{N} = \mathcal{F} \cup \mathcal{M}$. For the ith FGAA user and the jth MGAA user in set $\mathcal{S}_{\mathcal{N}}(t)$, only one user from the set that can hear each other can access the channel at a particular time.

$$\mathbb{I}_{i,j}^{p} = \begin{cases} 1, & \text{if } d_{i,j}(t) \leq \min\{r_i^p, r_j^p\} \\ 0, & \text{if Otherwise} \end{cases} \tag{5.20}$$

$$\sum_{i=1}^{|\mathcal{S}_{\mathcal{N}}(t)|} \alpha_i^p(t)\mathbb{I}_{i,j}^{p} + \sum_{j=1}^{|\mathcal{S}_{\mathcal{N}}(t)|} \beta_j^p(t)\mathbb{I}_{i,j}^{p} \leq 1, \forall i, j \in \mathcal{S}_{\mathcal{N}}(t) \tag{5.21}$$

5.3.4 Interfering Angle Based Resource Allocation

Interference pattern between FGAA and MGAA users is time-dependent due to the mobility of the MGAA users. We formulate the optimisation problem of the joint channel and transmit power allocation to both MGAA and FGAA users considering the mobility of the MGAA users to maximise the GAA network capacity as shown below:

$$\begin{aligned} \max \quad & \sum_{i=1}^{|\hat{\mathcal{F}}|} \alpha_i^p(t) C_{i,p}(t) + \sum_{j=1}^{|\hat{\mathcal{M}}|} \beta_j^p(t) C_{j,p}(t) \\ \text{s.t.} \quad & C1 : \alpha_i^p(t) \in \{0,1\}, \forall i \in \mathcal{S}_{\mathcal{F}}, \forall \mathcal{S}_{\mathcal{F}} \in S \\ & C2 : \sum_{i=1}^{|\mathcal{S}_{\mathcal{F}}|} \alpha_i^p(t) \leq 1 \\ & C3 : \beta_j^p(t) \in \{0,1\}, \forall j \in \mathcal{S}_{\mathcal{M}}(t), \forall \mathcal{S}_{\mathcal{M}}(t) \in S^* \\ & C4 : \sum_{j=1}^{|\mathcal{S}_{\mathcal{M}}(t)|} \beta_j^p(t) \leq 1 \\ & C5 : \sum_{i=1}^{|\mathcal{S}_{\mathcal{N}}(t)|} \alpha_i^p(t)\mathbb{I}_{i,j}^{p} + \sum_{j=1}^{|\mathcal{S}_{\mathcal{N}}(t)|} \beta_j^p(t)\mathbb{I}_{i,j}^{p} \leq 1 \\ & C6 : 0 < Pt_{i,b}^{p} \leq P_{max}^{\theta_i^p}, \forall b \in \hat{\mathcal{B}_i^p}(t) \\ & C7 : 0 < Pt_{i,b^*}^{p}, Pt_j^p \leq P_{max}, \forall b^* \in \mathcal{B}_i \backslash \hat{\mathcal{B}_i^p}(t) \\ & C8 : I_{K_{i,j}}^{m} \leq I_{th}, \forall j \in \mathcal{M}, \forall i \in \mathcal{N} \end{aligned} \tag{5.22}$$

where S and S^* is the superset of all the users that can hear each other for FGAA and MGAA users respectively. $\alpha_i^p(t)$ and $\beta_j^p(t)$ follow equation (5.16) and (5.17) respectively. To ensure a conflict-free resource allocation for FGAA users and MGAA users for the first type of conflict as shown in Figure 5.2, constraints $C6$

and $C7$ are used in the optimisation equation (5.22). For the second type of conflict to ensure only one user from the set that can hear each other can access the PAL channel at the particular time $C1$, $C2$, $C3$, $C4$ and $C5$ are used in our proposed work. Constraint $C8$ is to ensure that PAL users are protected from the harmful interference.

The above problem (5.22) is a mixed integer linear optimization problem which has a high computational complexity [110]. To reduce the computational complexity, we separate the problem (5.22) into a two-phase suboptimal problem, i.e. channel allocation phase and transmit power allocation phase.

Lemma 4. *Our proposed method increases spectrum utilisation compared to the traditional resource allocation methods. In traditional methods, in a scenario where the area is overlapped at a certain time only one user from the users with overlapped area can transmit at the same time at the same channel, i.e. area of transmission at a particular channel at the particular time will be* $\pi r_{i,p}^2(t)$ *or* $\pi r_{j,p}^2(t)$.

Overlapped area, i.e. the area of interference is given by:

$$\begin{aligned} IA_{i,j}(t) = r_{i,p}^2(t)\cos^{-1}\left(\frac{d_{i,j}^2(t)+r_{i,p}^2(t)-r_{j,p}^2(t)}{2r_{i,p}(t)d_{i,j}(t)}\right)+ \\ r_{j,p}^2(t)\cos^{-1}\left(\frac{d_{i,j}^2(t)-r_{i,p}^2(t)+r_{j,p}^2(t)}{2r_{j,p}(t)d_{i,j}(t)}\right)-\frac{1}{\sqrt{2}} \\ \sqrt{(2r_{j,p}^2(t)(r_{i,p}^2(t)+d_{i,j}^2(t))+(r_{i,p}^2(t)-d_{i,j}^2(t))^2-r_{j,p}^4(t))} \end{aligned} \tag{5.23}$$

The area with no transmission can be calculated using the area of sector and the overlapped area which is given by:

$$SA_{i,j}(t) = \frac{1}{2}r_{i,p}^2(t)\theta_{i,p}^s(t) - \left(\frac{1}{2}\epsilon_{i,th}^{\theta_{i,p}^s,2}(t)\theta_{i,p}^s(t) + IA_{i,j}(t)\right) \tag{5.24}$$

The area of transmission from proposed method is $\left(\pi r_{i,p}^2(t)+\pi r_{j,p}^2(t)-SA_{i,j}(t)\right)$ *whis is greater than the area of transmission from the traditional method, i.e.* $\pi r_{i,p}^2(t)$ *or* $\pi r_{j,p}^2(t)$.

Channel Allocation for FGAA Users and MGAA Users

Assuming GAA users are transmitting with the maximum transmit power, the channel allocation problem can be formulated as integer linear programming as shown below:

$$\begin{aligned}
\max \quad & \sum_{i=1}^{|\hat{\mathcal{F}}|} \alpha_i^p(t) C_{i,p}(t) + \sum_{j=1}^{|\hat{\mathcal{M}}|} \beta_j^p(t) C_{j,p}(t) \\
\text{s.t.} \quad & C1: \alpha_i^p(t) \in \{0,1\}, \forall i \in \mathcal{S}_{\mathcal{F}}, \forall \mathcal{S}_{\mathcal{F}} \in S \\
& C2: \sum_{i=1}^{|\mathcal{S}_{\mathcal{F}}|} \alpha_i^p(t) \leq 1 \\
& C3: \beta_j^p(t) \in \{0,1\}, \forall j \in \mathcal{S}_{\mathcal{M}}(t), \forall \mathcal{S}_{\mathcal{M}}(t) \in S^* \\
& C4: \sum_{j=1}^{|\mathcal{S}_{\mathcal{M}}(t)|} \beta_j^p(t) \leq 1 \\
& C5: \sum_{i=1}^{|\mathcal{S}_{\mathcal{N}}(t)|} \alpha_i^p(t) \mathbb{I}_{i,j}^p + \sum_{j=1}^{|\mathcal{S}_{\mathcal{N}}(t)|} \beta_j^p(t) \mathbb{I}_{i,j}^p \leq 1
\end{aligned} \tag{5.25}$$

For the optimisation problem (5.25) the left-hand side of the constraint is a unimodular matrix, and the right hand side is an integer. The proof in [111] shows that as a result of the unimodular property the optimal solution of integer linear programming is optimal of the problem.

Transmit Power Allocation for FGAA Users and MGAA Users

Based on the above channel allocation for GAA users transmit power is allocated to FGAA users and MGAA users by solving the following convex optimisation equation:

$$\begin{aligned}
\max \quad & \sum_{i=1}^{|\hat{\mathcal{F}}|} \alpha_i^p(t) C_{i,p}(t) + \sum_{j=1}^{|\hat{\mathcal{M}}|} \beta_j^p(t) C_{j,p}(t) \\
\text{s.t.} \quad & C6: 0 < Pt_{i,b}^p \leq P_{max}^{\theta_i^p}, \forall b \in \hat{\mathcal{B}_i^p}(t) \\
& C7: 0 < Pt_{i,b^*}^p, Pt_j^p \leq P_{max}, \forall b^* \in \mathcal{B}_i \backslash \hat{\mathcal{B}_i^p}(t) \\
& C8: I_{K_{i,j}}^m \leq I_{th}, \forall j \in \mathcal{M}, \forall i \in \mathcal{N}
\end{aligned} \tag{5.26}$$

To find the optimal transmit power allocation, we simplify the above objective equation using i^* where $i^* \in \mathcal{N}, \mathcal{N} = \mathcal{F} \bigcup \mathcal{M}$. The simplified objective equation is

$$C_{i^*}^p(t) = \frac{1}{|\mathcal{U}_{i^*}|} \sum_{i^*=1}^{|\mathcal{N}|} \sum_{u=1}^{|\mathcal{U}_{i^*}|} \log_2 \left(1 + \frac{Pt_{i^*}^p(t) h_{i^*,u}(t)}{P_N + \sum_{o \in \mathcal{N} \backslash \{i^*\}} Pt_o^p(t) h_{o,u}(t)} \right) \tag{5.27}$$

In our proposed method transmit power is allocated for each time slot t, and the timeframe is divided into N_T number of time slots, i.e. we need to solve the problem N_T times to find the optimal transmit power for GAA users for each time slot.

Theorem 5. *The optimisation equation (5.26) with the objective function (5.27) to maximise the GAA network capacity is concave and (5.26) with the constraints of transmit power and RMS interference to the PAL PA is convex.*

Proof. To prove the convexity of optimization equation (5.26), we need to prove that the objective function is concave with respect to α_i^p and Pt_i^p.

Firstly we define,

$$f_1(\alpha_i^p, Pt_i^p) = \alpha_i^p C_i^p \tag{5.28}$$

The objective function is the sum of $f_1(\alpha_i^p, Pt_i^p)$ for all the GAA users i.e. $i \in \mathcal{F}$ allocated to the PAL channel.

From (5.26) we get,

$$f_1(\alpha_i^p, Pt_i^p) = \alpha_i^p \log_2 \left(1 + \frac{Pt_i^p h_{i,u}}{\alpha_i^p \left(P_N + \sum_{o \in \mathcal{N} \setminus \{i^*\}} Pt_o^p(t) h_{o,u}(t) \right)} \right) \tag{5.29}$$

According to [117] f_1 is concave if Hessian matrix H is a negative semidefinite matrix. Hessian matrix H of f_1 can be arranged as [118]:

$$H = \begin{bmatrix} \frac{\partial^2 f}{\partial (\alpha_i^p)^2} & \frac{\partial^2 f}{\partial \alpha_i^p \partial Pt_i^p} \\ \frac{\partial^2 f}{\partial Pt_i^p \partial \alpha_i^p} & \frac{\partial^2 f}{\partial (Pt_i^p)^2} \end{bmatrix} \tag{5.30}$$

where,

$$\frac{\partial^2 f}{\partial (\alpha_i^p)^2} = -\frac{1}{\ln 2} \frac{\left(Pt_i^p h_{i,u}\right)^2}{\alpha_i^p \left(\alpha_i^p \left(P_N + \sum_{o \in \mathcal{N} \setminus \{i^*\}} Pt_o^p(t) h_{o,u}(t) \right) + Pt_i^p h_{i,u} \right)^2} \tag{5.31}$$

$$\frac{\partial^2 f}{\partial \alpha_i^p \partial Pt_i^p} = \frac{\partial^2 f}{\partial Pt_i^p \partial \alpha_i^p} = \frac{1}{\ln 2} \frac{Pt_i^p (h_{i,u})^2}{\left(\alpha_i^p \left(P_N + \sum_{o \in \mathcal{N} \setminus \{i^*\}} Pt_o^p(t) h_{o,u}(t) \right) + Pt_i^p h_{i,u} \right)^2} \tag{5.32}$$

$$\frac{\partial^2 f}{\partial (Pt_i^p)^2} = -\frac{1}{\ln 2} \frac{\alpha_i^p (h_{i,u})^2}{\left(\alpha_i^p \left(P_N + \sum_{o \in \mathcal{N} \setminus \{i^*\}} Pt_o^p(t) h_{o,u}(t) \right) + Pt_i^p h_{i,u} \right)^2} \tag{5.33}$$

$$H = \begin{bmatrix} -\frac{1}{\ln 2}\frac{\left(Pt_i^p h_{i,u}\right)^2}{\alpha_i^p\left(\alpha_i^p I_{i,o}^p + Pt_i^p h_{i,u}\right)^2} & \frac{1}{\ln 2}\frac{Pt_i^p (h_{i,u})^2}{\left(\alpha_i^p I_{i,o}^p + Pt_i^p h_{i,u}\right)^2} \\ \frac{1}{\ln 2}\frac{Pt_i^p (h_{i,u})^2}{\left(\alpha_i^c I_{i,o}^p + Pt_i^p h_{i,u}\right)^2} & -\frac{1}{\ln 2}\frac{\alpha_i^p (h_{i,u})^2}{\left(\alpha_i^p I_{i,o}^c + Pt_i^c h_{i,u}\right)^2} \end{bmatrix} \tag{5.34}$$

where $I_{i,o}^p(t) = P_N + \sum_{o\in\mathcal{N}\setminus\{i^*\}} Pt_o^p(t) h_{o,u}(t)$.

The eigenvalues of (5.34) is $-\left(\frac{1}{\ln 2}\frac{Pt_i^p h_{i,u}^2}{\left(\alpha_i^p I_{i,o}^p + Pt_i^p h_{i,u}\right)^2}\right)^2$ and $-\left(\frac{1}{\ln 2}\frac{h_{i,u}^2\left((Pt_i^p)^2 + (\alpha_i^p)^2\right)}{\alpha_i^p\left(\alpha_i^p I_{i,o}^p + Pt_i^p h_{i,u}\right)^2}\right) - \left(\frac{1}{\ln 2}\frac{Pt_i^p h_{i,u}^2}{\left(\alpha_i^p I_{i,o}^p + Pt_i^p h_{i,u}\right)^2}\right)^2$

For H to be a negative semidefinite matrix, it should be a Hermitian matrix with nonpositive eigenvalues. Hermitian matrix is a square matrix where $H = H^T$, H^T is the transpose of the H matrix. From (5.34) we can verify that H is a negative semidefinite matrix, i.e. Hermitian matrix with nonpositive eigenvalue and f_1 is concave. Similarly, $f_2(\alpha_j^p, Pt_j^p)$ is concave and the sum of two concave function, i.e. $\left(f_1(\alpha_i^p, Pt_i^p) + f_2(\alpha_j^p, Pt_j^p)\right)$ is concave [117]. The inequality constraint in optimisation equation (5.26) is convex, so the feasible set of the objective equation is convex and the optimization equation (5.26) is a convex problem [119]. The optimisation problem (5.26) is a convex optimisation problem as it also satisfies the proof in [119, 120] for Problem 2.

□

Based on the above proof, we obtain the optimal solution of (5.26) by using the Karush-Kuhn-Tucker (KKT) conditions. The Lagrangian of the above optimisation equation with objective function $C_{i^*}^p(t)$ for time t and the non-negative Lagrange multiplier λ which can be found using the interference constraint is given by:

$$\begin{aligned} \mathcal{L} = &\frac{1}{|\mathcal{U}_{i^*}|}\sum_{i^*=1}^{|\mathcal{N}|}\sum_{u=1}^{|\mathcal{U}_{i^*}|}\log_2\left(1 + \frac{Pt_{i^*}^p(t) h_{i^*,u}(t)}{I_{i,o}^p(t)}\right) \\ &- \lambda\left(\sum_{i=1}^{F^*(t)} Pt_{i^*}^p(t) h_{i,m}(t) + \sum_{j=1}^{M^*(t)} Pt_j^p(t) h_{j,m}(t) - I_{th}\right) \end{aligned} \tag{5.35}$$

According to the Kuhn Tucker conditions we get:

$$\frac{\partial \mathcal{L}}{\partial Pt_{i^*}^{p}} = \frac{(h_{i^*,u}(t))^{-1}}{\ln(2)\left(I_{i,o}^{p}(t) + Pt_{i^*}^{\hat{p}}(t)h_{i,u}(t)\right)} - \lambda h_{i,m}(t) = 0 \tag{5.36}$$

The optimal transmit power of the i^*th GAA user on the cth channel is given by:

$$Pt_{i^*}^{\hat{p}}(t) = h_{i^*,u}(t)^{-1}\left((\ln(2)\lambda h_{i,m}(t))^{-1} - I_{i,o}^{p}(t)\right) \tag{5.37}$$

The transmit power is time dependent as the sets of GAA users that can hear each other will change due to the mobility of the MGAA users.

The Lagrange multiplier λ is calculated using (5.37) and using the Karush-Kuhn-Tucker condition, i.e.$\lambda\left(\sum_{i=1}^{F^*(t)} Pt_{i^*}^{p}(t)h_{i,m}(t) + \sum_{j=1}^{M^*(t)} Pt_{j}^{p}(t)h_{j,m}(t) - I_{th}\right) = 0$

FGAA Users and MGAA Users Resource Allocation Algorithm

In the proposed algorithm, i.e. Algorithm 3 joint transmit power and channel allocation method is proposed for FGAA users and MGAA users. Algorithm 1 has the computational complexity of $(\mathcal{O}(|\mathcal{F}||\mathcal{M}||\mathcal{C}|)$.

5.4 Numerical Results

We consider a scenario in which there are 2 PAL channels with 3 PAL users allocated to each PAL channel. In this work, we consider 15 FGAA users randomly located within a 500×500 meters area, and 4 MGAA users travelling in a fixed path. We randomly locate 6 GAA user equipments for each GAA user. All the results are computed in MATLAB. For the simulations, we used the FCC proposed maximum allowed transmit power of 24 dBm, RMS interference threshold of -80 dBm, and the central frequency of 3.6 GHz. In this work, we consider that the train is moving at 60 km/hr. We consider a PAL PA of 50m and time slot of 1 seconds each.

Figure 5.4 shows the CDF of the average GAA capacity from our proposed method with MGAA users at 30km/hr, 60km/hr, 90km/hr, 120km/hr compared to [100]. In [100] only one user from the set that can interfere with each other can transmit at the same time, however in our proposed method both MGAA users and

Algorithm 3 Interfering angle based method for GAA users Resource Allocation

Input: P_{max}, I_{th}

for FGAA i, $i = \{1, ..., |\mathcal{F}|\}$ **do**

  for MGAA j, $j = \{1, ..., |\mathcal{M}|\}$ **do**

    for PAL channel c, $p = \{1, ..., |\mathcal{P}|\}$ **do**

      Calculate the carrier sensing range, i.e. r_i^p and r_j^p using P_{max} in (5.5) for both FGAA and MGAA users.

      Find the interfering angle using $\theta_i^p(t) = 2\cos^{-1}\left(\frac{d_{i,j}^2(t)+r_i^p(t)^2-r_j^p(t)}{2r_i^p(t)d_{i,j}(t)}\right)$

      Find the sets of overlapping GAA users and the interfering angle using (5.6).

      Find $\hat{\mathcal{B}_i^p}(t)$ set of beams that lies in $\theta_i^p(t)$.

      Find the maximum transmit power, i.e. $P_{max}^{\theta_{i,b}^p}(t)$ for $\hat{\mathcal{B}_i^p}(t)$ set of beams using (5.9).

      Considering all GAA are transmitting with P_{max} we find the set of GAA users that can transmit at the same time using

$$\text{maximize} \quad \sum_{p=1}^{|\mathcal{P}|}\left(\sum_{i=1}^{|\mathcal{F}|} C_{i,p}(t) + \sum_{i=1}^{|\mathcal{M}|} C_{j,p}(t)\right)$$
$$\text{subject to} \quad C1, C2, C3, C4, C5$$

      Find $\mathcal{U}_i^*$and $\hat{\mathcal{U}}_i$ using the location information.

      Find the transmit power allocation ensuring the PAL protection criteria is satisfied using

$$\text{maximize} \quad \sum_{p=1}^{|\mathcal{P}|}\left(\sum_{i=1}^{|\mathcal{F}|} C_{i,p}(t) + \sum_{i=1}^{|\mathcal{M}|} C_{j,p}(t)\right)$$
$$\text{subject to} \quad C6, C7, C8$$

      Find the optimal transmit power using

$$Pt_{i^*}^{\hat{p}}(t) = h_{i^*,u}(t)\left((\ln(2)\lambda h_{i,m}(t))^{-1} - I_{i,o}^p(t)\right)$$

    end for

  end for

end for

Output: $\alpha_i^p(t)$, $\beta_j^p(t)$, $Pt_{i,b}^p$, Pt_j^p

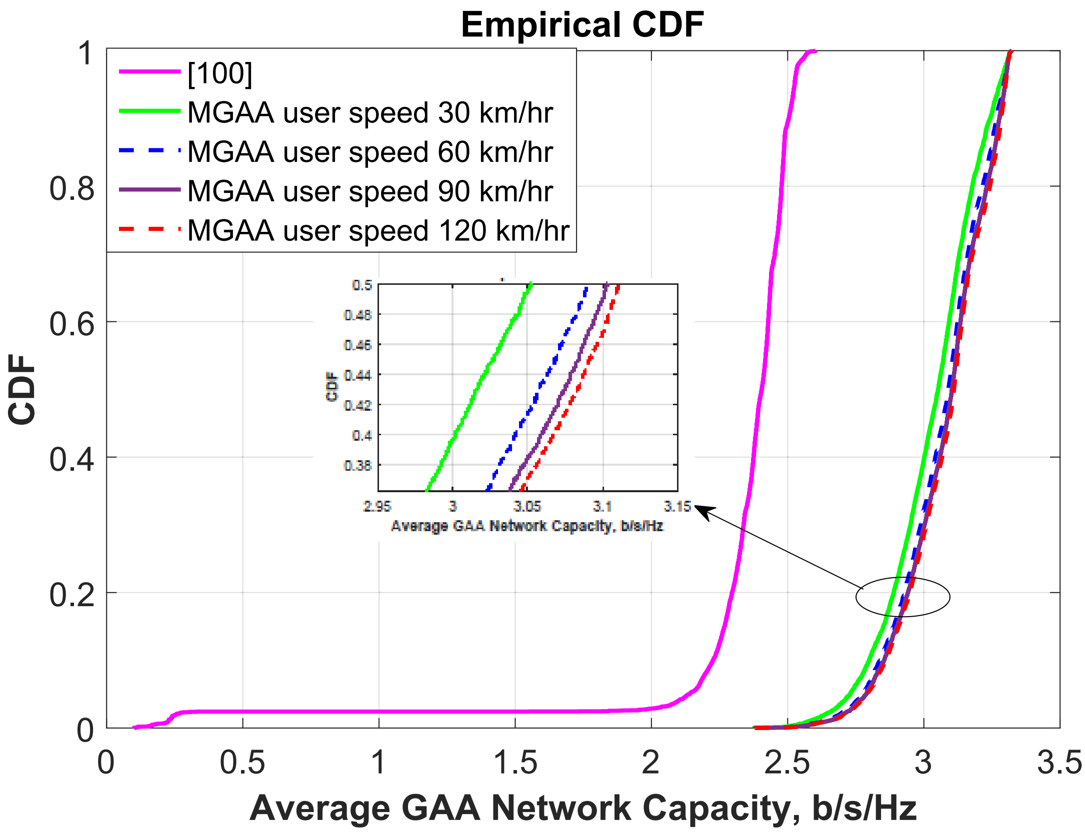


Figure 5.4: Average GAA users capacity considering MGAA users with different speed compared to [100]

FGAA users from the same interfering set can transmit at the same time using our proposed maximum allowed transmit power in the interfering angle. If the speed of the vehicle is lower, the vehicle will be in the same interference set for a longer time. Figure 5.4 show that average GAA user capacity increases as the speed increases, as the MGAA user will be in the same interference set for less time. If FGAA users and MGAA users are in the same interfering set GAA users need to ensure the interference protection to the PAL users PA as well as ensure the conflict-free resource allocation along among GAA users.

To find the optimal solution for the above joint channel and transmit power allocation is very difficult with a large number of GAA users. To compare our proposed method with the optimal solution, we consider a simple scenario with 2 FGAA users and 1 MGAA user with 1 UE for all GAA users. Figure 5.5 shows a comparison of our proposed method to the optimal solution. We can observe an average decrease of 29.68% in our proposed method as compared to the optimal

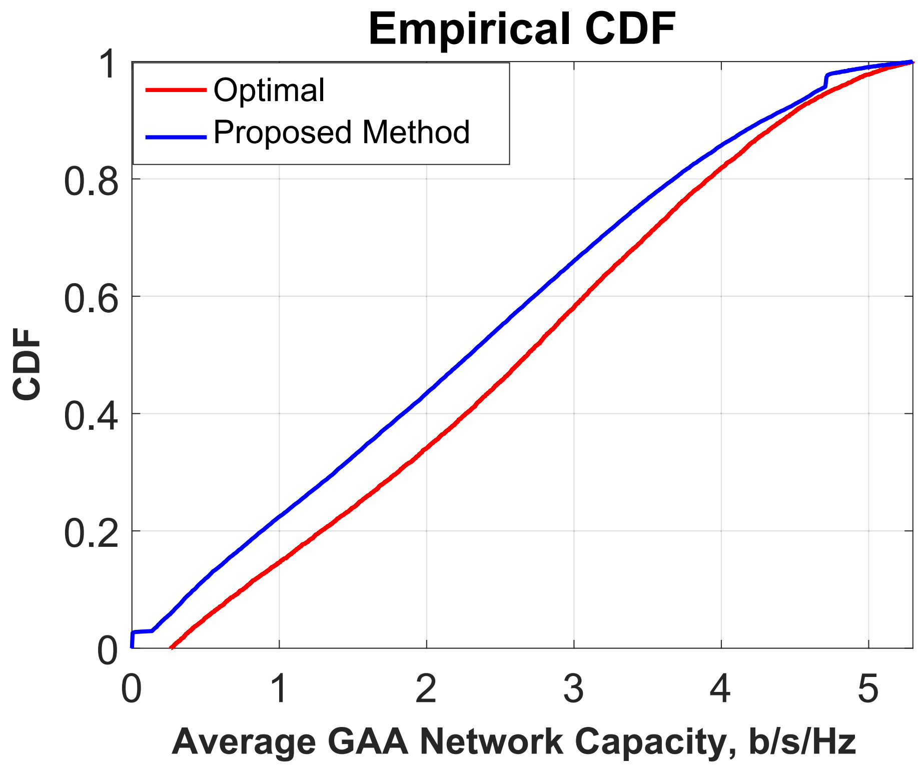


Figure 5.5: Comparision of our proposed method with optimal for the test case with 2 FGAA and 1 MGAA users

solution.

In SAS, RMS interference from a GAA user to the PAL PA should be −80 dBm to protect the PAL users from harmful interference. In this work we consider 3 PAL users allocated to a single PAL channel, and to protect PAL users GAA users need to ensure the RMS interference protection at the PAL PA is satisfied. Figure 5.6 shows that the RMS interference from GAA users to the PAL user PA is below the predetermined threshold of −80 dBm.

Figure 5.7 shows a comparison of our proposed method to [102]. In [102] only one user from the set that can hear each other are allocated to a channel, however in our proposed method using interfering angle based resource allocation both FGAA user and MGAA user are allocated to the same PAL channel due to which RMS interference is more from our proposed method. The results show that RMS interference from our proposed method is greater than [102], however both methods satisfy the FCC criteria to protect the PAL users from harmful interference.

Figure 5.8 shows the transmit power allocation to GAA users based on the

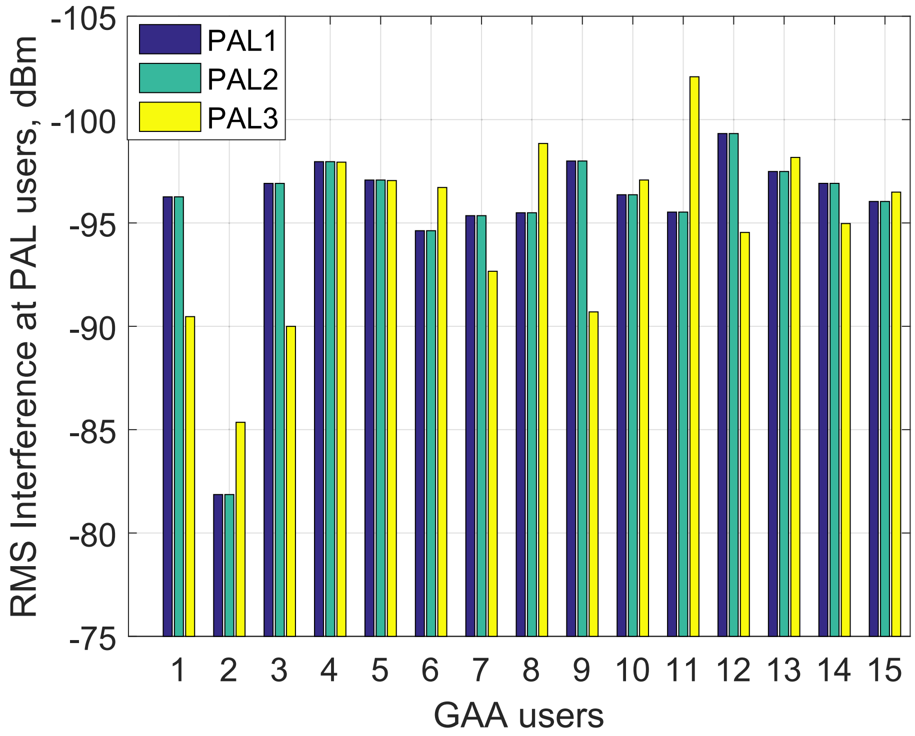


Figure 5.6: RMS interference from GAA user to multiple PAL users protection area allocated to the same PAL channel

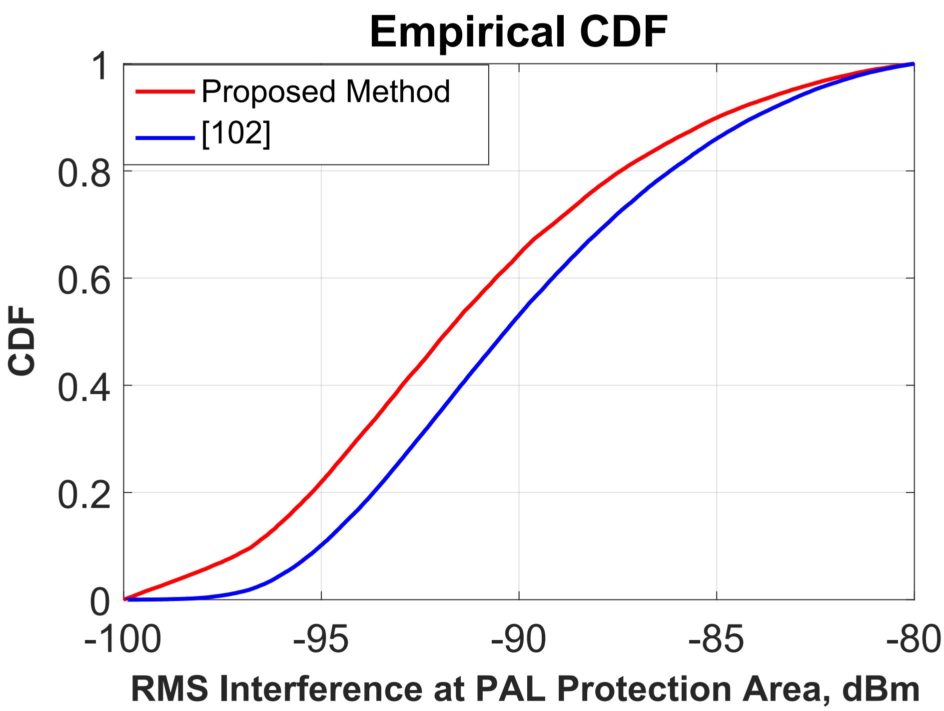


Figure 5.7: RMS interference at PAL user protection area from our proposed method and [102]

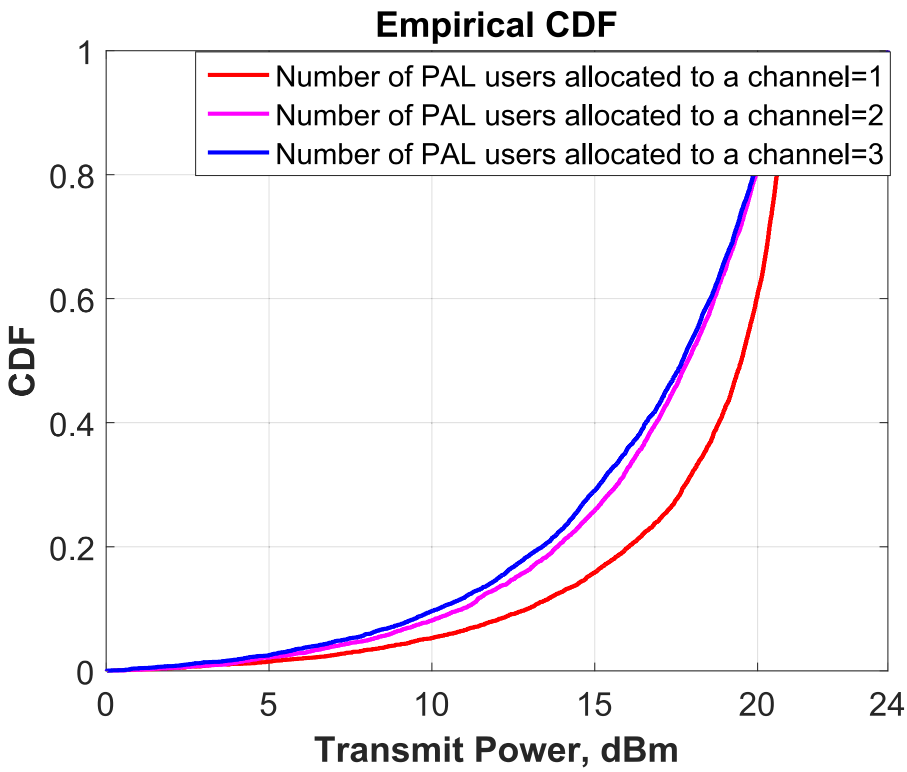


Figure 5.8: Transmit power allocation of GAA users with different number of PAL users in the same channel

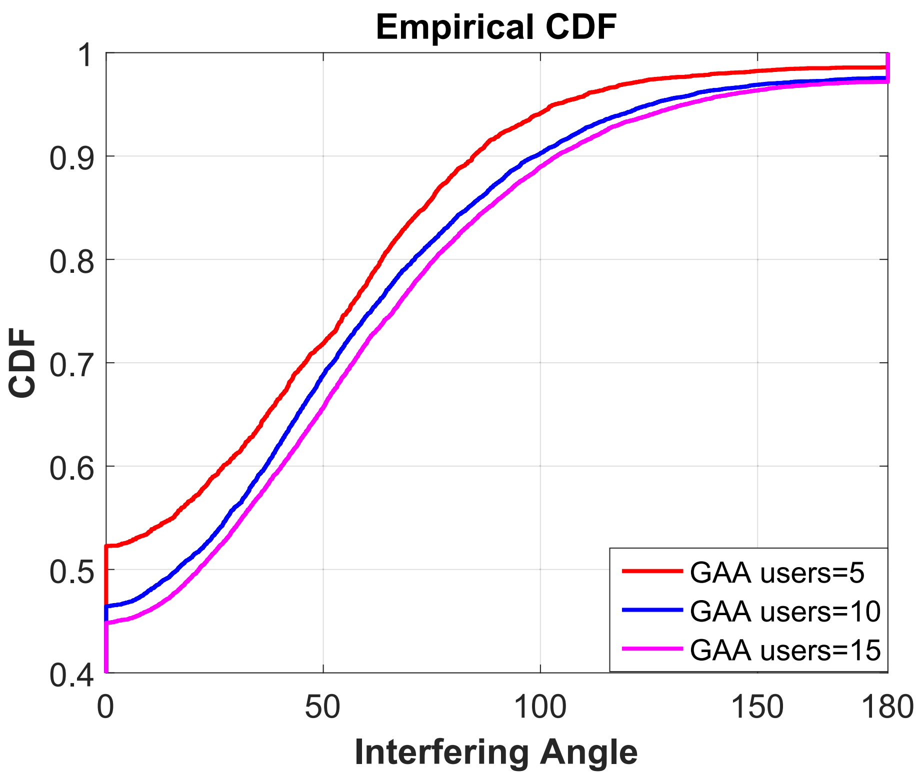


Figure 5.9: Interfering angles for different number of GAA Users

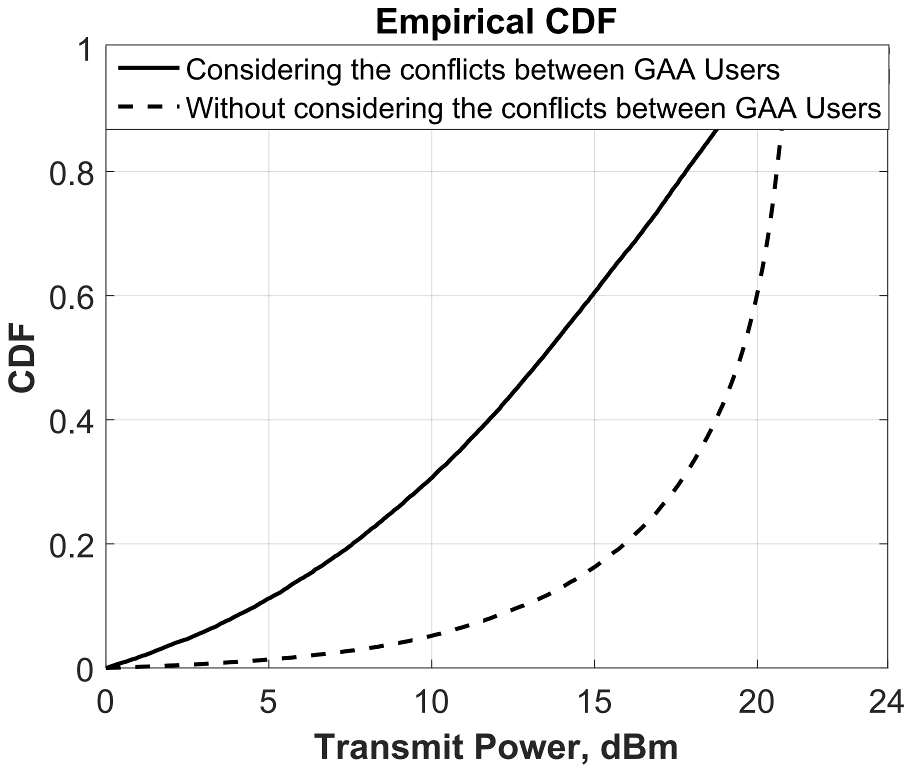


Figure 5.10: Transmit power with and without considering the conflicts

number of PAL users allocated to the PAL channel. The results show that less transmit power is allocated to GAA users as the number of PAL users increases. As the number of PAL users increases GAA users needs to ensure that the interference criteria are satisfied for all the PAL users.

Figure 5.9 shows the interfering angle between GAA users, i.e. the overlapping angle for the different number of GAA users. The results show that as the number of GAA users increases the interfering angle between GAA users also increases. Hence, for the dense deployment of small cells overlapping area increases significantly causing network performance degradation due to interference.

Figure 5.10 shows a comparison between transmit power allocation of GAA users with and without considering the conflicts between GAA users. Most of the resource allocation method [115, 116] only considers the interference to primary users. However, in our proposed transmit power allocation method we consider the hidden node problem to reduce the interference between GAA users. The results show that transmit power allocation is reduced when considering the overlapping area, however our proposed method considers the conflicts between GAA users and interference protection to PAL users.

5.5 Summary

In this chapter, we proposed an interfering angle based channel and transmit power allocation method to MGAA and FGAA users considering coexistence to PAL users as well as self-coexistence between FGAA users and MGAA users. The maximum allowed transmit power in the interfering angle is proposed that ensures the conflict-free channel allocation to both MGAA users and FGAA users on the same channel at the same time. The simulation results show that the average GAA capacity can be maximised from the proposed method while satisfying the interference constraint at the PAL protection area.

Chapter 6

Conclusion

This thesis focuses on spectrum sharing in future wireless networks. Different resource allocation schemes have been proposed to maximise the capacity taking into consideration the interference protection to priority users, and co-channel coexistence in spectrum sharing framework-Spectrum Access System. In this chapter, we summarize the main conclusions of this thesis in Section 6.1, then in Section 6.2 we specify the directions for future work.

6.1 Remarks

The conclusions of this thesis are listed below:

- We proposed an optimal transmit power and transmission time fraction allocation scheme for GAA users. Our approach ensures the PAL users interference criteria are satisfied. Numerical results show that our approach is effective in maximising the capacity of GAA users by taking into consideration the transmission time fraction of GAA users.

- We proposed a method to calculate the switching overhead in the SAS system. Our proposed method decides the optimal channel switching schedule that maximises the average capacity of GAA users while satisfying the interference constraint at the PAL protection area. We proposed a user selection method based on the optimal channel switching schedule for the GAA users in the given channel. Numerical results show that the average capacity of GAA users can be maximised by switching the GAA users with a lower transmission time fraction to a different channel when a PAL user starts the transmission.

- We proposed a fair and efficient spectrum utilisation for GAA users. Using the FCC proposed threshold for received power, we find the sets of GAA users that can hear each other. GAA users that can hear each other cannot transmit at the same time in the same channel, which results in some users utilising the channel for a long time and some users not getting a transmission opportunity. To ensure all GAA users in the same set get a transmission opportunity, we allocate the joint transmit power and transmission time fraction to GAA users utilising our proposed interference threshold for the set. Our proposed method maximises the average capacity of GAA users using an equal interference threshold allocation to sets that can hear each other rather than an equal time allocation scheme in order to maximise the fairness.

- We proposed the set based interference aware resource allocation for GAA users in the Spectrum Access System to maximise the average GAA sum capacity. Using the location information of the GAA users we find GAA users that belong to a single set and multiple sets. GAA users in multiple sets require careful planning for a conflict-free resource allocation. In this work, we propose a conflict-free channel allocation to GAA users using the set information as shown in the simulation results. Our proposed method allocates multiple GAA users to the same channel at the same time in the dense area.

- We proposed a transmit power adjustment for the sets of GAA users that can hear each other. The adjusted interference budget is calculated for the GAA users utilising the interference budget of the transmitting GAA users and interference budget increment received from the other GAA users that belong to the same set. Transmit power allocation is done using the adjusted interference budget while satisfying the interference constraint at the PAL protection area. Simulation results show that our proposed method maximises the GAA network capacity by around 19.62%, and mitigates interference between both

GAA and PAL users as well as GAA and GAA users.

- We proposed a method to calculate the RMS interference from GAA users to the PAL protection area. Our proposed RMS interference method ensures the interference from all the transmitting GAA users at all points in the PAL protection area is below the FCC proposed interference threshold. Numerical results show that the interference criteria are satisfied in all the points in the PAL protection area.

- We proposed an interfering angle based joint channel and transmit power allocation method to MGAA users and FGAA users considering coexistence to PAL users as well as self-coexistence between FGAA users and MGAA users. To ensure self coexistence between FGAA users and MGAA users, we consider the impacts of MGAA users transmission on FGAA users. For mobile and fixed GAA users that are hidden from each other, the user equipments in the overlapped area are interfered, with which significantly reduces the GAA users network performance. The upper bound of the transmit power for the beams in the interfering angle is proposed that ensures a conflict-free channel allocation to both MGAA users and FGAA users on the same channel at the same time. The simulation results show that the average GAA capacity can be maximised from the proposed method while satisfying the interference constraint at the PAL protection area.

6.2 Future Work

In this thesis, we addressed several critical issues in the future wireless network and proposed different resource allocation schemes. However, with the increasing number of new services, there are still some other problems or scenarios in a spectrum sharing framework worth considering for future work.

- In this study, we consider multiple PAL and GAA users randomly located in a census tract reporting to the same SAS. In the future network with the increasing number of new services, it is worth considering multiple PAL and

GAA users randomly located in a census tract reporting to a different SAS. In a scenario with multiple SASs a fair distribution of resources among SAS needs to be also considered.

- Fairness in resource allocation is an important issue and there is still a lot of work to be done to ensure fairness between users. With the dense deployment of users and throughput maximisation schemes to meet the increasing demands, the fairness issue may arise with some users getting more transmission opportunity and some getting less or no transmission opportunity. In this work, we have considered the fairness between GAA users in the set that can hear each other. However, it is important to consider fairness in the ultra dense small cell network where the distance between two small cells is only a few meters.

- In future wireless networks, mobile nodes have been proposed to enhance performance. In this work, we had considered the nodes installed in a train moving with a deterministic speed. However, for buses, the speed and path are not fixed and it highly depends upon the traffic conditions which will affect the analysis derived for deterministic mobility. The position of the bus at a particular time depends upon the speed, so the interfering set of nodes prediction utilising the traffic condition is worth considering.

- GAA users could request multiple contiguous channels which is worth considering in future works. In SAS, channel availability is highly dependent on the location of PAL and GAA users. Location dependent channel availability makes the channel contiguity request from GAA users more challenging to be addressed.

Abbreviations

5G	5th Generation
CA	Channel Allocation
CCA	Clear Channel Assessment
CR	Cognitive Radio
CBRS	Citizen Broadband Radio Service
CBSD	Citizen Broadband Radio Service Device
CDF	Cumulative Density Function
DoD	Department of Defence
ETSI	European Telecommunication Standards Institute
ESC	Environmental Sensing Capability
FCC	Federal Communication Commission
FSS	Fixed Satellite Services
GAA	General Authorized Access
IA	Incumbent Access
ITU	International Telecommunication Unions
LBT	Listen Before Talk

LSA Licensed Shared Access

MNO Mobile Network Operators

NPRM Notice of Proposed Rulemaking

NR New Radio

NTIA National Telecommunications and Information Administration

PA Protection Area

PAL Priority Access Licensee

PU Primary User

QoS Quality of Service

RMS Root Mean Square

SAS Spectrum Access System

SINR Signal-to-Interference-and-Noise-Ratio

SU Secondary User

TVWS TV White Space

UE User Equipment

UHF Ultra High Frequency

VHF Very High Frequency

Bibliography

[1] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 20172022 White Paper", February 2019. [Online]. https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.pdf

[2] S. Mattisson, "An Overview of 5G Requirements and Future Wireless Networks: Accommodating Scaling Technology," *IEEE Solid-State Circuits Magazine*, vol. 10, no. 3, pp. 54-60, Summer 2018.

[3] S. Mattisson, "Overview of 5G requirements and future wireless networks,"*ESSCIRC 2017 - 43rd IEEE European Solid State Circuits Conference*, Leuven, 2017, pp. 1-6.

[4] 5G Americas, "5G Services and Use Cases White Paper," November 2014. [Online]. http://www.5gamericas.org/files/9615/1217/2471/5G_Service_and_Use_Cases__FINAL.pdf

[5] Y. Ye, D. Wu, Z. Shu, Y. Qian, "Overview of LTE Spectrum Sharing Technology". *IEEE Access*, November 2016.

[6] GSMA, "Spectrum Sharing", *GSMA Public Policy Position*, November 2018. [Online]. https://www.gsma.com/spectrum/wp-content/uploads/2018/11/Spectrum-Sharing-Positions.pdf

[7] M. K. Mueck, S. Srikanteswara, B. Badic, "Spectrum Sharing: Licensed Shared Access (LSA) and Spectrum Access System (SAS)". *Intel*, October 2015.

[8] ETSI TS 103 235 V1.1.1: Reconfigurable Radio Systems (RRS); System Architecture and High Frequency Level Procedures for operation of Licensed Shared Access (LSA) in the 2300 MHz - 2400 MHz band.*uropean Telecommunication Standards Institute,* 2015.

[9] "Report and Order and Second Further Notice of Proposed Rulemaking". *Federal Communications Commision,* 2015.

[10] "Order on reconsideration and second report and order". *Federal Communications Commision,* 2016.

[11] European Telecommunication Standards Institute, "ETSI TS 103 235 V1.1.1: Reconfigurable Radio Systems (RRS); System Architecture and High Frequency Level Procedures for operation of Licensed Shared Access (LSA) in the 2300 MHz -2400 MHz band", 2015.

[12] M. M. Sohul, M. Yao, T. Yang and J. H. Reed, "Spectrum access system for the citizen broadband radio service," *IEEE Communications Magazine*, vol. 53, no. 7, pp. 18-25, July 2015.

[13] M. Palola, M. Hoyhtya, P. Aho, M. Mustonen, T. Kippola, M. Heikkila, S. Yrjola, V. Hartikainen, L. Tudose, A. Kivinen, R. Ekman, J. Hallio," Field Trial of the 3.5 GHz Citizen Broadband Radio Service Governed by a Spectrum Access System (SAS)".*2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2017, pp. 1-9.

[14] ITU-T. "5G Basics", 2017. [Online] https://www.itu.int/dms_pub/itu-t/opb/tut/T-TUT-IMT-2017-1-PDF-E.pdf

[15] C. Xin, P. Paul, M. Song and Q. Gu, "On Dynamic Spectrum Allocation in Geo-Location Spectrum Sharing Systems," *IEEE Transactions on Mobile Computing*, vol. 18, no. 4, pp. 923-933, 1 April 2019.

[16] X. Yuan, Y. Shi, X. Qin, Y. T. Hou, W. Lou, S. Kompella, S. F. Midkiff, and J. H. Reed, "Beyond overlay: Reaping mutual benefits for primary and secondary

networks through node-level cooperation," *IEEE Trans. Mobile Comput.*, vol. 16, no. 1, pp. 215, Jan. 2017.

[17] L. Sun, W. Wang, and Y. Li, "The impact of network size and mobility on information delivery in cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 1, pp. 217231, Jan. 2016.

[18] Y. Zhang, G. Yu, Q. Li, H. Wang, X. Zhu, and B. Wang, "Channel-hopping-based communication rendezvous in cognitive radio networks," *IEEE/ACM Trans. Netw.*, vol. 22, no. 3, pp. 889902, Jun. 2014.

[19] F. Hu, B. Chen and K. Zhu, "Full Spectrum Sharing in Cognitive Radio Networks Toward 5G: A Survey," *IEEE Access*, vol. 6, pp. 15754-15776, 2018.

[20] R. H. Tehrani, S. Vahid, D. Triantafyllopoulou, H. Lee and K. Moessner, "Licensed Spectrum Sharing Schemes for Mobile Operators: A Survey and Outlook," *IEEE Communications Surveys and Tutorials*, vol. 18, no. 4, pp. 2591-2623, Fourthquarter 2016.

[21] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys and Tutorials*, vol. 11, no. 1, pp. 116-130, First Quarter 2009.

[22] X. Kang, Y. Liang, H. K. Garg and L. Zhang, "Sensing-Based Spectrum Sharing in Cognitive Radio Networks," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 4649-4654, Oct. 2009.

[23] A. Ben Jemaa, M. Turki and W. Guibne, "Enhanced energy detector via algebraic approach for spectrum sensing in cognitive radio networks," *2012 7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, Stockholm, 2012, pp. 113-117.

[24] S. K. Sharma, T. E. Bogale, L. B. Le, S. Chatzinotas, X. Wang and B. Ottersten, "Dynamic Spectrum Sharing in 5G Wireless Networks With Full-Duplex Technology: Recent Advances and Research Challenges," *IEEE Communications Surveys and Tutorials*, vol. 20, no. 1, pp. 674-707, Firstquarter 2018.

[25] H. O. Kpojime and G. A. Safdar, "Interference Mitigation in Cognitive-Radio-Based Femtocells," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 3, pp. 1511-1534, thirdquarter 2015.

[26] G. I. Tsiropoulos, O. A. Dobre, M. H. Ahmed and K. E. Baddour, "Joint channel assignment and power allocation in cognitive radio networks," *2014 IEEE Global Communications Conference*, Austin, TX, 2014, pp. 876-881.

[27] G. I. Tsiropoulos, O. A. Dobre, M. H. Ahmed and K. E. Baddour, "Joint channel assignment and power allocation in cognitive radio networks," *2014 IEEE Global Communications Conference*, Austin, TX, 2014, pp. 876-881.

[28] Z. Yu, C. Zhai and J. Liu, "Time domain spectrum sharing with wireless power transfer in cognitive radio network," *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Hong Kong, 2015, pp. 1437-1441.

[29] M. El Tanab and W. Hamouda, "Resource Allocation for Underlay Cognitive Radio Networks: A Survey," *IEEE Communications Surveys and Tutorials*, vol. 19, no. 2, pp. 1249-1276, Secondquarter 2017.

[30] K. Hamdi, W. Zhang, and K. B. Letaief, "Joint beamforming and scheduling in cognitive radio networks, *IEEE GLOBECOM*, Washington, DC, USA, Nov. 2007, pp. 29772981.

[31] A. Massaoudi, N. Sellami, and M. Siala, "Scheduling scheme for cognitive radio networks with imperfect channel knowledge," *IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun. Mobile Wireless Netw. (PIMRC)*, London, U.K., Sep. 2013, pp. 31453149.

[32] J. Mitola and G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13-18, Aug. 1999.

[33] S. Bayhan and F. Alagoz, "Scheduling in centralized cognitive radio networks for energy efficiency," *IEEE Trans. Veh. Technol.*, vol. 62,no. 2, pp. 582595, Feb. 2013.

[34] M. Hasegawa, H. Hirai, K. Nagano, H. Harada, and K. Aihara, "Optimization for centralized and decentralized cognitive radio networks," *Proc. IEEE*, vol. 102, no. 4, pp. 574584, Apr. 2014.

[35] Y. Liang, L. Lai, and J. Halloran, "Distributed cognitive radio network management via algorithms in probabilistic graphical models," *IEEE J.Sel. Areas Commun.*, vol. 29, no. 2, pp. 338347, Feb. 2011.

[36] J.A. Bazerque and G. B. Giannakis, "Distributed spectrum sensing for cognitive radio networks by exploiting sparsity," *IEEE Trans. Signal Process.*, vol. 58, no. 3, pp. 18471862, Mar. 2010.

[37] 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 and Tutorials*, vol. 18, no. 1, pp. 824-847, Firstquarter 2016.

[38] A. De Domenico, E. Calvanese Strinati and M. Di Benedetto, "A Survey on MAC Strategies for Cognitive Radio Networks," *IEEE Communications Surveys and Tutorials*, vol. 14, no. 1, pp. 21-44, First Quarter 2012.

[39] W. Xiong, A. Mukherjee, and H. M. Kwon, "MIMO cognitive radio user selection with and without primary channel state information," *IEEE Trans. Veh. Technol.*, vol. 65, no. 2, pp. 985991, Feb. 2016.

[40] E. Driouch, W. Ajib, and A. B. Dhaou, "A greedy spectrum sharing algorithm for cognitive radio networks," *Proc. Int. Conf. Comput. Netw. Commun. (ICNC),* Jan. 2012, pp. 10101014.

[41] M. E. Tanab, W. Hamouda, and Y. Fahmy, "Distributed opportunistic scheduling for MIMO underlay cognitive radio networks," *Wireless Commun. Mobile Comput.*, vol. 16, no. 15, pp. 22122224, Jun. 2016.

[42] M. E. Tanab, W. Hamouda, and Y. Fahmy, "On the distributed resource allocation of MIMO cognitive radio networks," *Proc. IEEE Glob. Commun. Conf. (GLOBECOM)*, San Diego, CA, USA, Dec. 2015, pp. 16.

[43] J. R. Gllego, M. Canales, and J. Ortn, “Distributed resource allocation in cognitive radio networks with a game learning approach to improve aggregate system capacity,” *Elsevier Ad Hoc Netw.*, vol. 10, no. 6, pp. 10761089, Aug. 2012.

[44] A. G. Marques, L. M. Lopez-Ramos, G. B. Giannakis, and J. Ramos, “Resource allocation for interweave and underlay CRs under probability-of-interference constraints,” *IEEE J. Sel. Areas Commun.*, vol. 30, no. 10, pp. 19221933, Nov. 2012.

[45] L. M. Lopez-Ramos, A. G. Marques, and J. Ramos, “Joint sensing and resource allocation for underlay cognitive radios,” *Proc. IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, Florence, Italy, May 2014, pp. 72837287.

[46] L. B. Le and E. Hossain, “Resource allocation for spectrum underlay in cognitive radio networks,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 53065315, Dec. 2008.

[47] S. Singh, P. Teal, P. Dmochowski, A. Coulson, “Interference Management in Cognitive Radio Systems - a convex optimisation approach”. *2012 IEEE International Conference on Communications (ICC),* Ottawa, ON, 2012, pp. 1884-1889.

[48] S. Kusaladharma, P. Hearth, C. Tellambura, “Impact of Transmit Power Control on Aggregate Interference in Underlay Cognitive Radio Networks”. *2014 IEEE International Conference on Communications (ICC),* Sydney, NSW, 2014, pp. 1567-1572.

[49] K. Hamdi, W. Zhang, and K. B. Letaief, “Joint beamforming and scheduling in cognitive radio networks,” in Proc. IEEE GLOBECOM, Washington, DC, USA, Nov. 2007, pp. 29772981.

[50] A. Massaoudi, N. Sellami, and M. Siala, “Scheduling scheme for cognitive radio networks with imperfect channel knowledge,” in Proc. IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun. Mobile Wireless Netw. (PIMRC), London, U.K., Sep. 2013, pp. 31453149.

[51] X. Ying, M. M. Buddhikot and S. Roy, "SAS-Assisted Coexistence-Aware Dynamic Channel Assignment in CBRS Band," *IEEE Transactions on Wireless Communications*, vol. 17, no. 9, pp. 6307-6320, Sept. 2018.

[52] A. Sahoo, "Fair resource allocation in the citizens broadband radio service band," *2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Piscataway, NJ, 2017, pp. 1-2

[53] K. B. S. Manosha et al., "A channel allocation algorithm for Citizens Broadband Radio Service/Spectrum Access System, " *2017 European Conference on Networks and Communications (EuCNC)*, Oulu, 2017, pp. 1-6.

[54] R. Karaki and A. Mukherjee, "Coexistence of Contention-Based General Authorized Access Networks in 3.5 GHz CBRS Band," *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, Porto, 2018, pp. 1-6.

[55] Y. Song, K. W. Sung and Y. Han, "Coexistence of Wi-Fi and Cellular With Listen-Before-Talk in Unlicensed Spectrum," in IEEE Communications Letters, vol. 20, no. 1, pp. 161-164, Jan. 2016.

[56] A. S. W. Marzuki, I. Ahmad, D. Habibi and Q. V. Phung, "Mobile Small Cells: Broadband Access Solution for Public Transport Users," *IEEE Communications Magazine, vol. 55, no. 6, pp. 190-197, June 2017.*

[57] W. Cheng-Xiang, F. Haider, X. Gao, X. You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher, E. Hepsaydir "Cellular Architecture and Key Technologies for 5G Wireless Communication Networks," IEEE Commun. Mag., vol. 52, 2011, pp. 12230.

[58] J. M. Peha, W. Johnston, P. Amodio, and T. Peters, "The public safety nationwide interoperable broadband network: A new model for capacity, performance and cost," *FCC White Paper*, Jun. 2010. [Online]. Available: http://transition.fcc.gov/pshs/docs/releases/DOC-298799A1.pdf

[59] J. Li and Y. Han, "Multi-RAT Wireless Network Capacity Optimization under Optimal Spectrum Splitting in LTE-U", *2016 IEEE Wireless Communications and Networking Conference,* Doha, 2016, pp. 1-6.

[60] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?" *IEEE Journal on Selected Areas in Communications,* vol. 32, no. 6, pp. 10651082, June 2014.

[61] S. Singh, P. Teal, P. Dmochowski, A. Coulson, "Interference Management in Cognitive Radio Systems - a convex optimisation approach", *2012 IEEE International Conference on Communications (ICC),* Ottawa, ON, 2012, pp. 1884-1889.

[62] S. Kusaladharma, P. Hearth, C. Tellambura, "Impact of Transmit Power Control on Aggregate Interference in Underlay Cognitive Radio Networks", *2014 IEEE International Conference on Communications (ICC),* Sydney, NSW, 2014, pp. 1567-1572.

[63] T. Zhang, L. An, Y. Chen, K. Chai, "Aggregate Interference Statistical Modeling and User outage Analysis of Heterogeneous Cellular Networks", *2014 IEEE International Conference on Communications (ICC),* Sydney, NSW, 2014, pp. 1260-1265.

[64] L. Vijayandran, P. Dharmawansa, T. Ekman, C. Tellambura, "Analysis of Aggregate Interference and Primary System Performance in Finite Area Cognitive Radio Networks", *IEEE Transactions on Communications,* vol. 60, no. 7, pp. 1811-1822, July 2012.

[65] Q. Xiao, Q. Gao, L. Xiao, S. Zhou, J. Wang, "An Optimal Opportunistic Spectrum Access Approach", *2009 IEEE International Conference on Communications Workshops,* Dresden, 2009, pp. 1-5.

[66] X. Kang, Y. Liang, A. Nallanathan, "Optimal Power Allocation for Fading Channels in Cognitive Radio Networks under Transmit and Interference Power Constraints", *2008 IEEE International Conference on Communications,* Beijing, 2008, pp. 3568-3572.

[67] A. D. Sezer, S. Gezici, "Optimal Channel Switching for Average Capacity Maximisation in the presence of Switching Delays",*IEEE Wireless Conference and Networking Conference,* 2016.

[68] A. Moghaddam, U. T. Nguyen, "Evaluation of channel switching overhead for multicast communications in wireless mesh networks",*2016 IEEE 7th Annual Ubiquitous Computing, Electronics and Mobile Communication Conference,* New York, NY, 2016, pp. 1-7.

[69] M. Yun, Y. Zhou, A. Arora, and H.-A. Choi, "Channel-assignment and scheduling in wireless mesh networks considering switching overhead",*IEEE International Conference on Communications,* pp. 16, 2009.

[70] M. Harris and S. Harvey, "Channel switching overhead for 802.11b",*Technical Report,* 2009.

[71] Y. Xu, Y. Hu, Q. Chen, T. Song, R. Lai, "Robust resource allocation for multitier cognitive heterogeneous networks",*2017 IEEE International Conference on Communications (ICC),* 2017, pp. 1-6.

[72] M. Brown, C. Marshall, D. Yang, M. Li, J. Lin, G. Xue, "Maximizing Capacity in Cognitive Radio Networks Under Physical Interference Model",*IEEE/ACM Transactions on Networking,* vol. 25, no. 5, pp. 3003-3015, Oct. 2017.

[73] Hongdou Li, Yongyu Chang, Fanrong Hao, Aidong Men, Jian Zhang, Wei Quan, "Study on dynamic channel switch in License-Assisted-Access based on Listen-Before-Talk", *2016 International Symposium on Wireless Communication Systems (ISWCS),* 2016, pp. 506-510.

[74] S. S. Kalamkar, J. P. Jeyaraj, A. Banerjee and K. Rajawat, "Resource Allocation and Fairness in Wireless Powered Cooperative Cognitive Radio Networks", *IEEE Transactions on Communications,* vol. 64, no. 8, pp. 3246-3261, Aug. 2016.

[75] P. Kong and G. K. Karagiannidis, "Backhaul-Aware Joint Traffic Offloading and Time Fraction Allocation for 5G HetNets," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 11, pp. 9224-9235, Nov. 2016.

[76] P. kyostii, J. Meinila, L. Hentila, X. Zhao, T. Jamsa, C. schneider, M. Narandzic, M. Milojevic, A. Hong, J. Ylitalo, V. Hollappa, M. Alatossava, R. Bultitude, Y. Jong, T. Rautiainen, "Winner II channel models",*Information Society Technologies,* 2008.

[77] S. S. Kalamkar, J. P. Jeyaraj, A. Banerjee and K. Rajawat, "Resource Allocation and Fairness in Wireless Powered Cooperative Cognitive Radio Networks",*IEEE Transactions on Communications,* vol. 64, no. 8, pp. 3246-3261, Aug. 2016.

[78] R. Jain, D. Chiu, W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems", *Eastern Res. Lab., Digit. Equip. Corp., Farmingham,* Sep. 1984.

[79] S. Boyd, L. Vandenberghe, "Convex Optimization", *Cambridge Univ. Press,* 2004.

[80] R. Fan, W. Chen, J. An, F. Gao and G. Wang, "Robust Power and Bandwidth Allocation in Cognitive Radio System With Uncertain Distributional Interference Channels," *IEEE Transactions on Wireless Communications,* vol. 15, no. 10, pp. 7160-7173, Oct. 2016.

[81] Amendment of the Commissions Rules with Regard to Commercial Operations in the 3550-3650 MHz Band. *Report and Order and Second Further Notice of Proposed Rulemaking in GN Docket No. 12-354,* April 2015.

[82] E. Drocella, J, Richards, R. Sole, F. Najmy, A. Lundy, P. McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology", *NTIA Report 15-517*, June 2015.

[83] X. Tan, H. Zhang and J. Hu, "Capacity maximisation of the secondary link in cognitive radio networks with hybrid spectrum access strategy", *IET Communications,* vol. 8, no. 5, pp. 689-696, March 27 2014.

[84] Q. Xiao, Q. Gao, L. Xiao, S. Zhou, J. Wang, "An Optimal Opportunistic Spectrum Access Approach", *2009 IEEE International Conference on Communications Workshops,* Dresden, 2009, pp. 1-5.

[85] X. Kang, Y. Liang, A. Nallanathan, "Optimal Power Allocation for Fading Channels in Cognitive Radio Networks under Transmit and Interference Power Constraints", *2008 IEEE International Conference on Communications,* Beijing, 2008, pp. 3568-3572.

[86] B. Yuksekkaya, H. Inaltekin and C. Toker, "Optimum Uplink Power Control under Power and Interference Constraints", *2013 IEEE 78th Vehicular Technology Conference (VTC Fall),* Las Vegas, NV, 2013, pp. 1-5.

[87] E. Drocella, J, Richards, R. Sole, F. Najmy, A. Lundy, P. McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology", *NTIA Report 15-517*, June 2015.

[88] M. Yousefvand, N. Ansari, S. Siavakash, "Maximizing Network Capacity of Cognitive Radio Networks by Capacity Aware Spectrum Allocation", *IEEE Transactions on Wireless Communications,* September 2015.

[89] H. Xu, Z. Yang, N. Huang, J. Wang, J. Shi, M. Chen, "Channel Allocation and Power Control in D2D Uplink Underlaid Cellular Networks", *2016 IEEE Globecom Workshops (GC Wkshps)*, 2016, pp. 1-6.

[90] R. Wang, J. Zhang, S.H. Song, K. B. Letaief, "QoS-Aware Channel Assignment for Weighted Sum-Rate Maximization in D2D Communications", *2015 IEEE Global Communications Conference (GLOBECOM)*, 2015, pp. 1-6.

[91] S. Li, Q. Ni, Y. Sun, G. Min, "Resource Allocation for Weighted Sum-Rate Maximization in Multi-User Full-Duplex Device-to-Device Communications: Approaches for perfect and Statistical CSIs", *IEEE Access,* vol. 5, pp. 27229-27241, 2017.

[92] H. B. Salameh, "Rate-maximization Channel Assignment Scheme for Cognitive Radio Networks", *2010 IEEE Global Telecommunications Conference GLOBECOM*, 2010, pp. 1-5.

[93] Q. Song, X. wang, T. Qiu, Z. Ning, "An Interference Coordination-Based Distributed Resource Allocation Scheme in Heterogeneous Cellular Networks," *IEEE Access*, vol. 5, pp. 2152-2162, 2017.

[94] Y. Han, E. Ekici, H. Kremo, O. Altintas, “Throughput Efficient Channel Allocation Algorithms in Multi-Channel Cognitive Vehicular Networks”, ‘*IEEE Transactions on Wireless Communications*, vol. 16, no. 2, pp. 757-770, Feb. 2017.

[95] H. Xu, Z. Yang, N. Huang, J. Y. Wang, J. Shi and M. Chen, “Channel Allocation and Power Control in D2D Uplink Underlaid Cellular Networks”, *2016 IEEE Globecom Workshops (GC Wkshps)*, 2016, pp. 1-6.

[96] A. Sahoo, “ Fair resource allocation in the citizens broadband radio service band,” *2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN),* 2017, pp. 1-2.

[97] T. Xue, X. Dong, Y. Shi, “Resource-Allocation strategy for Multiuser Cognitive Radio Systems: Location-Aware Spectrum Access”, *IEEE Transaction on Vehicular Technology,* vol. 66, no. 1, Jan 2017.

[98] *Amendment of the Commission Rules With Regard to Commercial Operations in the 3550-3650 MHz Band*, Federal Communications CommissionStd. GN Docket No. 12-354, Apr. 2015.

[99] *Amendment of the Commission Rules With Regard to Commercial Operations in the 3550-3650 MHz Band*, Federal Communications CommissionStd. FCC 16-55 A1,GN Docket No. 12-354, May 2016.

[100] M. Yousefvand, N. Ansari and S. Khorsandi, “Maximizing Network Capacity of Cognitive Radio Networks by Capacity-Aware Spectrum Allocation,” in *IEEE Transactions on Wireless Communications*, vol. 14, no. 9, pp. 5058-5067, Sept. 2015.

[101] H. Zhang, C. Jiang, N. C. Beaulieu, X. Chu, X. Wang and T. Q. S. Quek, “Resource Allocation for Cognitive Small Cell Networks: A Cooperative Bargaining Game Theoretic Approach,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3481-3493, June 2015.

[102] D. T. Ngo, S. Khakurel and T. Le-Ngoc, "Joint Subchannel Assignment and Power Allocation for OFDMA Femtocell Networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 342-355, January 2014.

[103] M. El-Absi, M. Shaat, F. Bader and T. Kaiser, "Interference Alignment With Frequency-Clustering for Efficient Resource Allocation in Cognitive Radio Networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 12, pp. 7070-7082, Dec. 2015.

[104] D. Xu, Y. Li, Z. Feng and P. Zhang, "Resource allocation for multiuser cognitive radio with primary user's cooperation," *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, Houston, TX, 2011, pp. 1419-1423.

[105] R. Karaki and A. Mukherjee, "Coexistence of Contention-Based General Authorized Access Networks in 3.5 GHz CBRS Band," *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, Porto, 2018, pp. 1-6.

[106] X. Ying, M. M. Buddhikot and S. Roy, "Coexistence-aware dynamic channel allocation for 3.5 GHz shared spectrum systems," *2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Piscataway, NJ, 2017, pp. 1-2.

[107] S. Jangsher and V. O. K. Li, "Resource Allocation in Moving Small Cell Network," *IEEE Transactions on Wireless Communications*, vol. 15, no. 7, pp. 4559-4570, July 2016.

[108] S. Jangsher and V. O. K. Li, "Resource allocation in cellular networks employing mobile femtocells with deterministic mobility," *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, Shanghai, 2013, pp. 819-824.

[109] S. Jaffry, S. F. Hasan and X. Gui, "Making a case for the moving small cells," *2016 26th International Telecommunication Networks and Applications Conference (ITNAC)*, Dunedin, 2016, pp. 249-251.

[110] W. Sun, D. Yuan, E. G. Strom and F. Brannstrom, "Cluster-Based Radio Resource Management for D2D-Supported Safety-Critical V2X Communications," *IEEE Transactions on Wireless Communications*, vol. 15, no. 4, pp.

[111] H. B. Salameh, "Efficient Resource Allocation for Multicell Heterogeneous Cognitive Networks With Varying Spectrum Availability," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 8, pp. 6628-6635, Aug. 2016.

[112] C. Tang and C. Chen, "Switched-beam antenna for small cell application," *2016 International Symposium on Antennas and Propagation (ISAP)*, Okinawa, 2016, pp. 100-101.

[113] C. Tang and G. Chiou, "Switching beam antenna for LTE small cell application," *2017 International Symposium on Antennas and Propagation (ISAP)*, Phuket, 2017, pp. 1-2.

[114] P. I. Bantavis, C. I. Kolitsidas, T. Empliouk, M. Le Roy, B. L. G. Jonsson and G. A. Kyriacou, "A Cost-Effective Wideband Switched Beam Antenna System for a Small Cell Base Station," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 6851-6861, Dec. 2018.

[115] B. Yuksekkaya, H. Inaltekin and C. Toker, "Optimum Uplink Power Control under Power and Interference Constraints," *2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, Las Vegas, NV, 2013, pp. 1-5.

[116] B. Yuksekkaya and C. Toker, "Power and Interference Regulated Water-Filling for Multi-Tier Multi-Carrier Interference Aware Uplink," *IEEE Wireless Communications Letters*, vol. 7, no. 4, pp. 494-497, Aug. 2018.

[117] S. Boyd, L. Vandenberghe," Convex Optimization." *Cambridge Univ. Press,* 2004.

[118] H. Zhang, C. Jiang, X. Mao and H. Chen, "Interference-Limited Resource Optimization in Cognitive Femtocells With Fairness and Imperfect Spectrum Sensing," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 3, pp. 1761-1771, March 2016.

[119] R. Fan, W. Chen, J. An, F. Gao and G. Wang, "Robust Power and Bandwidth Allocation in Cognitive Radio System With Uncertain Distributional Interference Channels," *IEEE Transactions on Wireless Communications,* vol. 15, no. 10, pp. 7160-7173, Oct. 2016.

[120] R. Fan and H. Jiang, "Average rate maximization in relay networks over slow fading channels," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 8, pp. 3865-3881, Oct. 2011.