Distributed Algorithms and Application of Game Theory in Cognitive Radio Networks

Abstract

Due to the proprietary spectrum allocation paradigm and the boom of wireless communications, spectrum scarcity has become an increasingly pressing problem. Cognitive Radio (CR) is a promising technology to provide high bandwidth via dynamic spectrum access, where unlicensed users are allowed to utilize licensed spectrum, as long as their operation doesn't cause harmful interferences, or no primary users are sensed with respect to a certain probability. This spectrum usage paradigm prompts new challenges to both research and application. One challenge is the spectrum allocation problem needs reformulation as primary users should be considered in the problem formulation. The second issue is how to improve the accuracy of sensing result by applying robust cooperative sensing. The robust clustering maintains the clusters for longer time under primary users' unexpected activities, so as to gains more benefits from cooperative sensing. Routing on cognitive radio network needs to consider the influence from primary users besides the conventional concerns in ad hoc network.

As available spectrum or resources for cognitive radio users is dependant on their locations, cognitive radio users are suitable to make decisions autonomously, with or without utilizing the knowledge from neighbourhood or centralized entity. This thesis solves a series of problems with distributed solutions. As a suitable theoretical tool, game theory is used to analyse certain problems and help to derive and verify solutions.

In this dissertation, we solve three problems residing from physical layer up to network layer in CRN with distributed solutions. We solve the power and spectrum allocation problem in IEEE 802.22 networks. After deciding the maximal transmission power on each secondary cellular base station, we formulate the distributed spectrum allocation problem in TV white space scenario into a canonical congestion game, then propose distributed algorithm corresponding to the behaviour of player in the game. Power allocation is conducted on the channel decided before. On MAC layer, a distributed clustering scheme for CRN is proposed and the formed clusters are much less vulnerable against primary users' activity, besides, the scheme is able to produce desired cluster sizes. The process of finalizing cluster membership is innovatively formulated into a congestion game, and light-weighted distributed scheme is accordingly derived. The proposed clustering scheme can be easily applied to other scenarios, where certain similarity exists in local area. On network layer, we propose lighted weighted geographic routing scheme for CRN. Spectrum aware virtual coordinate is proposed, thus light weighted geographic routing can be applied to decide the next hop. Finally, using thorough simulations and numerical results, we investigate various aspects of the proposed algorithms and analyse their performance.

This thesis is based on the following papers, which are referred in the text respectively.

Di Li; Zhichao Lin; Stoffers, Mirko; Gross, James, "Spectrum aware virtual coordinates assignment and routing in multihop cognitive radio network," IFIP Networking Conference (IFIP Networking), 2015 , vol., no., pp.1,9, 20-22 May 2015 doi: 10.1109/IFIPNetworking.2015.7145337

Di Li; Gross, J., "Distributed TV spectrum allocation for cognitive cellular network under game theoretical framework," Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on , vol., no., pp.327,338, 16-19 Oct. 2012 doi: 10.1109/DYSPAN.2012.6478156

Di Li; Gross, J., "Robust Clustering of Ad-Hoc Cognitive Radio Networks under Opportunistic Spectrum Access," Communications (ICC), 2011 IEEE International Conference on , vol., no., pp.1,6, 5-9 June 2011 doi: 10.1109/icc.2011.5963426

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INTRODUCTION

Wireless networks have experienced unprecedented growth in the past few decades and will going on evolving in the future. Due to the propagation characteristics and regulations, only a small portion of electromagnetic spectrum which spans from 8.3 kHz to 3000 GHz is suitable for commercial application. These spectrum is divided into bands (also referred as channels) and allocated to different services. As one kind of limited and precious resource, radio spectrum is strictly regulated by the national administration. The channels are assigned or leased by governments to different operators and entities. In most cases, the operators pay high price for the commercial usage of certain spectrum, and the usage is exclusive for them [34]. This spectrum management policy rules out the unlicensed users to use the spectrum, thus strictly protects the interest of the spectrum licensees. This spectrum access module is referred *exclusive use model* [133], and is the mainstream of spectrum access worldwide, and many existing wireless applications work on the licensed spectrum. For instance, the second-generation (2G) wireless cellular network GSM (global system for mobile communications) in Europe works with GSM-900 band (from 890 MHz to 960 MHz) and GSM-1800 (1710 MHz to 1880 MHz), and the third-generation (3G) wireless cellular network works from 1.8 GHz to 2.4 GHz [98]. The excludability of licensed spectrum can also be open to other user with conditions. The spectrum licences either sell and trade the licensed spectrum, or dynamically use the spectrum within a certain region according to different traffic patterns [124]. Open spectrum access [88] is proposed in 1995 for full openness of entry, which allows access to spectrum through access fees which are determined by demand and supply. It is claimed that open spectrum access brings in benefits, as for spectrum licensees, the fixed costs on securing the licensed spectrum can be converted into marginal costs, and for the market, the incentives for collusive pricing can be eliminated. But as the *openness* here is fully controlled by the licensees, this spectrum usage is still exclusive .

In contrary to exclusive use model, certain spectrum are assigned for open sharing for peer users, the representative example is the unlicensed industrial, scientific, and medical (ISM) radio band, which supports versatile wireless applications and a prosperous industry, i.e., WiFi. Many spectrum sharing strategies are proposed to cope with the technical challenges [67].

1.1 Hierarchical Spectrum Access

The proliferation of wireless network constantly arises urgent demand on bandwidth and throughput since the first generation of telecommunication in 1980s, which accordingly encourages the efficient use and reuse of the electromagnetic spectrum. The next generation of telecommunication technology 5G, which is reported to come true in 2020, requires a leap forward of spectrum efficiency [62]. The resorted applications under the label of 5G [31], i.e., machine to machine communication, internet of things, etc, requires high speed and lower investment cost, but this is changeling as the achieved capacity approaches Shannon capacity, and most spectrum are licensed. Meanwhile, the actual spectrum usage measurement conducted by FCC tells that at many locations or time, the licensed spectrum is idle [6], and there exists a large number of spectrum bands which have considerable dormant time intervals [17].

To seek more opportunities from spectrum, it is natural to consider opening the licensed spectrum to unlicensed users, if the interference perceived by licensed users are restricted. We adopt the terms proposed in [133], and call this spectrum usage policy as *hierarchical access model*, where licensed users are called primary users, and unlicensed users are named as secondary users. Hierarchical access model gives a promising solution to the reclamation of new electromagnetic spectrum and the improvement of spectrum efficiency.

1.2 Cognitive Radio

Throughout this thesis, we use *cognitive radio networks* to compound the networks composed with secondary users which work in either spectrum underlay or spectrum overlay style. There are two reasons, firstly, this name explicitly tells a distinctive property of the devices in the networks, their cognition to their environment, secondly, cognitive radio has become a synonym of the technology employed in the hierarchical spectrum access paradigm in academia and industry in the recent years.

The definition of cognitive radio evolves with the development of radio technology and regulations. We choose two representative definitions to give a formal description of cognitive radio. Cognitive radio is firstly proposed by Mitola III who defines the concept of CR in his dissertation [82] as follows:

> ... personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.

FCC (Federal Communications Commission in U.S.) describes CR [3] as,

> a radio that can change its transmitter parameters based on interaction with the environment in which it operates. . . . This interaction may involve active negotiations with other spectrum users and/or passive sensing and decision

> making (smart radio) within the radio. The majority of CRs will probably be SDRs [1], but a CR does not necessarily use software, nor does it need to be field programmable.

In this thesis, we see cognitive radio as a device which is able to sense, detect, learn and monitor the surrounding radio frequency environment, or to access a certain database to retrieve primary users' information, so as to reconfigure its radio operating parameters (e.g., center frequency, bandwidth and transmit power) on the fly to avoid interfering primary users. Cognitive radio may only practice one portion of the aforementioned functionalities according to actual situation. Apparently, the cognitive radio users which conduct spectrum sensing are usually work with spectrum overlay paradigm, and the cognitive radio users which have means to get information of primary users are suitable to work with spectrum underlay paradigm. Based on this definition, throughout this thesis the secondary users working with both spectrum underlay and overlay are named as cognitive radio users, besides, the cognitive radio network is deemed to be composed with cognitive radio users, whose acronym is CRN.

1.2.1 Spectrum Management

To adapt to dynamic spectrum environment and make use of the available licensed spectrum, cognitive radio users need to manage the available spectrum by conducting the following procedures sequentially, detecting the available spectrum with spectrum sensing, selecting the proper spectrum for communication, and sharing the spectrum with other secondary users. These functions are incorporated into so called cognitive cycle as described in [16].

Spectrum Sensing

To know which chunk of spectrum is available is the foundation of spectrum management. In underlay spectrum usage scenario, CR users get to know the available spectrum by means of spectrum sensing. In overlay spectrum usage scenario, secondary users can in principle access all the licensed spectrum. In this procedure, quality of the available channels is determined with several parameters, i.e., band width, operating frequency, path loss, wireless link errors, link layer delay, and the upper bound of interference on the primary user working on that channel, which decides the maximal permissible transmission power of secondary users. Besides, the statistical behaviours of primary users is also an important factor.

Spectrum Decision

After knowing the available spectrum, CR users select the most appropriate band according to their requirements on quality of service (QoS). This procedure involves considering the statistical behaviours of the primary users so as to accessing the channel quality fairly.

[1] software defined radio is a radio communication system which is able to receive any modulation across a large frequency spectrum, and transmit on desired spectrum band.

Spectrum Sharing

Then secondary users are to make use of these selected channels, or in other words, to share the spectrum with other secondary users. As there may be multiple secondary users trying to use the same channel, spectrum sharing is important to coordinate the behaviour of secondary users to avoid deteriorating the performance of secondary users. Spectrum sharing involves choosing proper channels to mitigate co-channel or adjacent interference, or adjusting transmission power to achieve promise between transmitter's and other secondary users' performance, or adopting a certain media access paradigm to use the spectrum fairly and efficiently. Spectrum sharing also involves consideration on primary users, i.e., when many secondary users work on the same channel, the accumulated interference caused by secondary users could exceed the interference threshold on primary users.

Some work in research community models the spectrum availability with stochastic or statistic model, which is helpful when deciding which channel to use. [79] proposes discrete Markov chain and adjusts duty circle models to describe the availability of licensed spectrum for GSM on 900/1800 MHz. [116] models the channel holding time with geometric and log-normal distributions. Statistics of previous sensing results is used to predict spectrum state in the future [66]. Such models provide more complete information on the availability of the licensed channels.

The available licensed spectrum which spans a wide frequency band exhibits different characteristics [72]. Based on the requirements of interested communication, CR users need to identify the characteristics of the spectrum, which include channel quality (channel capacity, error rate, path loss, etc.) [72], channel switching delay [23], and channel holding time, i.e., the expected time duration that the primary users don't occupy the channel before any one occupies again.

1.2.2 Representative Cognitive Radio Networks

In this section, we introduce two types of cognitive radio networks, and the problems we tackle in this thesis reside in these networks.

Cognitive Radio Ad Hoc Network

Cognitive radio ad hoc network (CRAHN) is composed with autonomous mobile cognitive radio users which work with overlay spectrum sharing paradigm. CRAHN is usually represented as an undirected graph G. Cognitive radio users constitute the vertices, the edge between two vertices is decided not only by the distance, propagation and attenuation properties between the two vertices, but also the spectrum availability on both vertices, i.e., when they can decode the received signal from each other correctly, and there is common channel available between them on which communication is conducted, then an bidirectional edge is available on graph G. As to ad hoc network, the graph is constant when users are static. As to cognitive radio ad hoc network, due to primary users' activity, an edge between two vertices is decided by the fact that whether the two vertices can simultaneously access the same licensed channel. Hence, the corresponding graph is dynamic under primary users' operation, which imposes extra difficulties on network organization, routing and many other network functionalities.

IEEE 802.22 Standards

IEEE 802.22 [1] is the standard for Wireless Regional Area Networks (WRAN), which defines a cellular network paradigm for secondary equipments working on unused TV channels in overlay manner. Unused TV spectrum is termed as TV White space by the Federal Communications Commission (FCC) [8], which is licensed to incumbent users such like digital TV, analog TV, and wireless microphone. Unlicensed users consists of White Base Stations (WBSes) and customer premises equipments (or terminals for short), where each terminal is served by one base station. As to unlicensed users, detecting incumbent users is challenging because the FCC requires the unlicensed users should be able to detect the presence of signals from TV stations or wireless microphone at a received power level of -114 dBm [108]. Thus FCC doesn't require the sensing ability on unlicensed users, but regulates the secondary usage of TV white space in a prudent manner, including the spectrum bands permitted to use based on their location, the transmission power, the distance away from TV service area and so on. IEEE 802.22 largely complies FCC regulations on the utilization of TVWS.

There exists a centralized database, and every unlicensed user should register its type and geographic location to one TV database. The centralized database notifies the secondary users the available spectrum at their places, and is possible to decide transmission parameters for them, i.e., spectrum to be used, or transmission power. Note this database takes the functionality of spectrum sensing in addition to spectrum decision and sharing, thus IEEE 802.22 adopts centralized spectrum decision for unlicensed users. The feasibility of this centralised paradigm is largely due to the characteristics of TV channel, as TV channel usage follows a slow and scheduled pattern. When two or more base stations operate on the same channel, TDMA like mechanism for WBSes is adopted.

Recent standard published in Nov. 2010 suggests both sensing ability as well as database look-up to avoid affecting primary systems.

1.3 Spectrum Sharing Paradigms

How is the available licensed spectrum shared among secondary users is a fundamental problem in CRN, because it decides secondary users' performance, and it also poses threat to interferer primary users. In this section, we introduce spectrum sharing from three different perspectives.

1.3.1 Classification in Respect of the Relation between Primary and Secondary Users

sharing can also be classified by network architecture and spectrum allocation behaviour [16] respectively. In this section, we introduce these classifications to vision spectrum sharing from different prospectives.

Spectrum Underlay

One approach is *spectrum underlay*, where the interference generated by secondary users on the primary receivers should be under a threshold. This kind of spectrum sharing restricts the secondary users' transmission power, but is able to achieve high data rate in short range. When implementing spectrum underlay, secondary users are allowed to operate near the primary users when the interference caused on primary users is taken care [29]. Figure 1.1 shows a spectrum underlay sharing scenario, where some secondary users operate within the TV service area when the caused interference by the secondary users on the TV receiver is lower than threshold.

Spectrum underlay is mainly conducted with a centralized controller, which has global knowledge of primary users' location, the attenuation between all secondary transmitters and all primary receivers. Then the centralized controller calculates the maximal permitted transmission power with certain optimization solutions in a situation where secondary users pose the maximal thread to primary users' operation, where all the secondary users work one the same licensed spectrum. Working with spectrum underlay paradigm, spectrum sensing functionality on secondary users becomes auxiliary [8, 9].

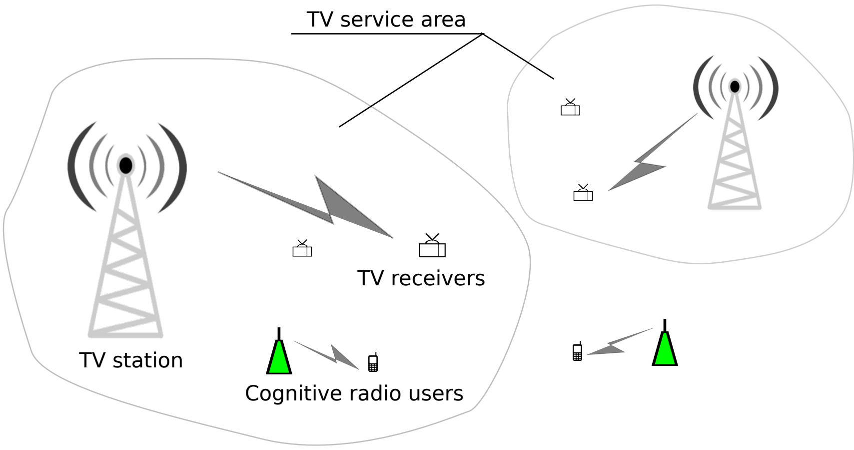

Figure 1.1 The concept of overlay spectrum usage in a TV service scenario. The hull shows the range of a TV service area, inside and out of which secondary users work on the licensed channels.

Spectrum Overlay

The other approach is *spectrum overlay*, where secondary transmitters are only allowed to transmit when the primary users are detected as being idle. In this paradigm, secondary users should monitor the spectrum of interest preactively to detect primary users' appearance. The detection metrics include received primary users' signal power, spectral correlation or beacons [126]. Spectrum sensing requires sophisticated technologies when primary users' signal is weak, and can be improved by learning technologies or cooperation among multiple secondary users [18]. When spectrum sensing accuracy can be guaranteed above certain threshold, transmission power restrictions can be removed from secondary users.

Spectrum administration bodies FCC of U.S. [8] and Electronic Communications Committee (ECC) in Europe [9] encourage to adopt both spectrum sensing and location based method.

1.3.2 Classification Based on Architecture

Based on architecture, spectrum sharing can be classified as centralized and distributed spectrum sharing.

Centralized Scheme

Centralized spectrum sharing relies on a centralized entity where the strategy of spectrum usage is decided. There is considerable number of centralized approaches proposed for spectrum sharing in cognitive radio network, global optimality is reported as to different objectives, but centralized solution is not suitable in many real world situations.

First, central authority or controller is not available in many CRNs, e.g., CRAHN. Second, when the centralized decision maker exists, the centralized entity needs to collect spectrum availability sensed on all the secondary users, computes the spectrum usage strategy and distributes it. A large number of control messages are generated during these processes. When primary users intensely access the spectrum, resulting in frequent change of available spectrum, the control overhead becomes higher, and it is different for the centralized entity to obtain a full and up to date picture of the spectrum availability in the whole network .

Centralized scheme is suitable in certain scenarios, e.g., when the primary users are TV stations and receivers which work on certain channels for hours of time, spectrum can be seen as constant. When the secondary users access the spectrum in underlay paradigm, they need to take care not to cause more interference than threshold on primary users. In this case the channel usage, i.e., working channel and transmission power, can be decided on the centralized controller.

Decentralized Scheme

Working with distributed spectrum sharing paradigm, secondary users autonomously decide their spectrum usage strategies. Distributed scheme requires secondary users to exchange information i.e., user ID, channel availability, etc. with its neighbourhood. It is reported that control overhead takes more than 50% of messages [52]. If we can reduce the overhead, spectrum utilization and the number of users can be increased, and network performance can be improved. Decision is made only with local information, as a result, communication overhead is reduced when the distributed decision has quick convergence. As distributed schemes exploit mainly local observation, distributed schemes adapt to the varying environment quite well [130].

Distributed scheme may also make use of centralized entity when it is available and necessary, i.e., secondary users can access the centralized database to retrieve available channels in IEEE 802.22 cellular networks.

It is challenging to design distributed schemes. When the distributed decision is not properly designed, it is possible to trigger endless ripple effect across the network, i.e., one CR's decision on its strategy prompts neighbouring CR users to change strategies, and it changes its strategy again later due to neighbours' new strategies. In this thesis, the interaction between CR users will be discussed under game theoretical framework. With certain utility function, secondary users' interaction is *replicated* by a game which permits convergence. As to some problems, we need to carefully design the utility function so as to make the corresponding game to converge.

1.3.3 Classification Based on Cooperate or Not

Spectrum sharing can also be categorized into cooperative and non-cooperative spectrum sharing. As to cooperative spectrum sharing, secondary users take into consideration of the caused interference on other secondary users when deciding their spectrum usage. This pattern usually requires cluster structure to facilitate the negotiation of users in a neighbourhood [38]. Whereas with non-cooperative spectrum sharing, secondary users only consider the performance of their own.

Aforementioned classifications correlate with each other in certain aspects. For instance, non-cooperative spectrum sharing is usually conducted in distributed manner, whereas cooperative spectrum sharing can be implemented in both distributed and centralized manner, and the later needs the assistance from the centralized entity.

1.4 Problem Statement

In this thesis, the fundamental technical challenges to be addressed in this thesis are shown in Figure 1.2, which reside from physical layer to network work layer [2] are addressed.

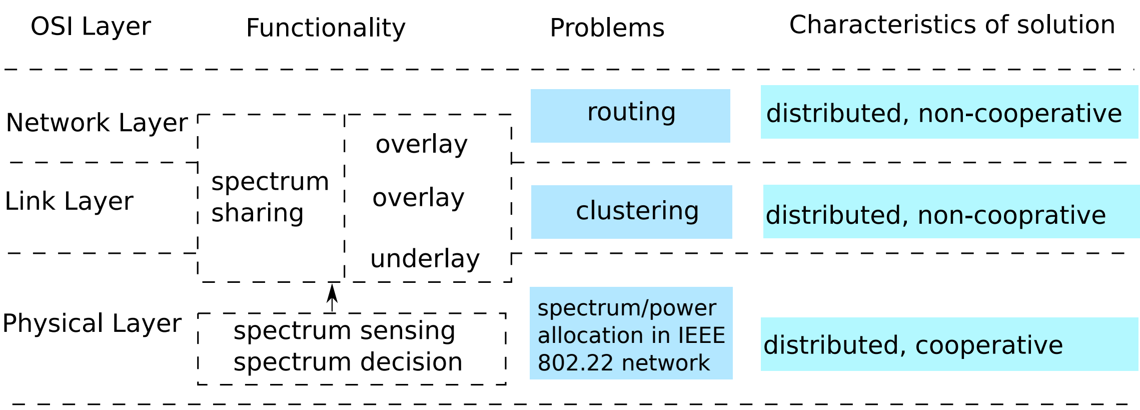

Figure 1.2 Spectrum management and the problems addressed in this thesis

The interaction among autonomous secondary users is a common scene in CRN as there usually lacks central controller. The secondary users endeavour to maximize their performance by choosing the channel and power, and meanwhile the accumulative interference caused on primary users should be below a threshold. How to refrain the accumulative interference to exceed the threshold is a critical question, and whether the distributed decision made by each secondary user on channel and transmission power improves performance is worth considering. After building the connected network with the chosen channel and transmission power, forming clusters with neighbours is a natural method to gain benefits, i.e., more accurate spectrum sensing, from local cooperation. How to form such clusters which can survive in front of the unpredictable activity of primary users is challenging. Having had solid CRN infrastructure, it is time to deliver services via routing. A light weight routing tailored for CRN is needed. In the following, we give full problem statements for the mentioned challenges.

1.4.1 Channel and Power Allocation in IEEE 802.22 Network

As introduced in Section 1.2.2, the TV white spectrum has appealing characteristics for secondary users, for instance, the TV spectrum spans wide frequency range, it is not used by TV services frequently and the spectrum availability lasts relatively longer. There have been regulations, standards proposed to utilize TV spectrum, all of which rely on the centralized database to manage the spectrum usage, i.e., channel and transmission power.

The conservative measures on the transmission power greatly restrict the full utilization of TV spectrum, and the channel allocation is not given consideration. As to the former problem, based on the information of geographic locations and attenuation parameters, the upper bound of transmission could be relaxed, and the centralised database is a suitable place to conduct this work. The later problem, at the first glance, has many similarities with the channel assignment problem which has been discussed extensively in the past decades, but the problem is unique as the transmission power on each user is different. As a result, the interference caused between co-channel transmitters is not symmetric, which disables the solutions proposed for the channel assignment problems in conventional networks, e.g., ad hoc networks, or mesh networks.

1.4.2 Robust Clustering in Ad Hoc Cognitive Radio Network

Clustering is an important paving stone for the practical utilization of the unused portions of the licensed spectrum. Clustering secondary users based on geographical proximity and other relevant properties together produces following benefits. Firstly, it is more efficient to solve common control channel (CCC) problem with cluster structure. Dedicated CCC which is allocated to all nodes for the purpose of control information exchange is regarded to be under utilization. Whereas, cluster based approaches group CR nodes into clusters based on their similarity of available unlicensed channels, so that the common channels within each cluster are used to carry the control messages [71]. Secondly, cluster structure facilitates cooperative sensing and increases the sensing reliability [110]. Thirdly, cluster structure supports coordinated channel switching and simplifies routing in ad-hoc cognitive radio networks [105].

The problem is defined by the following two metrics.

1. Abundance of control channels within cluster should be achieved. A large number of control channels within cluster means high robustness. When the current control channel gets occupied by primary user, cluster members can migrate to a new one

and the cluster is maintained. Besides, more control channels makes multiple concurrent transmission within cluster possible. In this thesis, a distributed clustering algorithm which is especially designed to support robustness under active primary users is proposed. Related works [132, 25, 121, 60] fail to pay attention to this aspect.

2. New scheme should be light weighted so that re-clustering can be quickly conducted when previous cluster is destroyed by primary user's activity. When all the common channels are occupied by primary users, cluster head selection and following procedure is conducted by the cluster members autonomously. [76] targets large number of control channels within cluster, but it intriguers high complexity.

1.4.3 Geographic Routing in CRN with Spectrum Aware Virtual Coordinate

Recent measurement in [91] shows the spectrum occupancy doesn't have significant spatial correlations between different locations. It follows that licensed spectrum is used by primary users heavily in some areas, whereas in the other areas licensed spectrum is available over longer timespan for secondary users to use. It is obvious to see that a routing path is better to go through the areas where primary users occupation is lower, as this alleviates or avoids the burden to cope with the changing or totally occupied spectrum when forwarding packets potentially with latency requirements. Geographic routing is a natural choice to realize this geography sensitive routing path. Geographic routing is light weight regarding the determination of next hop, and achieves high scalability in various wireless networks [13]. Merely knowing the geographic locations of its neighbours and the destination, a node is able to locally choose the next hop which has the smallest distance to the destination. However, in CRN dynamic link state renders geographic routing unsuccessful since packets are forwarded to the destination along the shortest path rather than avoiding areas heavily influenced by primary users. considering the available spectrum is geographically heterogeneous, applying geographic routing alike routing schemes in CRAHN is appealing, but the supporting coordinate system is missing.

1.4.4 Research Questions

Based on he previous analysis on the current secondary spectrum exploit, we conclude the problems into three distinct research questions. In the remainder of this thesis, we will provide answers to these questions.

Question Q1 - How to make full use of the TV spectrum, using the widely adopted network structure, preventing interference above threshold on primary TV receivers, and improve the performance of the secondary users.

Question Q2 - How to make the secondary users to form robust clusters against primary users' unpredictable activity?

Question Q3 - How to make use of the statistic information of the spectrum availability, so as to realize light weight geographic routing in CRN.

1.5 Contributions

Because of the characteristics of the problems, distributed schemes are adopted, and in order to coordinate the interaction between secondary users, game theory is used to formulate the problem and derive algorithms. We illustrate the contribution of this thesis by addressing the aforementioned questions.

Contribution 1: Distributed Channel and Power Allocation in IEEE 802.22 Network

In this thesis we cope with a special channel allocation problem where symmetric interaction doesn't exist, i.e., transmission power is identical among CR users, or the propagation path loss is not symmetric. The asymmetry disables the heuristic distributed schemes provided in [24, 67], and makes channel allocation problem not to fit into the congestion game model proposed in [75] which is the first paper to discuss channel allocation from the respective of game theory. We innovatively formulate this problem in to a canonical congestion game by utilizing the centralized database in TV white space scenario, and derive efficient distributed channel selection strategy.

This thesis addresses following two problems,

- Decide the maximal downlink transmission power. Both FCC regulation and 802.22 standard try to make TVBD transparent to incumbent users, but as long as TV system is not affected, i.e. certain quality of service is fulfilled, the strict restriction on unlicensed users can be relaxed so that more TVWS can be provided [69]. Abiding by the operation paradigm using data base, we investigate the maximal downlink transmission power for TVBDs by solving optimization problem where the cumulative interference on TV receivers is under a threshold.
- Distributed spectrum allocation scheme for TVBDs. According to 802.22 regulation, spectrum allocation is done centrally in TV database, this is not realistic when TVBDs belong to different economic interest groups, thus a distributed solution is needed. We propose efficient distributed scheme to allocate the TV channels in order to improve the quality of service of TVBDs. The major difference between our scheme and other spectrum allocation lies in that the downlink transmission power on different channel is different. We formulate this problem into a canonical congestion game, and derive the distributed algorithm from the best response behaviour of the player in the game.

Contribution 2: Light Weight Robust Clustering in CRAHN

We propose a decentralized clustering approach, which is able to form clusters whose sizes are not far away from the desired size, and the generated clusters are more robust than other robust clustering scheme, i.e., more secondary users residing in clusters against increasing affection from primary users. Compared to previous work, our proposed scheme involves much less control messages, and the generated clusters are significantly more robust. We formulate one procedure of the scheme into a singleton congestion game, which permits Nash equilibrium when CR users adopt best response strategy. On the basis of proposed scheme, we propose a light weighted version of ROSS, which requires exchanging less overheads.

Contribution 3: Spectrum Aware Virtual Coordinates in CRN

In this paper we propose SAViC, spectrum aware virtual coordinates for secondary users in multi-channel multi-hop CRN where secondary users are source limited. Virtual coordinate is independent of real geographic position, but decided by certain properties of the media among nodes, for instance, link quality or hop numbers [33]. The proposed virtual coordinate depicts the availability of licensed spectrum influenced by primary users, on top of which geographic routing decides the next hop with Euclidean distance metric, and unconsciously detours the primary affecting area, or cuts through the area with better access opportunity. This routing paradigm imposes little computation and communication cost on secondary users after assigning virtual coordinate, besides, it doesn't need real geographic location which is employed in [40, 77].

This scheme is composed with two steps,

- Design virtual coordinates so that virtual coordinates of any two secondary users reflect both geographic distance and opportunistic spectrum availability between them. We design them based on statistics of primary user's ON/OFF states which are obtained from local spectrum sensing.
- After deciding on the next hop, we adopt a lightweight heuristic method to decide which channel to transmit packet when multiple licensed channels exist in the network.

To summarize, as the Euclidean distance between two secondary users based on spectrum aware virtual coordinate reflects the availability of unlicensed channel in between from the angel of historical statistics, virtual coordinate contributes a large part to deciding on the on the next hop.

1.6 Outline

The structure of this thesis is as follows. In chapter 2, we introduce the tools used in solving the problems, i.e., game theory and optimization. Chapter 3 introduces the work on utilization of TV white space. The robust clustering problem is addressed in Chapter 4. In Chapter 5, virtual coordinate based on geographic routing is designed and geographic routing runs on the top of it. Finally, Chapter 7 concludes the thesis by summarizing our contributions and discussing the future work.

2

BACKGROUND

In the past few years, game theory has been extensively applied to problems in communication and networking [85, 115]. Game theory is a powerful mathematical tool for studying, modelling and analysing the interaction among rational decision makers which have conflicting objectives. When the network entities are seen as rational, game theory can be used to predict and guide the behaviour of them, and predict the outcome of the system with respect to certain metrics. In contrary to game theory where players agree on an equilibrium via autonomous behaviours, optimization problem, which attempts to optimize the welfare of either one equipment or whole network, is usually conducted on a single decision maker. In the following, we introduce some basics of game theory and optimization.

2.1 Algorithmic Game Theory

Game theoretic models are used to understand many challenging problems in communication systems, such as resource allocation, topology control, routing, security and so on. There are several reasons to apply game theory in communication systems.

- Communication equipments are rational. Although current communication equipments involve only a little artificial intelligence, they are supposed to be manufactured and operate based on standards to fulfil certain functions, but selfish behaviour may appear on certain individual equipments to achieve advantages over their peers [80].

  In communication system, a device is programmed to maximize or minimize the expected utility, which is perfectly rational. For instance, Wi-Fi equipments are manufactured complying the IEEE 802.11 standards. But it is possible that certain manufacturers or the personal who uses the Wi-Fi system (we use station in the following) manipulate certain parameters to achieve performance advantage over other stations in the network. When all the stations in one network are supposed to run distributed coordination function (DCF), i.e., the station must wait a random period of time, which is called contention window (CW), before accessing the media when it senses the media to be busy, a certain selfish station may not choose to wait and is keen on sensing media. The selfish behaviour causes more collisions for other stations, and possibly results in poor performance in the network. In this case, game theory facilitates the network operator to issue rules to make the selfish behaviour unprofitable, or it helps to analyse how much the impact caused by the selfish stations.

- Game theory is effective to solve networking problems. Algorithms can be retrieved from the analysis of a problem under the game theoretical framework. In the same example of media access in IEEE 802.11 DCF mentioned in previous item, if stations are allowed to modify the length of contention window, each station will adjust its contention window to obtain the best performance. [37] shows as long as each station greedily updates its CW to maximize certain utility, after certain time it will stop to do so as the current CW is the best as to the performance. In the case, the best response becomes a algorithm for Wi-Fi systems. Besides, outcome from game theory is robust [52]. As to optimization, when the information is not accurate or adequate enough, or the optimization itself is difficult to solve, the optimized results can be far from global optimality. Game theory based on the local information, which is easy to obtain, usually leads to Nash equilibrium (NE), which is usually sub optimal.

- Game theory is suitable to apply in cognitive radio network because of the properties of CRN. Firstly, only local information is needed, thus game theory is naturally suitable for designing distributed solutions for cognitive radio networks. Distributed solutions doesn't rely on centralized controller, and each user in the network adopts certain action as response to the other users or environment, this falls in the scope of game theory. Secondly, combinatorial nature of communication problems makes game theory as one of a few choices [52]. Many problems in wireless communication involve integer variables, i.e., channel assignment, selection of modulation levels or channel coding. It is always challenging to solve combinatorial optimization problems, whereas game theory is natural to describe it in a discrete form.

2.1.1 Basics of Game

In this section, we give a brief introduction of game theory and congestion game which is applied to solve problems in our thesis. The notations used in this thesis comply with [87].

A strategic game can be represented as a tuple $\Gamma = (\mathcal{N}, (\mathcal{S}_i)_{i\in\mathcal{N}}, (u_i)_{i\in\mathcal{N}})$, where

- $\mathcal{N}$ is a finite set of players.
- $\mathcal{S}_i$ is player i' set of strategies. Player i selects one strategy $s_i \in \mathcal{S}_i$ at one time to play the game.
- $\mathcal{S} = \mathcal{S}_1 \times \cdots \times \mathcal{S}_n$ is the set of states, which denotes all the possible ways that players may pick strategies.

Elements of a game	Components of one CRN
Player $\mathcal{N}$	secondary users
Strategies for player i, $\mathcal{S}_i$	working channels, transmission power, modulation, etc.
Utility of player i, u_i	performance in respect of SINR, throughput, etc.

Table 2.1 Components of problems in CRN and corresponding elements in game

- $s = (s_i, \cdots, s_n)$ is vector of strategies and also is called as one strategy profile, which represents an instance of all players' choices. There is $s \in \mathcal{S}$.
- The vector of strategies of opponents of player i is expressed as s_{-i}, and the corresponding strategy profile can be shown as $s = \{s_i, s_{-i}\}$. $u_i(s) = u_i(s_i, s_{-i})$ is the player i' outcome in strategy profile s.
- $u_i : \sqcap_{i \in \mathcal{N}} \mathcal{S}_i \to \mathbb{R}$ is the utility function of player i. $\mathcal{S}_{-i} = \sqcap_{i \in \mathcal{N} \setminus \{i\}} \mathcal{S}_i$ is the set of states of all the other players except for player i. As to each player i, its outcome is decided by its choice on strategy $s_i \in \mathcal{S}_i$, and is also dependant on the choices of other players $s_{-i} \in \mathcal{S}_{-i}$. Utility can also be denoted as $u_i(s)$ or $u_i(s_i, s_{-i})$ to stress that the outcome is made based on all players' strategies.

  Utility function is very important to specify a game, as it gives players preferences on the outcomes with respect to all strategy vectors $\mathcal{S}$. The value of the utility can be regarded as payoffs or costs depending on concrete scenarios. The sum of costs and payoffs are zero, and they can be used interchangeably.

When we want to use game theory to analyse a problem in CRN, it is critical to formulate appropriate components of the problem into corresponding elements of a game. The commonly used formulation is summarized in Table 2.1.

2.1.2 Basic Solution Concepts

In this section, we will introduce some basic solution concepts, some of them are used in this thesis.

Dominant Strategy Solution

In some games, each player has a unique best strategy, which is independent of the strategies chosen by the other players, then we say a game of this kind has a dominant strategy solution. The mathematical expression is, a strategy vector $s \in \mathcal{S}$ is a dominant strategy, if for each player i and each alternate strategy $s' \in \mathcal{S}$, there is,

$$u_i(s_i, s'_{-i}) \geq u_i(s'_i, s'_{-i})$$

Note that a dominant strategy solution may not give an optimal payoff to any of the players. This is the case in *prisoner's dilemma*, which is one of the most well known and well studied games. To confess is the dominant solution for both prisoners, which brings them longer time behind bars than that when both of them keep silent[1]. Only a few games have dominant strategy, and mechanism design [61] is developed to design games which have dominate strategy, and these dominate strategies lead to desirable outcome.

Nash Equilibrium

A desirable solution of games is the one that players choose strategy in accordance with their incentives, minimizing their own cost or maximizing their own payoff. Nash equilibrium successfully captures this property, and is the most discussed and pursued solution concept in game theory 2.1.

A strategy vector $s \in S$ is a *Nash equilibrium* if for any player i and each alternate strategy s_i', there is

$$u_i(s_i, s_{-i}) \geq u_i(s_i', s_{-i})$$

This means for any player in NE state, no unilateral deviation from its current strategy is more profitable. This also implies that, NE is self enforcing that once players agree on this solution, it is the best interest for every player to stick to its current strategy.

A dominant strategy is a Nash equilibrium, and is also the unique NE, but a NE is not necessarily a dominant strategy. There may be multiple NEs in one game, and NE may not be optimal for players. In prisoner dilemma, the dominating strategy is NE but is obviously not the optimal. Games with finite number of players and strategy set are guaranteed to have NE, whereas, games with an infinite number of players, or games with a finite number of players but they can access to an infinite strategy set may not have NE [87].

Being not unique and possibly sub-optimal, NE is still applied in extremely diverse applications due to the reasons in the beginning of this section. Thus, when pursue NE as solution, people should answer the following questions, The first question is, what is the gap between NE and global optimal? This can be partially answered by *price of anarchy (PoA)*, the ratio between the worst-case Nash equilibrium to the optimality is used to denote the quality of the solution.

Nash equilibrium is an appealing conception, but it doesn't tell how to reach this state. Hence, it is important to find an efficient algorithm to reach the equilibrium. Theoretical scientists tell *finding a Nash equilibrium* problem is a combinatorial problem ans is often very difficult (Chapter 2, [87]). Moreover, the notion of *NP-completeness* is not an appropriate concept of complexity for *finding a Nash equilibrium* problem as NE always exists, in stead. Nevertheless, in some games, because of the special strategy space structure, or players' special behaviours, efficient algorithm to reach NE exists.

Pareto Equilibrium

Pareto equilibrium (PE) is a subset of NE, PE is an action profile $\bar{s}$ such that there does not exist profile s with $u_i(s) \leq u_i(\bar{s})$ for each $i \in N$, and meanwhile $u_i(s) < u_i(\bar{s})$ for at least one $i \in N$. PE is the necessary condition of the global optimality and accordingly is more favoured, but its application in communication system is much less than NE because it is not easy to obtain PE.

[1] Prisoner's dilemma can be found in almost all the game theory textbooks, thus omitted in this thesis.

Pure NE and Mixed NE

In the aforementioned games, players deterministically play their chosen strategies and don't involve randomized strategies, then the achieved NE is called pure NE. When players play a game with certain randomization on strategies, and aim to maximize their expected payoff, we call the resulted NE as mixed NE. As to mixed NE, the action of a player is to choose certain strategies according to a vector of probabilities. In this thesis, we only consider pure NE, as players deterministically play a certain strategy, and the corresponding network components stick to certain operation instead to switch among several different operations based on a vector of probabilities.

Other solutions include correlated equilibrium, which also involves probability distribution over strategy vectors.

Individual Optimization and Game

As to a player in a game, when its utility u_i is function of its strategy s_i, and not the strategies chosen by all n players, then the maximization of its payoff or minimization of its cost becomes an optimization problem, and the game has n such optimization problems in total. Whereas as to a game, the payoff or cost of each player depends on both s_i and s_{-i}, both its own strategy and the strategies chosen by all other players.

2.1.3 Congestion Game

In accordance with [114], congestion game is a game where players simultaneously allocate sets of resources to minimize its utility, and the cost of a resource is a function of congestion, which is the number of players choosing the resource. Congestion game can be formulated from many problems in realistic world, e.g., minimisation of commuting time on the road for commuters, minimization of energy consumption in mobile cloud computing system [50].

Now we give the formal definition of congestion game. A congestion game [99][114] can be expressed by a tuple $\lambda = (\mathcal{N}, \mathcal{R}, (\mathcal{S}_i)_{i\in\mathcal{N}}, (g_r)_{r\in\mathcal{R}})$, where $\mathcal{N} = \{1, \ldots, N\}$ denotes the set of players (each each is labeled with a unique index number), $\mathcal{R} = \{1, \ldots, m\}$ the set of resources, $\Sigma_{i\in\mathcal{N}} \subseteq 2^{\mathcal{R}}$ is the strategy space of player i. Under strategy profile $s = (s_1, s_2, \cdots s_N)$, player i chooses strategy $s_i \in \mathcal{S}_i$, and the total number of users using resource r is $n_r(s) = |\{i \mid r \in s_i\}|$. The cost $g_r : \mathbb{N} \to \mathbb{Z}$ is a function of the number of users for resource r, $g_r^i = \sum_{r\in s_i} g_r(n_r(s))$. In our paper, g_r^i is referred as congestion of a game. Congestion game has good property that Nash equilibrium are guaranteed after finite improvement, thus it is an attractive game model which describes the problem where participants compete for limited resources in a non-cooperative manner.

Example: Server Matching

We introduce an exemplary congestion game *server matching* [68] to illustrate the extensive application of game theory in communication systems. Consider a couple of self-interested clients and servers as shown in Figure 2.1. Each client is allowed to access one server. The latency of one server increases with the *number of clients* attached to it. When clients try to choose one server which has the shortest latency, a congestion game is formed.

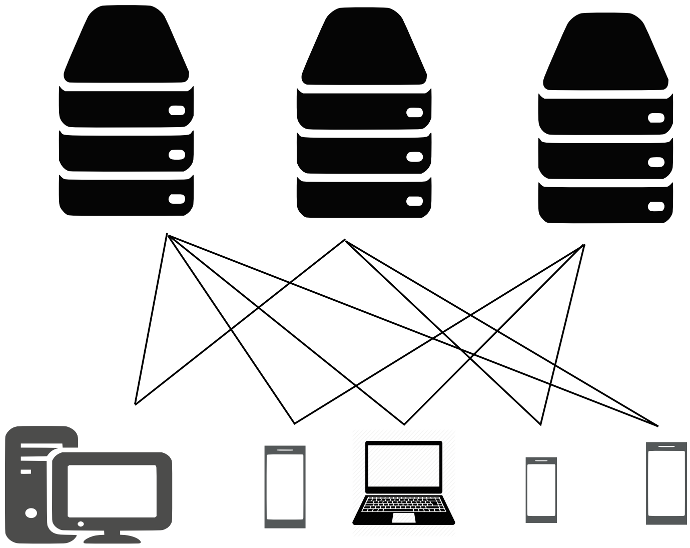

Figure 2.1 An example server matching, one server is possible strategy of the client at the other end of the connecting line

More formally, this corresponding congestion game is composed of players (the self-interested clients) and resources (servers), where players are allowed to choose certain resources to use. There is cost (latency) generated on a resource for the player whenever the player uses that resource, and the cost is monotonic increasing with the number of players using it. As congestion game permits convergence when every player always adopts the strategy which leads to better performance, thus in server matching problem, when clients choose a permissible server because of smaller predicted latency, then after finite number of choices, no client has motivation to switch any more.

Congestion game can also be used to model many other problems in internet-centric applications or cloud computing, where self-interested clients compete for the centralized resources and meanwhile interact with each other. For example, server selection is involved in distributed computing platforms [36], or users downloading files from cloud, etc.

Convergence Time Towards Nash Equilibrium

As to the convergence of congestion game, there is a proposition [114] saying, for every congestion game, every sequence of improvement steps is finite. In the following, we introduce the sketch of the proof of the proposition, as the proving procedure also reveal the number of improvement steps to reach Nash Equilibrium.

We firstly need to introduce Rosenthal's potential function $\phi(s) :\rightarrow Z$, where s is the strategy profile of all the players, $s = s_1 \times s_2 \times \cdots \times s_N$:

$$\begin{aligned} \phi(s) &= \sum_{r \in \mathcal{R}} \sum_{i=1}^{n_r(s)} g_r(i) \\ &= \sum_{i \in \mathcal{N}} \sum_{r \in s_i} g_r(n_r^i(s)) \end{aligned} \tag{2.1}$$

$n_r^i(s)$ is the number of players using resource r, whose indices are smaller than or equal to i, i.e., from $\{1, \cdots, i\}$. In the part after the second equality sign, $\sum_{r \in s_i} g_r(n_r^i(s))$ is a virtual value or cost that player i have when assuming the resource r is not used by players whose indices are greater than i.

The intuitive interpretation of the virtual cost is, according to [114], the cost of each player for choosing the strategy when it is inserted into the game. Let us assume player N is the last player to be inserted into the game, then $\sum_{r \in s_N} g_r(n_r^N(s))$ equals to the real cost that player n takes. When player N can decrease its cost by switching to another strategy by an unilateral move, then $\sum_{r \in s_N} g_r(n_r^N(s))$ and its potential decrease by the same amount. As the potential can be calculated by inserting the players with any sequence, each player will have the same property with play N, as we just discussed.

In summery, the change of the potential caused by one player's unilateral move from s_i to s_i' is equivalent to the change of gain (or loss) of that player.

$$\varDelta\phi(s_i \rightarrow s_i') = g^i(s', s_{-i}) - g^i(s, s_{-i}) \tag{2.2}$$

s_{-i} is the strategy profile for all players except for i. Thus the potential decreases with the update of players monotonically during the convergence process. Most importantly, as the potential of a congestion game is bounded by some finite quantity, and every improvement made by player decreases it, the length of any sequence of improvement steps is also finite.

2.2 Optimization

As discussed in Chapter 1, the available radio resources such as spectrum are very limited, in the meantime, new services raise great requirements for these resources. Resource allocation and its optimization are the methods to accommodate the needs. Various optimization problems are formulated to improve radio resource usage in CRN [127, 27, 123]. Optimization can be conducted from either global view or individual perspective.

Many wireless resource allocation problems are formulated as constrained optimization problems. Table 2.2 shows the commonly used parameters, objectives and constraints in optimization problems of wireless communication. A Part of the contents in Table 2.2 refers [52].

The solution to an optimization problems is decided by its property, i.e., convex, linear, integer, or non-convex non-linear, etc.

	Parametres	Optimization goals	Constraints
Application layer	source-coding rate, buffer priority, packet arrival rate	minimal delay	base layer transmission, strict delay requirement
Network layer	routing path	end to end delay/throughput	maximal hops, security concerns
MAC layer	transmission frequency, transmission priorities	maximal overall throughput, minimal buffer overflow probability	contentions, time/frequency slot
Physical layer	transmission power, modulation, channel coding rate	minimal over power consumption, maximal throughput, minimal BER	maximal transmission power, caused interference on licensed users, available channel coding rate

Table 2.2 Optimization problem of cognitive radio networks

3

DISTRIBUTED CHANNEL AND POWER ALLOCATION IEEE 802.22 NETWORKS

3.1 INTRODUCTION

Opportunistic utilization for secondary users working with TV broadcast spectrum (TV white space) is promising to cope with the scarcity of spectrum resources[8]. Firstly, more unused TV white frequencies become vacant than ever with the ongoing transition from analog to digital broadcasts. Secondly, the lower frequencies of TV band enable broadband access over much longer ranges compared to other bands with higher center frequencies. Nevertheless, services on TV receivers need to be protected with so called interference margin [69] which must not be exceeded jointly by all secondary users working on the the channel .

Federal Communications Commission (FCC) of U.S. and Electronic Communications Committee (ECC) in Europe have announced rules on the transmission power of white space for secondary users in US and Europe respectively[8, 9]. FCC adopts a minimum distance between secondary user and TV service area to guarantee that the interference margin is not exceeded by secondary users. The transmission power for fixed secondary users is fixed to 4 W which is a conservative setting. FCC assumes that the protection area is sufficient to protect the TV receivers, but it is not the case when there are multiple secondary equipments transmitting in the the same as is discussed in [63]. ECC's restriction requires that the secondary user adapt its transmission power in order not to violate the interference margin at exposed TV receivers. In this manner, secondary systems have to determine their maximum transmission power.

[2] interference margin is the maximal interference caused by secondary users, which doesn't violate TV service.

[3] In this chapter, channel and spectrum are used indiscriminately

FCC issued a memorandum [8, 7] in 2010, which removed the mandatory sensing requirements and thus greatly facilitates the use of the spectrum with geolocation based channel allocation. Work [84] follows this rule to obviate spectrum sensing and only rely on the database of TV incumbents to determine the white space availability on secondary users. The authors of [84] demonstrate the feasibility of predicting the available TV spectrum accurately using suitable propagation models (Longley-Rice and terrain wherein). A central controller contains the locations of all TV stations and secondary users, then the central controller calculates the RSSI level of TV UHF signals on all secondary users and accordingly determines the available TV spectrum for them. The authors give big impetus to the database method by developing sophisticated signal propagation modelling and efficient content dissemination scheme. Enlightened by this work, it can be seen that the RSSI level caused by secondary users on TV receivers can be calculated accurately in a centralized entity if secondary users' transmission power, geo-location and appropriate propagation model are provided. Inversely, given geo-location and appropriate propagation model, secondary users' maximum transmission power can be determined by the central entity according to the interference margin (maximum RSSI level from secondary users) at TV receivers.

To guarantee the protection on TV systems from harmful interference, FCC and IEEE propose a central database to regulate the access of TV spectrum by the secondary users. The centralized database registers the location and terrain information for all secondary users in the network, and decides the available channel and maximal permitted transmission power for each secondary user. It is natural to think to utilize the central database as a controller to assign channel and power usage, but the secondary users may belong to different commercial groups and they may not content with the assigned resource. This is more truer when the considering the available channels have different quality, i.e., interference level, and permitted transmission power. Hence, the spectrum sharing of the secondary users in 802.22 network is a distributed system where each secondary user maximizes its preferred utility, and meanwhile the aggregated interference generated by them should be kept below a certain threshold on the TV system.

In this chapter, the secondary users are assumed to be cellular systems consisting of base stations and associated terminals, all of which work on TV white spectrum. The corresponding secondary base stations are referred as white base stations (WBS). Some cellular networks, such as GSM or LTE network, work on Licensed spectrum, and they emphasis on providing satisfactory services to their end terminals by choosing proper transmission channel and power. As to cellular network working on TV white spectrum, they have to keep one eye on the primary users to make sure that TV service is not violated, which make the problem of channel and power selection even harder. It is possible that WBSes are owned and operated by different operators, thus completely centralized decision on the base stations' working channel and transmission power is infeasible. Hence we will look for distributed solution for this problem.

The rest of the chapter is organized as follows. we elucidate the system model in Section II, afterwards related work and problem formulation is presented in Section III. In Section IV, we discuss how to utilize the white space sufficiently by setting the transmit powers based on a convex problem formulation. We analyze the spectrum allocation problem under game theoretical framework and propose an algorithm in Section V, thereafter performance evaluation is presented in Section VI. Finally, we conclude our work and point out directions of future research in Section VII.

3.2 System Model and Problem Statement

Following the IEEE 802.22 standard, the primary systems considered in this chapter are digital TV (DTV) stations which use the TV spectrum legally. TV stations provide service to passive TV receivers which must not be interfered by secondary systems. The secondary systems are IEEE 802.22 Wireless Regional Area Network base stations (WBS) utilizing the TV spectrum with senseless mode [84]. WBSs locate within one area whereas TV areas locate around them. WBSes serve a set of end users/terminals without interfering TV receivers significantly. Denote the set of DTV stations by $\mathcal{K}$ and the collection of WBSs by $\mathcal{N}$ with $|\mathcal{N}| = N$. Furthermore, there are $\mathcal{C}$ channels considered in total with $|\mathcal{C}| = C$. These secondary systems are distributed over a certain area A and is surrounded by multiple DTV service areas, as Fig. 3.1 shows. When there are two WBSes work on the same channel, co-channel interference will be caused to each other by them, while, neighbouring channel interference is not considered. Each DTV station as well as each WBS utilizes exactly one channel We represent the usage of channel for WBS i with a binary vector $X_i^{|\mathcal{C}|\times 1} = \{\cdots, x_{ik}, \cdots\} \in \{0,1\}^{|\mathcal{C}|}$, where $k \in \mathcal{C}$ and binary variable x_{ik} denotes whether channel k is used by user i. As each node can only use one channel, for X_i, there is $\sum_{k=1}^{|\mathcal{C}|} x_{ik} = 1$. The transmission power of WBS i on channel c is P_i^c.

Let $c(i)$ denote the channel used by a WBS $i \in \mathcal{N}$. The TV channels are considered to be identical. In the rest of the chapter, we use WBS and secondary base station interchangeably. There are interference measurement equipment deployed on the TV service contours (as bold rectangles in Fig. 3.1), which represents the worst located TV receivers. For these interference alarming devices, an interference threshold should not be violated by the generated by the secondary users and noise, so that the TV services is guaranteed. The deploy of contours is decided by the TV operators, which varies according to the concrete location, geographic terrain and possible deployment of secondary networks. WBses are deemed to be static. We assume the secondary base stations are not under the same operators, thus there is no scheduling mechanism available among WBSes.

3.2.1 SINR on terminals

WBSs are interested in payload data exchange with their associated terminals with good quality of services (QoS). As to performance metric for this QoS provisioning, we choose the signal-to-noise-and-interference ratio (SINR) at the terminals, which is the ratio between the received power of signal of interest and the summed interference experienced by the terminal. We only focus on the down-link SINR.

Give a WBS i, another WBS which works on the same channel with i is denoted as $\bar{i}$. As to a certain terminal j associated to WBS i, the path loss between j and the serving WBS i and interfering WBS $\bar{i}$ are denoted as h_{ij} and $h_{\bar{i}j}$ respectively. The path loss is dependent on the distance between the corresponding equipments, e.g. $h_{ij} = K \cdot d_{ij}^{-\alpha}$, where α is the path loss exponent and K is a constant that models the reference loss over a single unit of distance. N_0 denotes the noise power. Shadowing without fading is considered in

[4] The assumption that one WBS only utilizes one channel is for convenience of analysis. In reality multiple channel usage (channel bonding) is requisite as one single TV channel's bandwidth is 6 MHz which is not adequate for a WBS to fulfil system requirement. We will relax this single channel usage assumption without hammering our scheme in the end of section **??**.

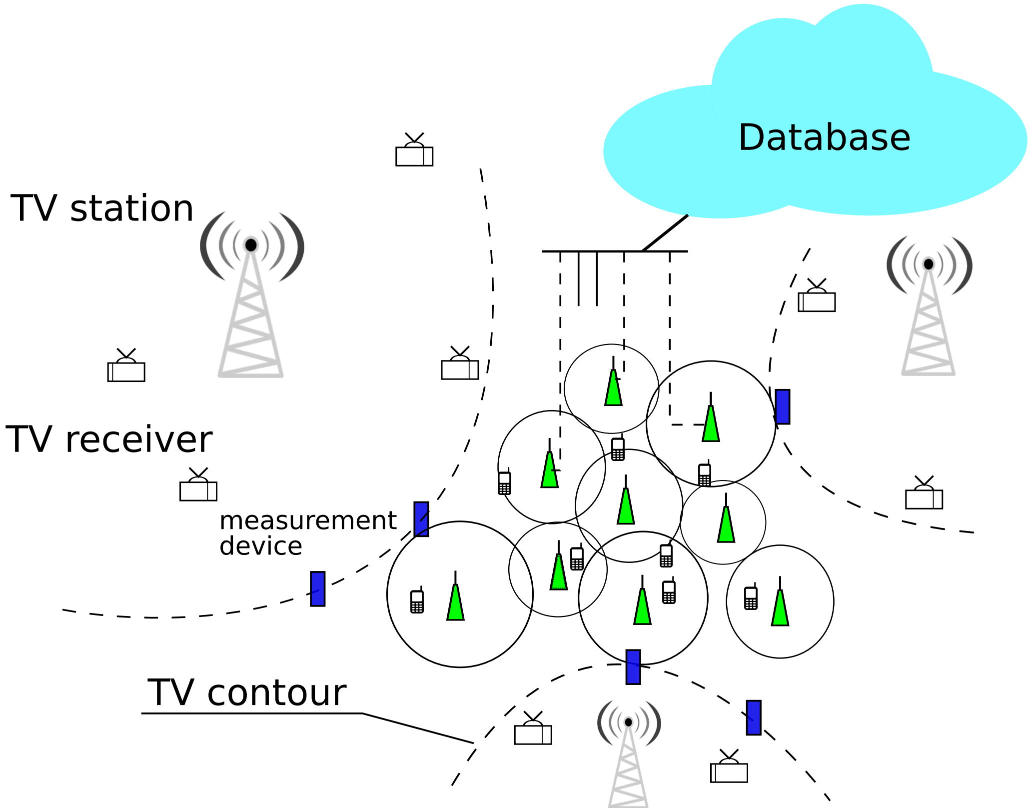

Figure 3.1 System model: WBS cells and DTV systems

our model. Based on the aforementioned notations, we get the sum of all disturbing RF effects (including interference) at terminal j (we assume the working channel is c) as the following,

$$f_j^c = \sum_{\bar{i}} (P_{\bar{i}}^c \cdot h_{\bar{i}j} \cdot z_{\bar{i}j}) + N_0 \tag{3.1}$$

where $P_{\bar{i}}^c$ denotes the transmit power of WBS $\bar{i}$ and $z_{\bar{i}j}$ models the zero-mean log-normally distributed shadow-fading with standard deviation σ_{SH} between $\bar{i}$ and j. Then we get the signal-to-interference-and-noise ratio (SINR) on end terminal j,:

$$\gamma_j = \frac{P_i^c \cdot h_{ij} \cdot z_{ij}}{f_j^c} \tag{3.2}$$

3.2.2 Problem Statement

As the distribution of mobile terminals is varying and influenced by many factors, i.e., the type of services provided to the terminals, the type of area and mobility of terminals, it is difficult to choose one terminal whose SINR is able to represent the worst case for SINR in that cell. Thus we propose a metric *QuasiSINR* which is independent on any terminals.

We are interested in improving the SINR on the terminals of each cell by rendering WBSes to decide their channel and transmission power. The distribution of mobile terminals is varying and influenced by many factors, i.e., the type of services provided to the terminals, the type of area and mobility of terminals. Thus when WBS decides its transmission parameter, it has to evaluate the SINR of all terminals. Furthermore, taking into consideration of terminals' SINR makes it very difficult to formulate WBS's preference on resources, i.e., channel, power. Thus, we propose a simplified metric *quasiSINR* for each WBS, which is independent on any terminals, and is able to reflects the SINR on a circle around the WBS in a conservative manner. QuasiSINR can be easily adjusted by changing the radius of the circle so that the the circle goes through the majority of the terminal users.

QuasiSINR of WBS

As Figure 3.2 shows, the discussed WBS is denoted as i, and the rest WBSes are denoted as j, j' and j'' respectively. We assume WBS i works on the channel k. An auxiliary dashed circle around WBS i is added, whose radius is δ.

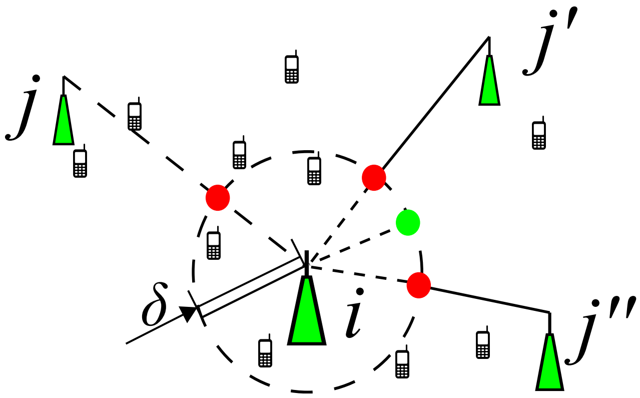

Figure 3.2 QuasiSINR is the ratio between the power of signal of interest on the green point with the co-channel interferences on the red points

We define the quasiSINR of WBS i as follows,

The power of the signal of interest on auxiliary circle is,

$$\tilde{P}_i = P_i \cdot h \cdot z = P_i^c \cdot \delta^{-\alpha} \cdot z \tag{3.3}$$

where h and z are the attenuation and fading from i to any point on the auxiliary circle. In Figure 3.2, $\tilde{P}_i$ equals to the power of the signal of interest received on the green dot

The interfering power from co-channel WBS j is,

$$\tilde{f}_{ji} = P_j^k \cdot h' \cdot z' = P_j^k \cdot (d_{ji} - \delta)^{-\alpha} \cdot z' \tag{3.4}$$

where h' and z' are the attenuation and fading from j to the nearest point on the auxiliary circle. In Figure 3.2, $\tilde{f}_{ji}$ equals to received interfering power from WBS j on the red dot on the connecting straight line between WBS i and j. The sum of interference on the intersections of auxiliary circle and connecting lines is,

$$\tilde{f}_i = \sum_{c(j)=k} \tilde{f}_{ji} \tag{3.5}$$

Then the quasiSINR is,

$$\begin{aligned} \tilde{\gamma}_i &= \frac{P_i^k \cdot h \cdot z}{\sum_{\substack{j \neq i, j \in \mathcal{N} \\ c(j)=c(i)}} (P_j^k \cdot h' \cdot z') + N_0} \\ &= \frac{P_i^k \cdot \delta^{-\alpha} \cdot z}{\sum_{j \neq i, j \in \mathcal{N}} (P_j^k \cdot (d_{ji} - \delta)^{-\alpha} \cdot z') + N_0} = \frac{\tilde{P}_i{}^k}{\tilde{f}_i{}^k} \end{aligned} \tag{3.6}$$

From the expression in Formula 3.3 and 3.5, we can see that qusaiSINR $\tilde{\gamma}_i$ employs a conservative numerator and a overestimated denominator, and we can see QuasiSINR is the ratio between the weakest signal of interest and the summation of the strongest interference. We can adjust the radius of the auxiliary circle δ to let WBS foster better service to terminals in certain area. For instance, to take care of the SINR on the border area of the cell, the radius δ can be set as the distance between WBS i and the furthest associated terminal. When the terminals are close to the WBS, δ can be set smaller to better fit to the terminals' distribution.

Because of the auxiliary circle, the interaction between co-channel WBSes are independent on the concrete end terminals. With QuasiSINR, the channel and power allocation problem will exclude terminals and thus simplify the problem. QuasiSINR will be validated in Section 3.9.

Calculation Instead of Measurement

In our system, every WBS can access the central database which stores all WBSes' geographic information, their operation parameters, i.e., working channel and transmission power, and the characteristics of radio frequency environment, i.e., parameters of attenuation and shadowing. To obtain the quasiSINR, we don't measurement the signal on the intersections shown in Figure 3.2, but instead to calculate them [63] according to Formula 3.6 andbased on the information stored in database.

Optimization

Our goal can be illustrated in the form of an optimization problem. To ensure fairness, instead of maximizing the sum of QuasiSINR of all WBSs, we try to minimize the sum of inversed QuasiSINR.

$$\begin{aligned} \text{Minimize} \quad & \sum_{i \in \mathcal{N}} \frac{1}{\tilde{\gamma}_i} \\ \text{subject to} \quad & \sum_{k=1}^{|\mathcal{C}|} x_{ik} = 1 \\ & p_{min} \leq p \leq p_{max} \end{aligned} \tag{3.7}$$

For every WBS, each channel in $\mathcal{C}$ experiences different levels of interference from other WBSs working on it. In order to provide better service to its end users and doesn't consider the services provided in other cells, WBS is liable to choose either the channel permitting higher transmission power or the one with less interference, or the channel compromising the two factors according to Formula 3.2. Achieving optimal white spectrum allocation in a distributed style is the goal of this work, furthermore, this distributed solution should converge fast and lead to an efficient and stable solution.

3.3 Related Work

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Some prototype applications which only rely on the TV database are proposed in cellular network [96, 45] and WiFi-like network [93] based on the FCC regulation.

Standardization activities are also ongoing on TVWS utilization, including 802.22 [1] for Wireless Regional Area Networks (WRAN), IEEE 802.11af [46] for WLAN, IEEE 802.15.4m [4] for 802.15.4 wireless networks in TVWS and 802.19.1 [5] for coexistence methods among local and Metropolitan Area Networks (MAN).

Scientific research on utilization of TVWS goes on in parallel with the regulatory agency. Spectrum sharing in TVWS is formulated as optimization problem, where the guarantee that TV receivers should not be affected by the cumulative interferences form TVBD is one constraint, and the signal interference (noise) ratio becomes the other. The objective can be maximizing TVBD's downlink transmission power [69], uplink transmission power [112], or best geographic distribution of TVBDs [128]. [39, 125, 30, 104, 48] emphasise on interference mitigation among TVBDs via spectrum allocation. Vehicular networks operating with TVWS assisted by TV database and cooperative sensing is discussed in [41]. Work [43] steps further from the database paradigm and makes efforts to utilize the 'grey space', where TVDB is allowed to operate even within the TV service area.

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Channel allocation facilitates CRN to improve throughput [111], or cooperatively relay [131] and so on. This thesis emphasises on co-channel interference mitigation with distributed channel allocation .

Mitigating co-channel interference via channel allocation has been attracting plenty of research efforts in the past ten years, from multiple channel mesh network [97], Ad hoc network [24, 67] up to cognitive radio network [125, 59]. Channel allocation problem is converted into colouring problem thus is NP hard [97], thus centralized optimization fails to produce Authors of [24, 67] propose heuristic algorithms utilizing best response based on the welfare on itself to assign channels among users. Simulated annealing is applied to mitigate co-channel interferences in [125]. For the same purpose, No-regret learning [59, 53] is exploit to optimize the choice on channel.

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Given all the other WBSes' channel/power selection in secondary network, one WBS is interested in choosing the channel experiencing the minimum interference, and utilizing the biggest possible transmit power in order to achieve better SINR at its terminals and meanwhile maximize their coverage [122, 55]. Nevertheless, high transmission power causes significant co-channel interference to other secondary cells operating on the same channel. Hence, secondary cells have to balance the own used transmit power with the interference caused on other cells as well as the interference experienced in their own cell while deciding on the channel to use (if multiple channels are available). Our goal is to find a strategy for WBSes to choose channel and power level in order to acquire good SINR on end terminals, in the same time protecting the primary users from harmful interferences. This joint power and channel allocation problem in cognitive radio scenario has drawn many attentions. The proposed solutions can be divided into two categories, centralized and distributed, which will be introduced sequentially.

As to centralized solutions, an optimization problem is always to formulated to solve the problem. In [56], the objective is to increase the number of supported terminals whose

SINR is above a threshold, and the constrains are to refrain the interferences on the primary users under a certain threshold. [26] minimizes the transmission power and meanwhile makes sure the SINR of terminal is above one threshold. This work fails to consider the protection of primary users. Other schemes expect for optimization is also used to tackle this problem. [94] proposes a heuristic algorithm considering the channel availability and transmission demand of each WBS. Spectrum allocation is solved after being formulated into a colouring problem. The aforementioned two schemes don't consider varying the transmission power.

As to decentralized schemes, in order to avoid or alleviate co-channel interference between neighbouring cells, and allow arbitrary number cells to be in the 802.22 network, [57] proposes distributed inter-network spectrum sharing scheme, where contention decisions are made in a distributed way and winner cells can use the shared channel. This work doesn't consider the role of transmission power in the co-channel interference. [55] discusses power control and channel assignment in both down-link and up-link communication in cellular network. Although the solution is distributed, Primary users are required to cooperate with secondary base station in a learning process to decide the transmission power, in addition, there is only one secondary base station considered whereas we are coping with the whole cellular network. An distributed power allocation (single channel) scheme based on learning for secondary networks is given in [47], where penalty function involving the interference threshold on primary systems is used. [122] deals with the join channel-power selection for multiple transmission links (pairs). The authors decompose the Lagrangian dual of the problem, then propose a distributed scheme based on the dual parameters. The scheme converges to pure Nash equilibrium, but in order to facilitate this scheme, monitors are required to watch interference from secondary users, moreover, monitors have to be equipped computational ability and interact with secondary users in the whole process of convergence. Distributed joint power and channel allocation is proposed in [89], each base station chooses optimal power level and channel to optimize its utility, which involves induced and received interference along with the interference on primary users. The execution of this scheme is formulated into an exact potential game. For each base station, after several rounds of best responses in terms of channel and power level, Nash equilibrium is achieved. There are some flaws hindering the application of this scheme. First of all, the paper doesn't provide means for base stations to obtain the needed information which is needed to calculate the utility function. Secondly, as how does the base station know the interference received on the primary users, it is not clear how to calculate the punishment in the utility function, which indicates whether and how much the interference threshold on primary users is violated. Thirdly, the convergence speed of the scheme is not given, in fact, as the problem is formulated into an potential game, converge speed, or to say the number of updates before convergence is a theoretic problem which is still unsolved [x]. Last but not least, as the utility function and the potential in the game are designed as the sum of received and introduced interference, the desired signal power and the punishment, the minimization of this 'sum' does indicates meaning performance metric, i.e., SINR on terminals, or the total transmission power consumption. [70] adopts cooperation game to research the coexistence of femtocells. Each femtocell distributed negotiate with neighbouring fremcells and form temporary coalition, but the purpose is to allocate resource block in terms of time and transmission power.

[26] proposes both centralized and decentralized solutions. Two distributed schemes are proposed, joint channel and power allocation is formulated into a weighted poten-

tial game, as an alternative workaround, the problem is solved in two sequential phases. Potential game is also adopted in work [42].

3.4 Problem Decomposition and Corresponding Related Works

In the aforementioned works, the protection on primaries users is taken care during deciding the channel and power selection, but in the current 802.22 standard, there exist no communication media between the secondary network and the primary users, besides, assume such communication media is available, the communication overhead between primary users and second users is considerable. Based on this analysis, we decide the maximal transmission power for each WBS on each channel before taking care of the channel and power allocation afterwards. By doing this, the protection on the primary users from harmful interferences is excluded from the latter consideration on channel and power allocation.

In this chapter we solve the channel and power allocation in downlink 802.22 network by solving three sequential sub problems:

- Firstly, given a set of secondary WBS and their geo-location, the maximum permitted transmit power on all channel for each WBS can be determined, so that the interference margin is impossible to be broken no matter how do WBSes utility the channel and power resources. In other words, the dynamics in the secondary network is transparent to primary system. This requires to consider the joint interference that the WBS have on the TV receivers of the considered service area.
- Secondarily, once the maximal transmit power has been determined, each WBS needs to choose its operating channel.
- Thirdly, transmission power is adjusted on the channel which is decided in the previous step.

While for the first problem a centralized approach is of interest, the following two problems will be solved by distributed schemes. In the following, we introduce the related works with the corresponding sub problems.

3.4.1 Maximal transmission power planning

To protect the TV contours from harmful interference from secondary base stations, the aggregate interference caused by WBSs on TV contours should be lower than interference margin [69]. The sufficient condition in the context of TV white space is formulated into a centralized linear programming program (LP). Adopting centralized scheme is due to the special network structure according to IEEE 802.22 standard. The standard required a centralized database to store the available channels for each secondary base station, thus centralized scheme can be conducted there after trivial modification. The objective function is to maximize the summation of all secondary base stations' transmission power, and the constraints are built to satisfy the sufficient condition for every TV contour.

3.4.2 Channel allocation with fixed transmission power level

After knowing the power limit on each channel, WBSs need to decide which channel to use so as to mitigate interference among WBSs and provide better SINR to its end users. Here we assume WBSs' transmission power is the biggest permitted and fixed. Such problem lies in *channel assignment problem* which has been well investigated in many scenarios. Channel assignment problem mainly cope with mitigating co-channel interference among users, which can be converted into coloring problem thus is NP hard [97]. Authors of [24, 67] propose heuristic algorithms utilizing best response based on the welfare on itself to assign channels among users, but the assumption that transmission power is identical and path loss is symmetric renders them problematic for our problem where transmission is nonidentical and the path loss is asymmetric. Distributed algorithm based on Learning is proposed in [58] for LTE to allocate the the resource block in down link, which leads to correlated equilibrium, but large number of steps hinter its application. [86] formulates channel assignment problem in ad-hoc cognitive radio network into potential game which leads to pure NE, a learning scheme achieving slightly better performance is provided for comparison, but they assume the transmission power is identical and there is no noise in the secondary network, and the proposed random access mechanism demands a huge amount of information to be exchanged, which is a real burden for network in ad-hoc structure. [44, 119] investigate the channel allocation problem under game framework in same collision domain, the authors proposes algorithms to converge to pure Nash equilibrium (NE) and strongly dominate strategy equilibrium respectively. As to our knowledge, there is no work dealing with channel allocation with such asymmetric interactions.

3.4.3 Power allocation

Working with the maximal permitted transmission power may not be the optimal in terms of power consumption and the SINR on terminals. Thus distributed power adjustment is conducted.

3.5 The Maximal Permitted Transmission Power

The WBSes work in underlay manner with primary TV stations, thus on each licensed channel, the generated interference should not excess the threshold associated with any TV service contours. We adopt the interference model and the optimization methodology from the work of [69] to plan the maximal transmission power for WBSs. Have a global view of the propagation parameters, geographic locations of WBSes and interference threshold of TV service contour, linear programming can be implied in the database.

For WBS $i \in \mathcal{N}$, the maximal transmission power allowed to be used on channel c is denoted as P_i^c. As to each channel $c \in \mathcal{C}$, the generated interference on each interference measurement device should be below than a predefined threshold. I_{pt}^c is deemed to be the smallest threshold. Then the maximal permitted transmission power on channel c for each WBS can be obtained by solving the following optimization problem,

$$\begin{aligned} \text{Maximize} \quad & \sum_{i\in\mathcal{N}} P_i^c \\ \text{subject to} \quad & \sum_{i\in\mathcal{N}} (P_i^c \cdot h_{i,pt} \cdot z) < I_{pt}^c, \end{aligned} \tag{3.8}$$

z is shadow fading with the same behaviour with that in 3.2. Here we only consider the interference caused by WBSs, Since their transmission power is higher and their altitude is higher[69], thus the downlink transmission contributes the main secondary interference[15], and the interference caused by white space end users is trivial and omitted.

Formula 3.8 will be solved for each channel $c \in \mathcal{C}$, after solving the $|\mathcal{C}|$ problems, the maximal transmission power over all channels (maximal power map) for every WBS is obtained.

If implying linear programming to decide the maximal transmission power, the WBSs locating far from TV contours contribute more to the sum of power with the biggest permitted power, as a result the maximal transmission power on each channel obtained with LP is seriously unbalanced. To address this fairness issue, we maximize the summation of the logarithmic value of every WBS's value, then for each channel $c \in \mathcal{C}$, we formulate the problem into a convex optimization problem.

$$\begin{aligned} \text{Maximize} \quad & \sum_{i\in\mathcal{N}} \log P_i^c \\ \text{subject to} \quad & \sum_{i\in\mathcal{N}} (P_i^c \cdot h_{i,pt} \cdot z) < I_{pt}^c, \end{aligned} \tag{3.9}$$

Figure 3.3 depicts the distribution of maximal transmission power levels obtained in 100 simulations. In each simulation the locations of TV contours are randomly decided around the WBSs. It can be seen that around half of WBSs' transmission power planed with LP is restricted to be the minimum transmission power, and the other half of WBSs' transmission power is the maximum permitted power. By applying convex programming, the planed maximal transmission power levels are distributed evenly in between the minimum and maximum permitted power. The gain of SINR on end terminals by applying convex optimization to decide the maximal transmission power is illustrated in the simulation section.

Optimization problem 3.9 provides the maximal transmission power without violating the TV contour, as there are multiple channels available in the network, as long as there are WBSs which work on a different channel from others, there will be a new interference margin for TV contour, which provides tolerance space for network dynamics such as new WBS starting to work or increased interference on TV contour because of variance of broadcast path condition.

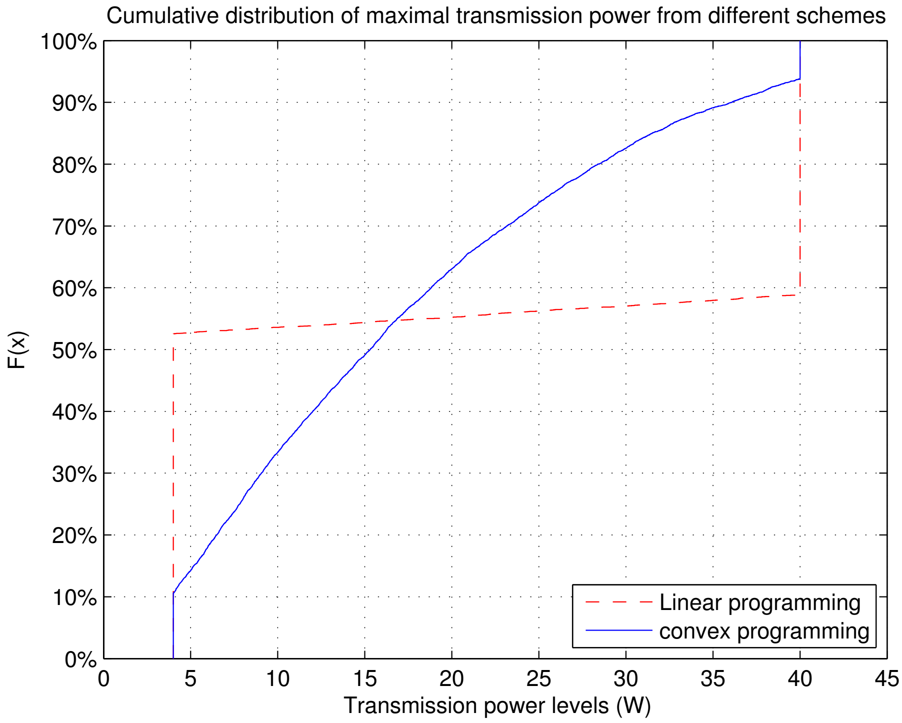


Figure 3.3 Distribution of maximal transmission power levels obtained from convex and linear programming respectively

3.6 Channel Allocation with Fixed Transmission Power

3.6.1 Centralized optimization programming

In the very beginning, we formulate the channel allocation problem into a binary quadratic programming problem which can be solved in a centralized way. For two nodes i and j, there is,

$$X_i^T X_j = \sum_{k=1}^{|\mathcal{C}|} x_{ik} \cdot x_{jk} = \begin{cases} 1 & \text{if } c_i = c_j \\ 0 & \text{if } c_i \neq c_j \end{cases} \tag{3.10}$$

The power levels across all channels are denoted by a constant vector $P^{|\mathcal{C}| \times 1}$, which possibly nonidentical to all nodes because of maximal channel planning. The power used by user i is $P_i^T X_i = \sum_{k=1}^{|\mathcal{C}|} P_i^k \cdot x_{ik}$.

Problem 3.7 can be modeled via general purpose nonlinear optimization:

$$\begin{aligned} \text{minimize:} \quad & \sum_{i=1}^{n} \frac{\sum_{j \in \mathcal{N}, j \neq i} P^T X_j (X_j^T X_i) h_{ji} z + N_0}{P^T X_i} \\ \text{subject to} \quad & \sum_{k=1}^{|\mathcal{C}|} x_{ik} = 1, x_{ik} \in X_i \in \{0,1\}^{|\mathcal{C}|} \end{aligned} \tag{3.11}$$

x_{ik} with $i \in \mathcal{N}, k = 1, 2 \cdots$ is binary variable. Problem 3.11 is a non-linear problem with binary variables, but it can be reformulated in to a quadratic programming problem as,

$$\begin{aligned} &\text{minimize} \\ &\sum_{i=1}^{n}\Big(\sum_{j\in\mathcal{N}, j\neq i}\sum_{k}\frac{P_j^k}{P_i^k}\cdot h_{ji}\cdot z\cdot x_{jk}\cdot x_{ik} + \sum_{k}\frac{N_0}{P_{ik}}\cdot x_{ik}\Big) \\ &\text{subject to: } \sum_{k=1}^{|\mathcal{C}|} x_{ik} = 1, x_{ik} \in X_i \in \{0,1\}^{|\mathcal{C}|} \end{aligned} \tag{3.12}$$

The reformulation is available in Appendix B. We use LINDO[10] which is a state of art non-linear problem solver to solve the problem, which employs Branch-And-Reduce method to get the global optimal for the problem. The result will be used as a reference in the simulation section with other schemes.

3.6.2 Distributed White space channel allocation technology (WitheCat): algorithm and protocol

In this chapter a distributed scheme for WBSs to allocate channels is proposed, which is named as white space channel allocation technology (WitheCat). WitheCat is depicted by algorithm 1 which is a best response process, where each WBS (referred as i) greedily searches for a preferred channel based on utility function u_i, and the sum of all WBSs' utilities is minimized after finite times of updates even the interaction between WBSs are asymmetric. The utility is as follows,

$$u_i = \frac{\sum\limits_{\substack{j\in\mathcal{N}, j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}_{ji}}{2\cdot\tilde{P}_i} + \frac{1}{2}\sum_{\substack{j\in\mathcal{N}, j\neq i,\\ c(\sigma_j)=c(\sigma_i)}}\frac{\tilde{f}_{ij}}{\tilde{P}_j} + \sum_{\substack{\mathcal{S}:i,j\in\mathcal{S},\\ c(\sigma_j)=c(\sigma_i)}}\frac{N_0}{C\cdot\tilde{P}_i} \tag{3.13}$$

where $\tilde{f}_{ij} = P_i \cdot h_{ij} \cdot z$ and $\tilde{f}_{ji} = P_j \cdot h_{ij} \cdot z$. Overlooking the constant coefficient 2, the first item of u_i is one part of the inversed QuasiSINR of station i. To minimize the first item, WBS i needs to choose a channel either permits larger transmission power or experiences less interference, whereas the larger power will increase the second item which is part of inversed QuasiSINR of other co-channel WBSs. Hence, the cost function presents a reasonable comprise between the welfare of one WBS and others. If WBS only emphasizes on its own utility (e.g. the first part of Formula 3.13), the best response process doesn't converge. We have following theorem:

Theorem 3.6.1. *With non-identical transmission power, if every WBS updates its channel based on algorithm 1 with utility based on its own interests, the process doesn't always converge.*

The proof is in Appendix A.

$c(i)$ is the current channel used by $i \in \mathcal{N}$. Imitating the player's behavior in the congestion game, each base station tries to find the channel $c \in \mathcal{C}$ that brings the smallest u_i based on

Algorithm 1: Spectrum selection for node i

Input: quasi distance d_{ij} for $\forall i, j \in \mathcal{N}$; path lose between i and any other WBS h_{ij}, $j \in \mathcal{N}, j \neq i$, and the fading z on it; noise N_0; total number of secondary base stations N; maximal transmission power $P_j^c, j \in \mathcal{N}, c \in \mathcal{C}$; $c(j)$, current channel used by $j \in \mathcal{N}, j \neq i$.

for $i \in \mathcal{N}$ **do**
    for $c \in \mathcal{C}$ **do**
        calculate $u_i(c)$ based on Formula 3.13
        if $u_i(c) < u_i(c(i))$ **then**
            $c(i) \leftarrow c$
        else
            $c(i)$ unchanged
    Notify data base of its channel usage, which notifies the other WBSs

the other stations' decisions, every channel update will decrease the summation of utilities in the whole network and finally converges to a pure Nash equilibrium(proof is in section 3.6.3.

Some parameters needed to calculate the utility are identical for all WBSs, such as quasi distance e, the total number of WBSs N, number of channels C, attenuation factor α, standard deviation σ_{WBS} in flat shadowing and noise N_0, albeit the following information is further needed to calculate u_i:

- $\sum_{\substack{j \in \mathcal{N}, j \neq i, \\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}_{ji}^c, c \in \mathcal{C}$: the received interference on i' virtual measurement point from other WBSs j working on the same channel for $\forall c \in \mathcal{C}$.
- $\tilde{f}_{ij}^c$: the interference caused by i on j's virtual measurement point when i works on channel $\forall c \in \mathcal{C}$.
- P_j^c: transmission power of j for using $\forall c \in \mathcal{C}$.

Unfortunately, it is difficult to get these interferences of interested measured, for station i, it is low efficient to scan all channels and obtain the interferences f_{ji} on virtual measurement point for each channel, furthermore, it is impossible to split the interference f_{ij} from the total interference received on WBS j' virtual measurement point.

Enlightened by the work of [84] which verifies the usage of Geo information in deciding the available channels, we let every WBS store the location information and maximal power map of all other WBSs, and it retrieves information about channel usage by other WBSs from centralized base station, after executing Algorithm 1, it reports to centralized base station for its channel update. As the location of WBSs and TV stations and the transmission channel and power of TV stations are generally static (entries of TV station change averagely once in 2 days[84]), except for the channel usage in the network, the change of the other data stored in WBS is infrequent.

We refer [86] to decide the sequence for WBSs to update their channel. [86] proposes a method like random access mechanism of CSMA/DA, where the access for broadcast medium is changed to getting access to the centralized center to retrieve the current channel usage and update its new channel. All WBS are able to access the database in one round (with random or Predetermined sequence). As WBSs are connected with database, the control messages needed to decide the sequence will not become a burden. Update of channels can happen in the boot phase, or when the quality of services (the SINR on its end users) of WBSs falls below a threshold, or a fixed time duration comes to end, or a new WBS joins in the network.

3.6.3 Analysis in game theoretical framework

We give an elegant proof on WhiteCat's convergence in the framework of congestion game theory. Formulating a spectrum sharing problem into a congestion game and the concept of *virtual resources* are firstly proposed in [75] which 'reversely engineer' the distributed channel allocation schemes proposed in [24, 67].

In congestion game, each player acts selfishly and aims at choosing strategy $\sigma_i \in \Sigma_i$ to minimize their individual cost. The gain (loss) caused by any player's unilateral move is exactly the same as the gain (loss) in the potential, which may be viewed as a global objective function. For problems where the potential of the problem is the same with the summation of the cost of all users, the cost function can be used as a utility function directly. This equivalence doesn't exist in our problem, but by carefully choosing the cost function for players, we can make sure that the change of individuals' cost is in the same direction with that of the global utility.

Bridging the game and practical scheme

We utilize the conception of virtual resource which is firstly introduced in [75]. In the following text, we use player and base station interchangeably.

- Player i' strategy space is $\Sigma_i = \{(i,j,c), j \in \mathcal{N}, j \neq i, c(\sigma_j) = c, c = 1, 2, \cdots, N\}$, and i has C admissible strategies, one strategy related with channel $c \in \mathcal{C}$ is described by the set of virtual resources it uses: $\sigma_i = \{(i,j,c), j \in \mathcal{N}, j \neq i, c(\sigma_j) = c\}$, note that virtual resource $(i,j,c) \neq (j,i,c)$.
- Under the strategy profile $\sigma = (\sigma_1, \sigma_2, \cdots \sigma_N)$, player i obtains a total cost of

$$g^i(\sigma) = \sum_{\substack{j \in \mathcal{N}, j \neq i, \\ c = c(\sigma_i) = c(\sigma_j)}} (g_{(i,j,c)}(n_{(i,j,c)}(\sigma)) + g_{(j,i,c)}(n_{(j,i,c)}(\sigma)) \tag{3.14}$$

The transmission power over all channels of player i is $\{p_{i1}, p_{i2}, \cdots, p_{i|\mathcal{C}|}\}$ and fixed. Path loss is assumed reciprocal: $h_{ij} = h_{ji}$, but nor is the flat fading z. To keep the formula clear in the following part, we denote $\tilde{f}_{ij} = P_i \cdot h_{ij} \cdot z$, $\tilde{f}_{ji} = P_j \cdot h_{ij} \cdot z$, $\tilde{P}_i = h_{iQ}$ for $i \in \mathcal{N}$, where $h_{ji} = h_{ij} = (d_{ji} - e)^{-\alpha}$, $h_{ii} = h_{jj} = e^{-\alpha}$, d_{ji} is the distance between base station i and j, and δ is the quasi distance introduced in section 3.2. N_0 is noise which is identical for any channel and any WBS. We define the cost function for virtual recourses (i,j,c) as follows,

$$g_{(i,j,c)}(k) = \begin{cases} \dfrac{\tilde{f}_{ji}}{2\tilde{P}_i} + \dfrac{\tilde{f}_{ij}}{2\tilde{P}_j} + \dfrac{C \cdot N_0}{N \cdot \tilde{P}_i} & \text{if } k = 2 \\ 0 & \text{otherwise} \end{cases} \tag{3.15}$$

As resource (i, j, c) only lies in the strategy space of player i and j, based on 3.15, cost of resource (i, j, c) is only decided by the number of players(0 or 2) using it, thus this is a typical congestion game which has infinite update property [114].

Substitute Formula 3.15 to Formula 3.14, we get the total cost for user i under strategy profile σ.

$$
\begin{aligned}
g^i(\sigma) &= \sum_{\substack{j\in\mathcal{N}, j\neq i,\\ c=c(\sigma_j)=c(\sigma_i)}} (g_{(i,j,c)}(2) + g_{(j,i,c)}(2)) \\
&= \sum_{\substack{j\in\mathcal{N}, j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \left(\frac{\tilde{f}_{ji}}{\tilde{P}_i} + \frac{\tilde{f}_{ij}}{\tilde{P}_j} + \frac{C\cdot N_0}{N}\left(\frac{1}{\tilde{P}_i} + \frac{1}{\tilde{P}_j}\right)\right) \\
&= \frac{\sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}_{ji}}{\tilde{P}_i} + \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \frac{\tilde{f}_{ij}}{\tilde{P}_j} + \frac{CN_0}{N} \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \left(\frac{1}{\tilde{P}_i} + \frac{1}{\tilde{P}_j}\right) \\
&= \frac{\sum_{\substack{j\in\mathcal{N}, j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}_{ji}}{\tilde{P}_i} + \sum_{\substack{j\in\mathcal{N}, j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \frac{\tilde{f}_{ij}}{\tilde{P}_j} + \frac{2CN_0}{N} \sum_{\substack{i\in\mathcal{S}\subset\mathcal{N},\\ \mathcal{S}:\forall i\in\mathcal{S}\\ c(\sigma_i)=c}} \frac{1}{\tilde{P}_i}
\end{aligned}
\tag{3.16}
$$

Let $\mathcal{S}$ denote the set of WBSs which work on the same channel. Now we try to get the potential over all WBSs, note that the summation of one WBS's congestion is related to its index. For any two WBS $i, j \in \mathcal{S}$ with $i < j$, the potential brought in by i is 0, while, that caused by j is in the form of $g_{(i,j,c)}(2) + g_{(j,i,c)}(2)$. In other words, for each interfering pair of WBSs, only the WBS with bigger index contributes to the potential. The total potential is,

$$
\begin{aligned}
G(\sigma) &= \sum_{r\in\mathcal{R}} \sum_{i=1}^{n_r(\sigma)} g_r(i) = \sum_{i\in\mathcal{N}} \sum_{r\in\sigma_i} g_r(n_r^i(\sigma)) \\
&= \sum_{i\in\mathcal{N}} \frac{\sum_{\substack{j\in\mathcal{N}, j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}_{ji}}{\tilde{P}_i} + \frac{CN_0}{N} \sum_{\substack{\mathcal{S}\subset\mathcal{N},\\ \forall i\in\mathcal{S}, c(\sigma_i)=c}} \mid\mathcal{S}\mid \sum_{i\in\mathcal{S}} \frac{1}{\tilde{P}_i}
\end{aligned}
\tag{3.17}
$$

Question:

When power is variable, is it still a congestion game, or potential game?

When players minimize their utilities (cost or potential) illustrated by Formula 3.16, the total congestion in the secondary network given by Formula 3.17 decreases monotonically before reaching one Nash equilibrium. Players' greedy update in the game to minimize its cost Function3.16, which ceases finally in pure Nash Equilibrium. The strategy and cost function of players in the game is transplanted as Algorithm 1 and utility Function 3.13 respectively.

Difference between equilibrium and the aimed variable

Here rises a question, is the final value obtained by Algorithm 1 exactly the same as the expression 3.17 representing a Nash equilibrium? The answer is that there is very little difference if interference is considered. Recall the target objective we want to minimize in Problem 3.7 is,

$$\begin{aligned}\sum_{i \in \mathcal{N}} \frac{\tilde{f}_i}{\tilde{P}_i} &= \sum_{i \in \mathcal{N}} \frac{\sum_{\substack{j \in \mathcal{N}, j \neq i, \\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}_{ji} + N_0}{\tilde{P}_i} \\ &= \sum_{i \in \mathcal{N}} \frac{\sum_{\substack{j \in \mathcal{N}, j \neq i, \\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}_{ji}}{\tilde{P}_i} + \sum_{i \in \mathcal{N}} (\frac{N_0}{\tilde{P}_i})\end{aligned} \tag{3.18}$$

Compare Formula 3.18 and 3.17, we find that the difference between the objective value and the final value promised by congestion game is the difference between the last items in Formula 3.18 and 3.17. When channels are evenly distributed, there is $C/N* \mid \mathcal{S} \mid \approx 1$, thus Formula 3.18 and 3.17 are approximately the same, but monotonicity on the decrease of expression 3.18 is not perceived whereas convergence to NE is still guaranteed. When $N_0 = 0$, the potential is exactly the same with the object we want to minimize.

From above analysis, we can see the assumption that each WBS only occupies one channel can be easily removed, for example, each WBS can access multiple channels, and we can regard that WBS consists of multiple WBSs (have the same location) and each of which works on one channel. Then the proof on convergence of WhiteCat can be applied directly to this case.

Note that the convergence of the game is independent on the the concrete form of the cost function. The reason we use function 3.16 is the total potential of the game is approximately the same with the total utility of all WBSs in the network, if the the goal of a problem varies and the total utility is different, a distinctive utility for each WBS should be accordingly proposed. Hence, we say that WhiteCat scheme provides a prototype for the problems where the interaction among users are asymmetric: based on a suitable utility involves the welfare of itself and its neighborhood community, the best response approach can converge in a decentralized style.

3.6.4 Communication overhead of Dicaps in the phase of channel allocation

Channel allocation with different transmission power is NP hard, this is one reason for us to propose distributed algorithm. DiCAPS is a distributed scheme but certain information of other WBSes is needed. The centralized base station is piggybacked to provided the needed information. As to a WBS, the number of such inquiries is the number of steps before convergence. The upper bound of total update steps is $2n^2$, thus averagely, the upper bound of update steps for each WBS is $2n$. We give the proof of this upper bound.

3.7 Variable transmission power after channel allocation

After deciding on the working channel, WBSes operate with the maximal permitted transmission power. As the utility defined in Section 3.6 is division of linear function of transmission power and received interference, it is natural to assume that there could exist a vector of transmission power $\{p_1, p_2, \cdots, p_N\}$ where $p_i < P^c_{max}, \forall i \in \mathcal{N}$, and the metric doesn't diverge much from the already achieved metric. But by using the metric as utility, there is no WBS has the motivation to diverge from the power level being used (the maximal permitted power) with other WBSes keep their transmission power the same.

We adopt the function form of utility proposed in [107].

$$u = \frac{E \cdot R}{p}(1 - e^{-0.5 \cdot \gamma})^L$$

This new utility is function of both its own transmission power and quasiSINR, thus one WBS doesn't need relevant information from other WBSes. This function has several attracting properties. It is a monotonically increasing function of γ for a fixed transmission power p, and it approaches to 0 when γ increases to infinity, and it is a monotonically decreasing of the transmission power p for a fixed γ. This function goes to 0 when p goes to either 0 or infinity. The WBSes keeps on minimizing this utility and finally result in nash equilibrium.

3.8 Joint Channel and Power Allocation

In the section 3.6, the problem is decomposed into sub problems which are solved sequentially, one is solved by linear/convex programming in the data center, the others are solved with distributed schemes. The decomposition of the original problem along with the distributed scheme may yield a result away from the optimal, so in this chapter, we propose centralized scheme which looking for the global optimal results in order to examine the performance of DiCAPS.

3.8.1 Centralized optimization

When we consider to optimize the transmission power and channel in the same time, the optimization problem 3.12 is not quadratic any more and becomes mixed integer nonlinear problem, for which there is no efficient solution. We reformulate problem 3.12 into a mixed binary quadratic optimization problem with some auxiliary variables created, i.e., binary number α, real number β and q, where

$$x_{jk} \cdot x_{ik} = \alpha^k_{ij} \tag{3.19}$$

$$\beta^k_{ij} = p^k_j \cdot \alpha^k_{ij} \tag{3.20}$$

$$\frac{1}{p_i^k} = q_i^k \tag{3.21}$$

Then the optimization problem can be stated as:

$$\begin{aligned}
&\text{minimize} \\
&\sum_{i=1}^{n}\Big(\sum_{j\in\mathcal{N},j\neq i}\sum_{k} q_i^k\cdot\beta_{ij}^k\cdot h_{ji}\cdot z + \sum_{k} N_0\cdot q_i^k\cdot x_{ik}\Big) \\
&\text{subject to:} \\
&x_{jk} + x_{ik} - \alpha_{ij}^k \leq 1 \\
&-x_{jk} - x_{ik} + 2\cdot\alpha_{ij}^k \leq 0 \\
&\beta_{ij}^k - p_j^{k,max}\cdot\alpha_{ij}^k \leq 0 \\
&-\beta_{ij}^k + p_j^{k,min}\cdot\alpha_{ij}^k \leq 0 \\
&\beta_{ij}^k - p_j^k - p_j^{k,min}\cdot\alpha_{ij}^k \leq -p_j^{k,min} \\
&-\beta_{ij}^k + p_j^k + p_j^{k,max}\cdot\alpha_{ij}^k \leq p_j^{k,max} \\
&\sum_{k=1}^{|\mathcal{C}|} x_{ik} = 1, x_{ik}\in X_i\in\{0,1\}^{|\mathcal{C}|} \\
&q_i\cdot p_i = 1
\end{aligned} \tag{3.22}$$

The objective function is quadratic, but the quadratic equality constraint makes this optimization problem very challenging to solve. Linearisation is possible when Q is positive definite 'Quadratic Optimisation with One Quadratic Equality Constraint'. As we don't regulate the location of the WBSes, and the attenuation is random among them, thus the positive definite can not be guaranteed. We use solver Lindo to look for the global optimum. This form of optimization is non linear, but several algorithms are available to obtain the global optimal [54, 102].

all the constraints except for the last one are linear. The first two constrains realizes Formula 3.19, the following four constraints realizes Formula 3.20. Due to the quadratic equability constraint $q_i \cdot p_i = 1$, the optimization problem is non-convex and only a few solvers are able to solve it by using global searching. One workaround to avoid global searching is to linearise the equality constraint. After linearising constraint $q_i \cdot p_i = 1$, the problem becomes mixed integer quadratic problem, and can be solved with Gurobi.

3.8.2 Distributed scheme

We use the solution proposed in [89] as comparison. As introduced in section 3.3, [89] formulates the non-cooperative power-channel allocation problem into a potential game, but the potential of the game is the sum of received and introduced interference, along with the received desired signal power on end user, which is not the SINR on the end user.

3.9 Performance Evaluation

We compare the performance of WhiteCat, with another two distributed heuristic schemes (Whitespace channel allocation selfish) WhiteCase and no-regret learning, besides, the centralized optimization and a random allocation are used for reference.

- *WhiteCase*: Each WBS selfishly updates its channel to achieve the best (as to the considered problem, smallest) possible utility based on Formula A.1.
- *No-regret learning*: Each WBS maps the probability of choosing each strategy to a certain proportion of the regret which the WBS may have if it doesn't choose that strategy, and the WBS choose the strategy with the biggest probability. WBSs update such mapping dynamically and this approach converges to correlated equilibrium. Please refer the original paper [53] for details.

A square area which is 60km x 60km is divided into 16 square blocks evenly, for each block there is one WBS locating in the middle of it. Same mount of end terminals distributed in each minor block, however, they don't necessarily belong the WBS which is nearest to them, in stead they choose the WBS to join, which causes the strongest received signal strength indicator (RSSI) on them. There is a 30km wide rim area around the square area, where TV contours are randomly located. The TV station which protected by TV contour works only with one channel. The location of WBSs and TV contours are illustrated in Fig. 3.4. The other parameters are listed in Table 3.14efsimulationparameter.

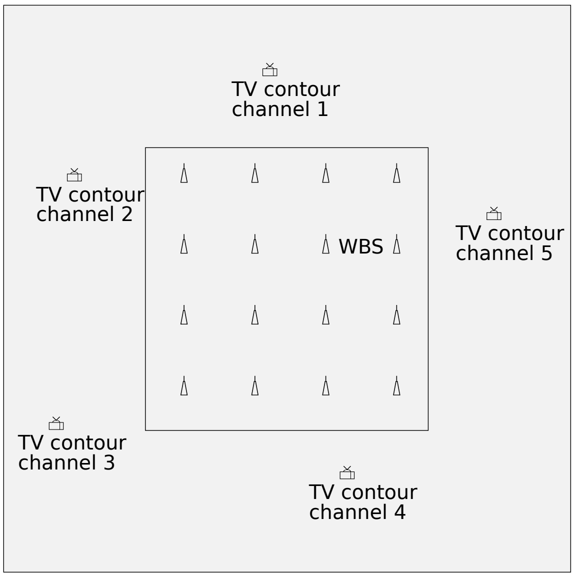


Figure 3.4 Layout of WBSs and TV contours

3.9.1 Maximal Permitted Power Decision and the Distributed Channel Allocation Schemes

In this section, firstly, we will evaluate which optimization in Section 3.5 is better to decide the maximal permitted transmission power, the adopted metrics are average power consumption, and SINR on end users. Then with the decided better method, we will compare

Number of channels	5
Number of WBSs	16
Noise	10^{-12}W
Length of the square to locate WBSs	60km
Distance between quasai terminal and WBS	7km
Interference threshold on TV contour	10^{-7}W
Path loss factor	2
Standard deviation in flat shadowing	8
Minimal WBS transmission power	4W
Maximal WBS transmission power	40W
Number of end terminals in network	800

Table 3.1 Simulation parameters

given the power map, how do the channel allocation schemes perform. We compare our proposed channel allocation scheme *whiteCat* with three other distributed schemes, the random allocation scheme, whiteCase, No-regret learning and the centralized quadratic optimization introduced in Section 3.6, which is named as *optimization*.

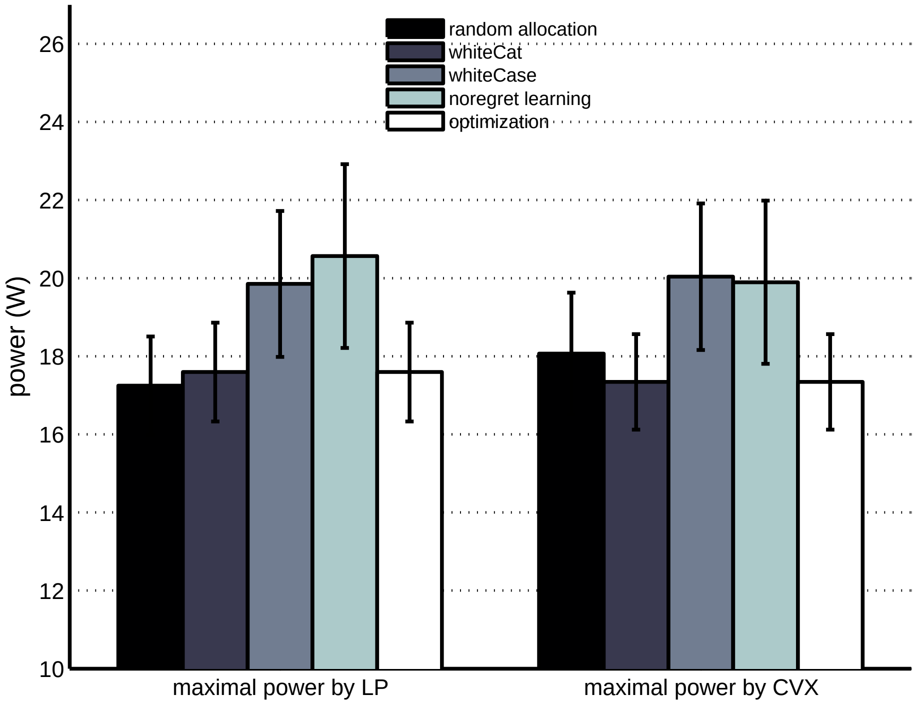


Figure 3.5 Power consumed by different distributed spectrum allocation schemes under different ways deciding the maximal transmission power map

Comparison of formulations to determine the maximal permitted power

In section 3.5, two different formulations are introduced to calculate the maximal permitted transmission power, i.e., convex optimization and linear optimization respectively. The convex optimization generates power levels which are with smaller difference compared with that obtained from linear optimization, which is shown in Fig. 3.3. In this

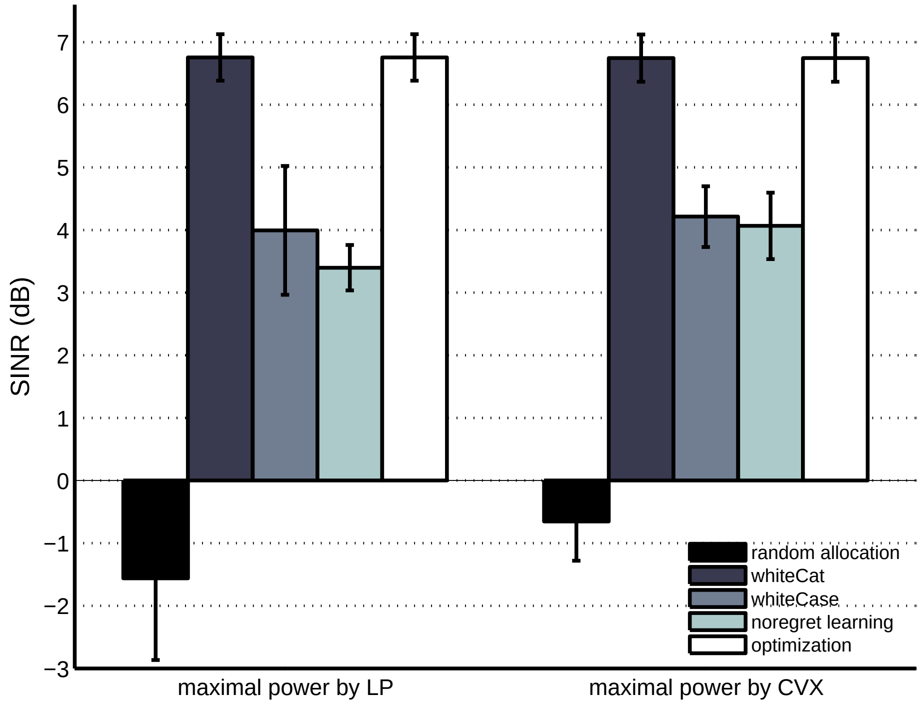


Figure 3.6 QuasiSINR achieved by different distributed spectrum allocation schemes under different ways deciding the maximal transmission power map

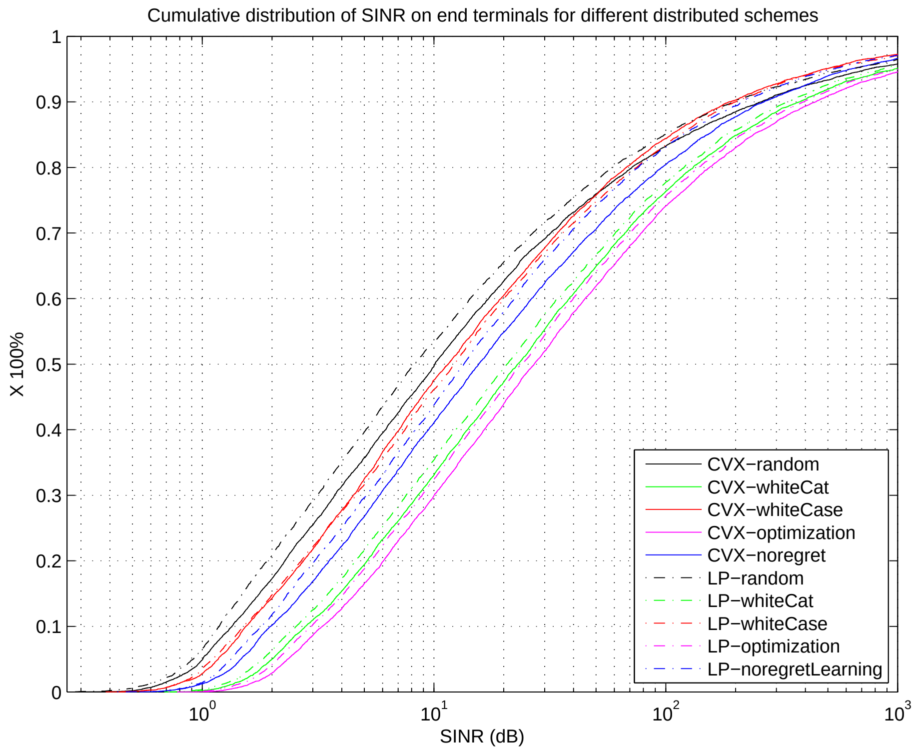


Figure 3.7 CDF of SINR on end users obtained by different CA schemes under different methods to decide the maximal transmission power map

section we will find out which formulation outperforms in terms of SINR on end terminals and transmission power consumption when distributed spectrum allocation schemes execute with the power maps. WBSs' location is fixed whereas the location of TV contours, end terminals and the sequence for WBS to update are randomly decided. In each run of simulation, end users select the WBS which brings it the best SINR performance. Simulations are done for 100 times. Fig. 3.5 and 3.6 show that when convex formulation is applied to decide the maximal power map, all the four distributed spectrum allocation schemes consume less transmission power consumption by 15% to 30% and achieve better QuasiSINR. The cumulative distribution function curve of SINR on end terminals is drawn in Figure 3.7, where the x axis represents SINR level, and the y axis shows the cumulative proportion of end terminals whose SINR equals or smaller than that level. The curves show that except for the random method, all three other distributed schemes perform better in low SINR area (SINR $< 10dB$) with convex formulation, while worse in the high SINR area. Hence we adopt convex formulation to decide the maximal transmission power in the following simulation.

Comparison among channel allocation schemes

After deciding the maximal permitted transmission power on each channel for each WBS, the data center distributes this maximal power map to all WBSes, and trigger the procedure of distributed channel allocation.

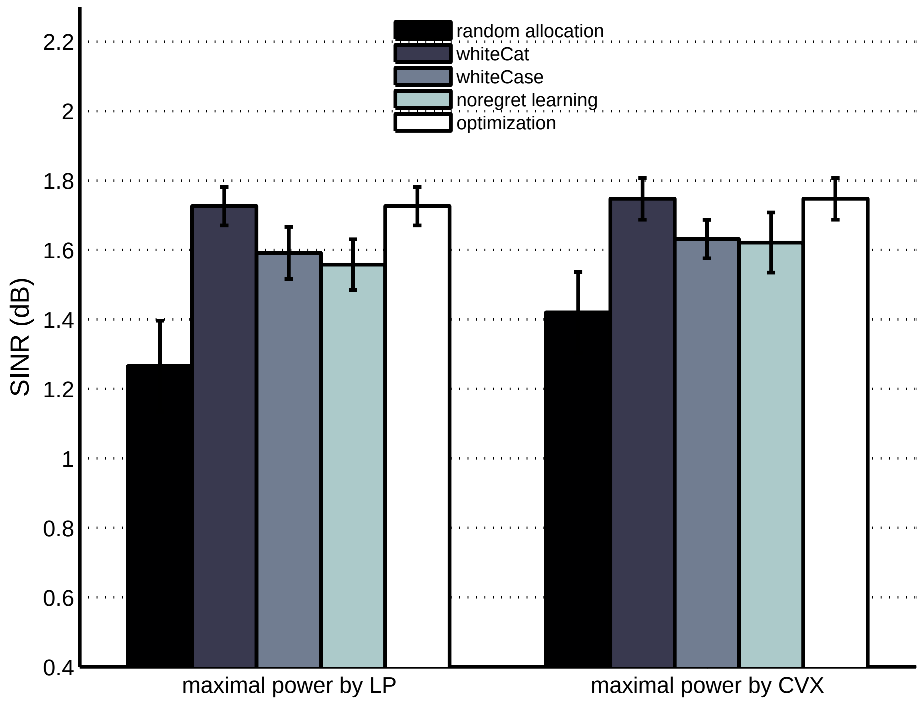


Figure 3.8 The average SINR of the 20% worst end terminals

The performance of the four spectrum allocation approaches working with the maximal power map calculated from convex formulation is elucidated in the right part of both Fig. 3.5 and 3.6. We can see that WhiteCat consumes 12% less transmission power than WhiteCase and No-regret learning schemes, whereas better QuasiSINR is obtained. The cumulative distribution function curve of SINR on end terminals with convex programming is presented in Fig. 3.7 with dash lines, we can see that for any cumulative proportion under 90%, the corresponding SINR level from Whitecat on end terminals is slightly (around 0.5-1 dB) but stably higher than that obtained by WhiteCase and No-regret schemes, and 3 dB higher than that in random scheme.

In each run of simulation, average value of the 20 % end terminals with the worst SINR is recorded, and the averaged such value over 100 simulations is illustrated in Figure 3.8 which shows WhiteCat achieves better performance for the worst suffered end terminals than WhiteCase and No-regret approaches.

Analysis on convergence process

In the congestion game, each player has at most $(n-1) * |\mathcal{C}|$ resources available for usage, so there is no polynomial steps converging to NE, while, simulation shows the algorithm can quickly converge to NE when the number of WBS is up to 100. Figure 3.9 depicts one instance of simulation, where WhiteCat converges quickly, No-regret produces oscillation but converges finally, while WhiteCase can not converge thus has to be enforced stop after 16000 updates.

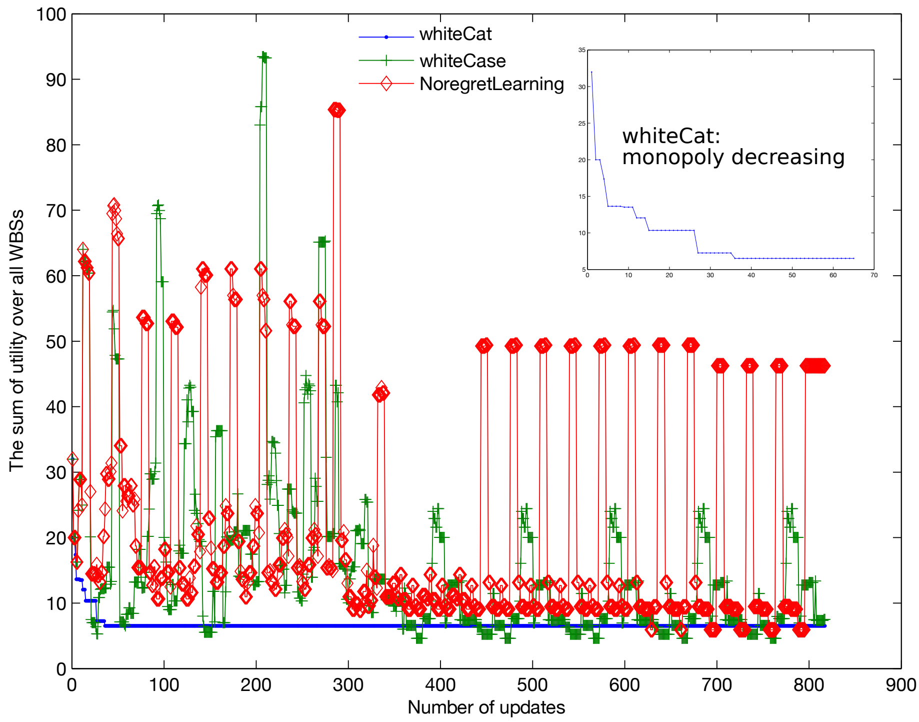


Figure 3.9 Convergence with three different schemes in one simulation instance

We also compare the convergence speed between WhteCat with no-regret scheme. We fix 16 WBSs' location working with 4 channels, whereas the location of TV contours and end terminals are randomly decided. We account each WBS accessing the base station (refer to 3.6.2) as *one step*. We record the number steps before convergence. Table 3.2 illustrated the average number of steps needed for convergence in 100 runs of simulations. As there is no guarantee for WhiteCase to converge, we stop the channel allocation process after 16000 steps (1000 rounds). We can see WhiteCat is 20 times faster than no-regret, and the relatively small confidence interval shows that WhiteCat's convergence is not affected obviously by different network conditions, which is reasonable as more knowledge of the network is known by users executing Whitecat. As to average running time for each convergence with Matlab, Whitecat is much smaller than the other two schemes, as the nonlinear solver LINDO to be discussed in next subsection, the running time is about 40 minutes. Figure 3.9 reflects one instance of the convergence of three schemes in one run of simulation. Notice that there is a slight rise when the value on the X-axis is 35, which comes from the difference between 3.18 and 3.17.

Scheme	average #steps	95% CI	average time
whitecat	58	5.6	2s
whitecase	4587	2742	50s
non regret	1916	1541	144s
potential game	120	10	4s

Table 3.2 Convergence speed of the distributed channel allocation schemes

Stability of SINR in the process of channel allocation

WBS provides service to end users in the process of channel allocation. A certain SINR corresponds to certain transmission configurations like modulation type and data rate. Oscillation of SINR may cause reconfiguration, reduced throughput or delay variance, thus is not preferred. We propose a metric *Cost of Oscillation* (COS) to represent the stability of SINR in the converging process. We assume each update step takes the same amount of time which is 1 time unit, the variance of SINR on end user i at time point $t+1$ compared with that at time t is $\Delta\gamma_i(t+1) = \mid \frac{\gamma_i(t+1)-\gamma_i(t)}{\gamma_i(t)} \mid$. The COS value for one network applied with a certain channel allocation scheme is,

$$COS = \sum_{t=1}^{T} \sum_{i \in \mathcal{N}} \Delta\gamma_i(t) \tag{3.23}$$

$\gamma_i(0)$ is the SINR for i before starting channel allocation. The variance of SINR in channel allocation process is shown in table 3.3 from which we can see WhiteCat achieves only 6% of oscillation on SINR compared with No-regret approach.

Scheme	COS	95% Confidence interval
Whitecat	8850	2984
Whitecase	246790	168050
No-regret	145460	1541

Table 3.3 Variance of SINR during the converging phase

3.9.2 Performance of joint power and channel allocation: cascaded distributed schemes vs. joint distributed/centralized schemes

As introduced in section 3.7, after channel allocation is conducted, transmission power will be adjusted in a distributed manner. In other words, power and channel allocation is completed after executing two sequential distributed schemes. As comparisons, we implement two joint power channel allocation schemes. One is centralized optimization shown in section 3.8.1, which is used as upper bound in the comparison. The other one is distributed joint power and channel allocation scheme [89] which has been introduced in section 3.3. As we have discussed, scheme proposed in [89] doesn't aim to improve the SINR on end terminals, but on the sum of produced and received interferences.

The performance of joint channel and power allocation schemes are presented in Fig. 3.10, 3.11 and 3.12 in terms of total utility, power consumption and achieved quasiSINR respectively.

In Fig. 3.10, we can see that together with the distributed power allocation method, DiCAPS achieves similar utility with the centralized channel allocation optimization, and the utility is close to the centralized joint channel and power allocation This means that DiCAPS approaches the upper bound in terms of total utility. Fig. 3.11 shows DiCAPS together with power allocation consumes the least power. Fig. 3.12 demonstrates the cumulative distribution of SINR on all end terminals, .

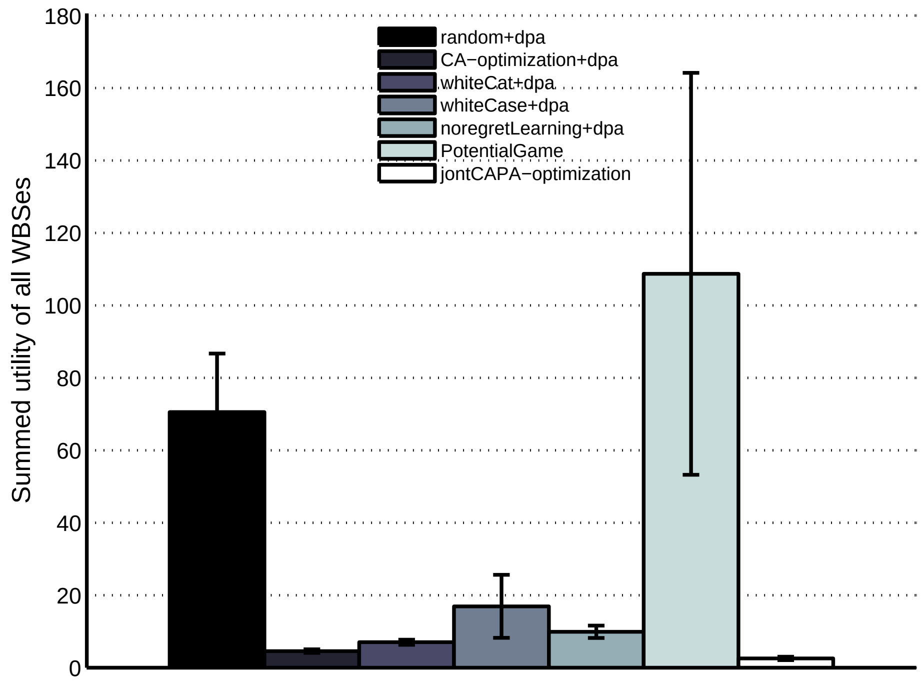


Figure 3.10 Summed utility of all WBSes, which is the objective in problem 3.7. dpa in legend represents *distributed power allocation*

3.10 Conclusion

We propose a method to assign maximum transmission power to secondary users to make full use of the white TV spectrum. The second contribution of this chapter is the design of a distributed channel assignment scheme called WhiteCat which is designed for secondary users to decide which chunk of spectrum should be used in order to improve cell performance in the down-link transmission direction. WhiteCat provides end terminals better SINR with less transmission power, and converges to one pure Nash equilibrium in a faster speed compared with two other schemes (greedy best response as well as a no-regret learning scheme). WhiteCat is formulated into a standard congestion game which proves the convergence of the scheme. WhiteCat requires a central data base containing information about the previously allocated channels to secondary users as well as their positions and propagation information among the base stations. Compared to previous

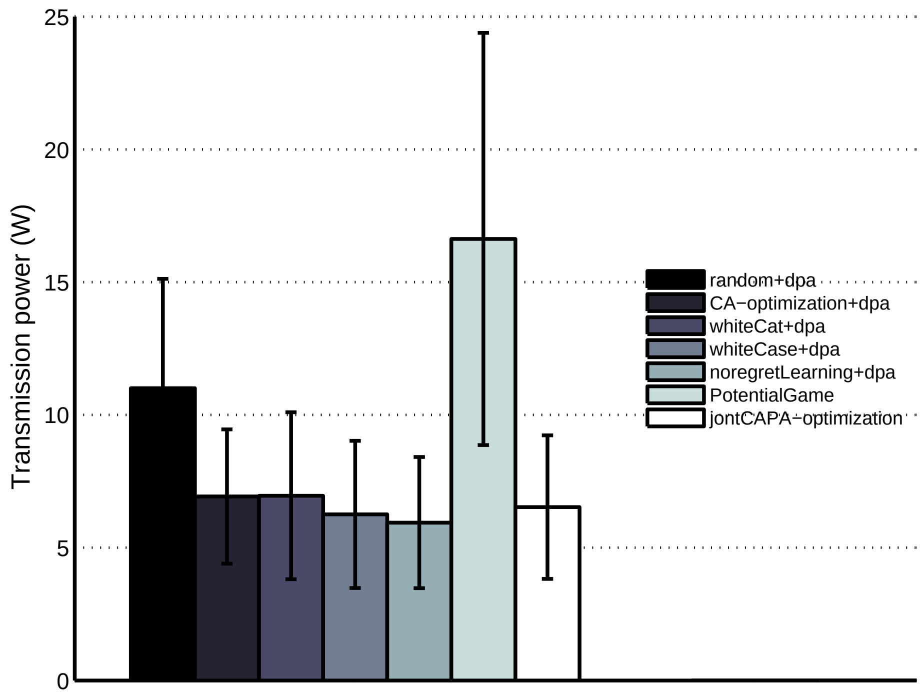


Figure 3.11 Average transmission power of one WBSes

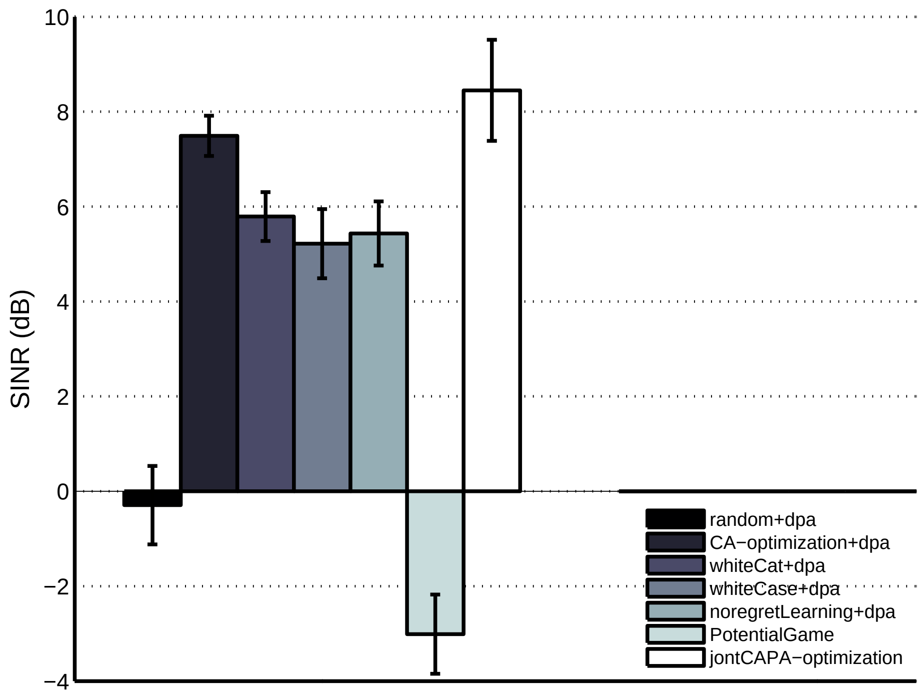


Figure 3.12 Average quasiSINR of a WBS

work that suggests the use of a central data base for base station registration and channel validation, this is a minor overhead to be introduced. For future work we will address the problem of allowing base stations to set the transmit power arbitrarily within the maximum transmit power limit.

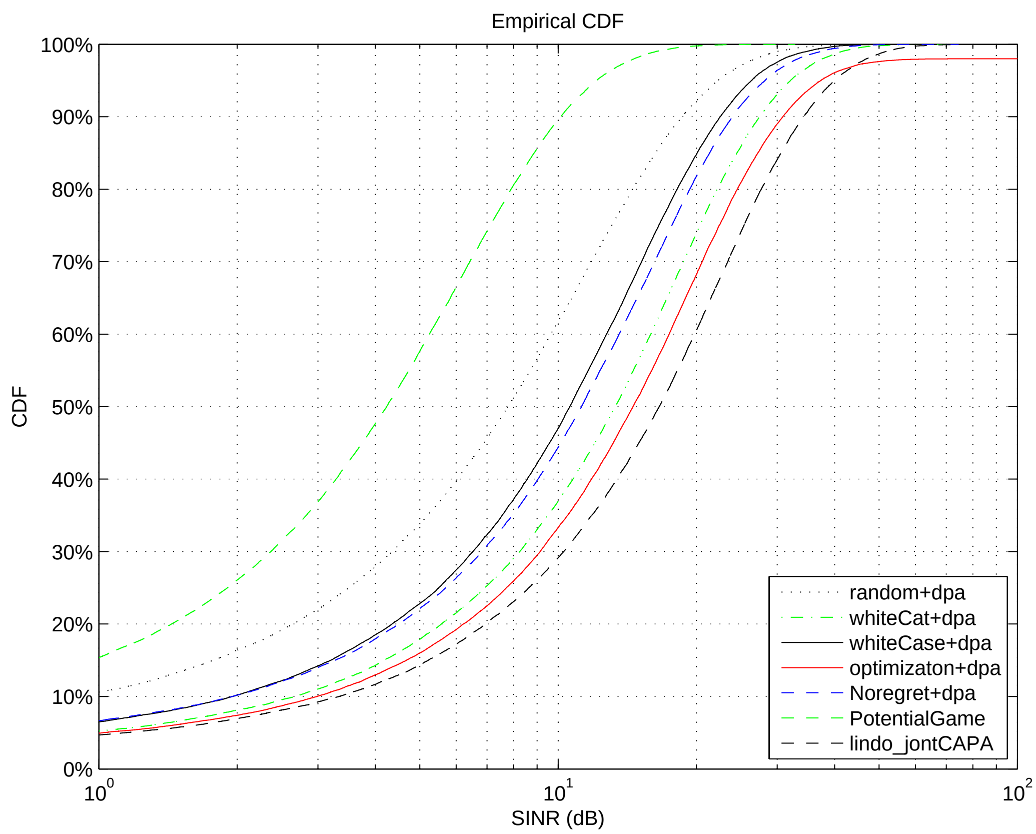


Figure 3.13 SINR on end users after channel and power allocation

A

Proof of Theorem 3.6.1

For selfish best response approach, the utility function is set as follows,

$$u_i = \frac{\sum_{c(i)=c(i)} \tilde{f}_{ji} + N_0}{P_i \cdot h_{ii}} \tag{A.1}$$

Proof. In order to simplify the proof, we assume $N_0 = 0$. Consider one WBS i executing algorithm 1 with utility A.1, and updates its channel from c_i to c_i', we denote $u_k', k \in \mathcal{N}$ as the utility of WBS k when i chooses channel c_i', accordingly, the summation of utilities of all WBSs after i changing to c_i' is $U' = \sum_{\forall k \in \mathcal{N}, c(i)=c_i'} u_k'$.

$$\begin{aligned}
U' &= u_i' + \sum_{j \in \mathcal{N}, j \neq i} u_j' \\
&= u_i' + \sum_{j \in \mathcal{N}, j \neq i} (u_j + (u_j' - u_j)) \\
&= u_i' + \sum_{j \in \mathcal{N}, j \neq i} u_j + \sum_{j \in \mathcal{N}, j \neq i} (u_j' - u_j) \\
&= u_i' + \sum_{j \in \mathcal{N}, j \neq i} u_j + \sum_{\substack{j \in \mathcal{N}, \\ j \neq i, \\ c(j)=c_i'}} (u_j' - u_j) + \sum_{\substack{j \in \mathcal{N}, \\ j \neq i, \\ c(j)=c_i}} (u_j' - u_j) \\
&+ \sum_{\substack{j \in \mathcal{N}, j \neq i, \\ c(j) \neq c_i', c(j) \neq c_i}} (u_j' - u_j) \\
&= u_i' + \sum_{j \in \mathcal{N}, j \neq i} u_j + \sum_{\substack{j \in \mathcal{N}, \\ j \neq i, \\ c(j)=c_i'}} (\frac{\tilde{f}_{ij}}{\tilde{P}_j}) - \sum_{\substack{j \in \mathcal{N}, \\ j \neq i, \\ c(j)=c_i}} (\frac{\tilde{f}_{ij}}{\tilde{P}_j})
\end{aligned} \tag{A.2}$$

where,

$$\begin{aligned} u_i' &= u_i + \Delta u_i(c_i \to c_i') \\ &= u_i + \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(j)=c_i'}} (\frac{\tilde{f}_{ji}}{\tilde{P}_i}) - \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(j)=c_i}} (\frac{\tilde{f}_{ji}}{\tilde{P}_i}) \end{aligned} \tag{A.3}$$

bring A.3 into A.2, we get,

$$\begin{aligned} U' = U &+ \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(j)=c_i'}} (\frac{\tilde{f}_{ji}}{\tilde{P}_i}) - \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(j)=c_i}} (\frac{\tilde{f}_{ji}}{\tilde{P}_i}) \\ &+ \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(j)=c_i'}} (\frac{\tilde{f}_{ij}}{\tilde{P}_j}) - \sum_{\substack{j\in\mathcal{N},\\ j\neq i,\\ c(j)=c_i}} (\frac{\tilde{f}_{ij}}{\tilde{P}_j}) \end{aligned} \tag{A.4}$$

According to algorithm 1, the summation of second and third items, which is the variance of i' utility, is negative. If we can confirm the summation of fourth of the last four items is negative, the whole utility of the network decreases with i' each update. For simplification, we assume that the channel is symmetric, which means, $h_{ij} = h_{ji}$, and z is identical among all WBSs. Then, the problem we want to confirm is equivalent to the following: Given the in-equation with n, m are natural numbers

$$\sum_{i=1}^{m} \alpha_i < \sum_{i=1}^{n} \beta_i, \tag{A.5}$$

Prove the following in-equation is correct or not,

$$\sum_{i=1}^{m} (\alpha_i + \frac{1}{\alpha_i}) < \sum_{i=1}^{n} (\beta_i + \frac{1}{\beta_i}), \tag{A.6}$$

We propose a small contradiction to prove A.6 is not true. When $m = 2, n = 1$, and $\alpha_1 = 1, \alpha_2 = 0.5, \beta = 2.1$, we can see that although $\sum_{i=1}^{m} \alpha_i = 1.5 < \sum_{i=1}^{n} \beta_i = 2.1$, there is $\sum_{i=1}^{m}(\alpha_i + \frac{1}{\alpha_i}) = 4.5 > \sum_{i=1}^{n}(\beta_i + \frac{1}{\beta_i}) = 2.58$. hence, with WBS's update, it is possible that $U' > U$, thus there is no monotonically convergence by utilizing A.1. □

Notice that the last four items in A.4 is exactly the change of summation of utilities of all WBSs after i' update if WhiteCat is executed, hence the monotonic convergence of WhiteCat is proved here analytically if noise is considered to be zero. If noise is considered, we can follow the conclusion in the end of 3.6.3 that WhiteCat converges without monotonicity.

B

Deviation of Problem 3.11

We reformulate the objective problem 3.11 which is a binary non-linear programming to binary quadratic programming as follows,

$$
\begin{aligned}
&\sum_{i=1}^{n} \frac{\sum\limits_{j\in\mathcal{N},j\neq i} P^T X_j (X_j^T X_i) h_{ji} z + N_0}{P^T X_i} \\
&= \sum_{i=1}^{n} \left(\frac{\sum\limits_{j\in\mathcal{N},j\neq i} \sum\limits_{k} (P_{jk}\cdot x_{jk}\cdot x_{ik}\cdot x_{jk}\cdot h_{ji}\cdot z) + \sum\limits_{k} N_0 \cdot x_{ik}}{P^T X_i}\right) \\
&= \sum_{i=1}^{n} \left(\frac{\sum\limits_{j\in\mathcal{N},j\neq i} \sum\limits_{k} (P_{jk}\cdot x_{jk}\cdot x_{ik}\cdot h_{ji}\cdot z)}{P^T X_i} + \frac{\sum\limits_{k} N_0 \cdot x_{ik}}{P^T X_i}\right) \\
&= \sum_{i=1}^{n} \left(\sum_{j\in\mathcal{N},j\neq i} \sum_{k} \frac{(P_{jk}\cdot x_{jk}\cdot x_{ik}\cdot h_{ji}\cdot z)}{P^T X_i} + \sum_{k} \frac{N_0 \cdot x_{ik}}{P^T X_i}\right)
\end{aligned} \tag{B.1}
$$

we now simplify the first item in the parenthesis. If we assume secondary base station i is working on channel m, then there is $x_{im} = 1$, then

$$
\begin{aligned}
\frac{P_{jk}\cdot x_{jk}\cdot x_{ik}\cdot h_{ji}\cdot z}{P^T X_i} &= \frac{P_{jk}\cdot x_{jk}\cdot x_{im}\cdot h_{ji}\cdot z}{P_{im}\cdot x_{im}} \\
= \frac{P_{jk}\cdot x_{jk}\cdot h_{ji}\cdot z}{P_{im}} &
\end{aligned} \tag{B.2}
$$

other wise, formula B.2 equals to 0.

Similarly, for the second item in the bracket,

$$
\frac{N_0 \cdot x_{ik}}{P^T X_i} = \frac{N_0}{P_{ik}} \cdot x_{ik} \tag{B.3}
$$

then, formula B.1 becomes,

$$\sum_{i=1}^{n}\Big(\sum_{j\in\mathcal{N},j\neq i}\sum_{k}\frac{P_{jk}}{P_{ik}}\cdot h_{ji}\cdot z\cdot x_{jk}\cdot x_{ik}+\sum_{k}\frac{N_0}{P_{ik}}\cdot x_{ik}\Big) \tag{B.4}$$

which is a binary quadratic programming problem.

4

ROBUST CLUSTERING of AD HOC COGNITIVE RADIO NETWORK

4.1 Introduction

Cognitive radio (CR) is a promising technology to solve the spectrum scarcity problem [81]. In CR systems, primary users access their allocated spectrum band whenever there is information to be transmitted. In contrast, CR users (forming cognitive radio networks, abbreviated as CRN) can only access primary channels after validating the channel is idle. This refers to the process of sensing a particular channel and verifying (with a previously specified probability of error) that it is not used by a primary user currently. This form of spectrum sharing is also referred to as opportunistic spectrum access.

As introduced in Chapter 1, efficient spectrum sensing is identified as to be critical to the success of cognitive radio networks [100]. Cooperative spectrum sensing is able to effectively cope with noise uncertainty and channel fading, thus improves the sensing accuracy remarkably [19]. Clustering is regarded as an effective method used in cooperative spectrum sensing [110, 132]. Collaborative sensing relays on the consensus of CR users within certain area, and decreases considerably the false sensing reports caused by fading and shadowing of reporting channel.

Clustering is also efficient to let all CR users[1] within the same cluster stop payload transmission on the operating channel and initiate the sensing process, so that the all the CR nodes within the one cluster are able to vacate the channel swiftly when primary users are detected by at least one CR node residing in the cluster [117]. With cluster structure, the possibility that one CR node interferes neighbouring clusters after vacating the channel due to primary node appearance is reduced [95], as it can be notified by cluster head or other cluster members about the possible collision. Clustering algorithm has also proposed to support routing in cognitive ad-hoc networks [12].

[1] User and node are used interchangeably in this chapter

Except for the advantages brought in by clustering, there is an issue on clustering structure itself in cognitive radio network. As the activity of primary users is controlled by licensed operators which are generally not known to CR users, the connectivity between CR nodes in a CRN is not guaranteed. For a pair of communicating CR nodes, whenever a primary user is detected to be operating on the working channel, CR nodes have to retreat that working channel. The affected CR nodes switch to one other idle channel if there are available idle channels, if not, the communication is cut down. As a result, when coexisting with primary users, the ability for one pair of CR nodes to maintain communication with licensed channels is totally decided by primary users' activity.

Although the communication among secondary users is vulnerable under the affection of primary users, which is objective in the eyes of secondary users, there is something can be done by secondary users when they form clusters. To maintain one cluster operating on licensed channels, at least one common channel is available for all members in that cluster. When the increase of channel occupation by primary users is assumed to be random, a cluster with more channels will stand ground with higher probability. Thus the number of available common channels in the cluster indicates robustness of it when facing uncontrolled influence from primary users. It is not difficult to see that forming clusters with different neighbours leads to different amount of common channels in the clusters. As a result, how to form the clusters plays an important role on the robustness of clusters in CRN.

To solely pursue connectivity robustness against the primary users' activity, i.e., to achieve more common channels within clusters, which is adopted by [xxxxxSOCxxxxxx], the ultimately best clustering strategy is ironically that each node constitutes one single node clusters. Apparently this contradicts our motivation of proposing cluster in cognitive radio network. This contradiction indicates that, the robustness discussed in terms of number of common channels carries little meaning when the sizes of formed clusters are not given consideration. Besides, cluster size plays import roles in certain aspects. For instance, cluster size is one decisive factor in power preservation [60, 20], and it is also influence the accuracy of cooperative spectrum sensing [xxxxxx]. Hence, cluster size should be given consideration when discussing cluster robustness against primary users.

In this chapter, a decentralized clustering approach ROSS is proposed. ROSS is able to form clusters whose sizes are not far away from the desired size, and the generated clusters are more robust than other robust clustering scheme, i.e., more secondary users residing in clusters against increasing affection from primary users. Compared to previous work, ROSS involves much less control messages, and the generated clusters are significantly more robust. In ROSS, cluster head is selected through coordination within its neighborhood, and then cluster membership is decided locally and its convergence is proved under game theoretic framework. On the basis of ROSS, we propose ROSS-DFA which is a light weighted version of ROSS, which requires exchanging less overheads. Throughout this chapter, we refer both ROSS-DGA and ROSS-DFA, along with these added size control feature, as *variants of ROSS*.

The rest of chapter is organized as follows. After reviewing related work in section 4.2, we present our system model in Section 4.3. Then we introduce our clustering scheme ROSS and its variants in section 4.4. Centralized scheme is given discussion in section 4.5. Performance evaluation is in section 4.6. Finally, we conclude our work and point out direction future research in section 4.7.

4.2 Related Work

Prior to the emergence of open spectrum access, as an important method to manage network, clustering has been proposed in for ad hoc networks [64, 74, 28], wireless mesh networks [12], and wireless sensor networks [12] and . In ad hoc and mesh networks, the major focus of clustering is to preserve connectivity (under static channel conditions) or to improve routing. In the context of sensor networks, the emphasis of clustering has been on longevity and coverage. Overhead generated by clustering in ad hoc network is analysed in [109, 120].

As to cognitive radio networks, clustering schemes are also proposed, which target different aspects. Work [121] improves spectrum sensing ability by grouping the CR users with potentially best detection performance into the same cluster. Clustering scheme [60] obtains the best cluster size which minimizes power consumption caused by communication within and among clusters. [60] proposes clustering strategy in cognitive radio network, which looks into the relationship between cluster size and power consumption and accordingly controlling the cluster size to decrease power consumption. Cogmesh is proposed in [38] to construct clusters by the neighbour nodes which share local common channels, and by interacting with neighbour clusters, a mesh network in the context of open spectrum sharing is formed. Robustness issue is not considered by this clustering approach. [118] targets on the QoS poisoning and energy efficiency. This approach first decides on the relay nodes which minimize transmission power consumption, then the chosen nodes become cluster heads and clusters are formed in a dynamic coalition process. This work emphasis on power efficiency and doesn't take into account the channel availability and the issue of robustness of the formed clusters. In [132, 25], the channel available to the largest set of one-hop neighbours is selected as common channel which yields a partition of the CRN into clusters. This approach minimizes the set of distinct frequency bands (and hence, the set of clusters) used as common channels within the CRN. However, bigger cluster sizes generally lead to less options within one cluster to switch to if the common channel is reclaimed by a primary node. Hence, this scheme does not provide robustness to formed clusters. [22] deploys cluster structure in order to implement common channel control, medium access with multiple channel and channel allocation. The node with the maximum number of common channels within its k-hop neighborhood is chosen as cluster head, but how to avoid one node appearing in multiple clusters is not given consideration.

Clustering robustness is considered in [71, 76]. Authors [71, 76] emphasis on improving the numbers of common channels within clusters, in order to strengthening robustness of clusters, but the perused metric is not examined or proved to be able to sustain cluster structure. The authors consider the balance between the number of idle common channels within cluster and cluster size and propose an algorithm that increases the number of common channels within clusters. One drawback of this scheme is, in order to increase the number of common channels within clusters, the scheme excludes certain CR nodes from the formed clusters, so that isolated nodes have to form clusters themselves. Besides, this scheme leads to a high variance on the size of clusters, which is not desired in certain applications as discussed in [60, 22].

4.3 System Model

Let us consider a two dimensional area where primary and secondary users coexist together.

Spectrum sensing and etiquette

The set of primary users and secondary users are presented by $\mathcal{P}$ and $\mathcal{N}$ separately, and there are $|\mathcal{P}| = P$ and $|\mathcal{N}| = N$. The collection of non-overlapping licensed frequency bands is denoted as $\mathcal{F}$ with $|\mathcal{F}| = F$. We assume that primary users have a relatively low variation in activity (periods of activity and inactivity in the range of seconds or minutes). CR users have the same transmission range on both licensed and control channel. Primary users also have fixed transmission range on the licensed channels[2]. As to two secondary users, if the distance in between them is smaller than secondary users' transmission range, we assume the pair is able to communicate on both control channel and licensed channel, and the both are considered to be neighbours of each other.

Primary users access the allocated channels in $\mathcal{F}$ according to its need without sending any explicit notification to secondary users. Secondary users conduct spectrum sensing independently, by which the secondary users validate the channels to be available or not. [3] The available channels sensed on secondary user i is denoted by V_i and $|V_i| \leq F$.

Any user outside the transmission range of the transmitter can not receive data from it, i.e., any CR user outside primary users' transmission ranges can not detect their existence, whereas a CR user can always communicate with CR sender, or detect the operating primary user, when it locates within the CR sender or the operating primary user's transmission range. As the transmission range of primary users is limited and secondary users are at different locations, secondary users have different views on the occupancy of the spectrum (apart from the fact that there might be false negatives in the sensing process), i.e., $V_i \neq V_j$, for $i \neq j$. One control channel[4] is assumed to be available for the CR nodes to exchange control messages in the process of cluster formation. The transmission range of CR user on control channel is identical with that on licensed channel. Over the control channel, secondary users exchange their spectrum sensing results V_i with one hop neighbours.

Cognitive radio network

Cognitive radio network is constituted by all the secondary users in $\mathcal{N}$. When licensed channels are available on two neighbouring secondary nodes in the same time, payload

[2]This assumption is made to simplify the discussion, and doesn't affect the effectiveness of the proposed scheme

[3]The spectrum availability can be validated with a certain probability of detection. Spectrum sensing/validation is out of the scope of this thesis.

[4]Note that the assumption on control message is only to simplify the discussion so that we can focus on the kernel of this chapter, robustness of clusters. The control messages involved during the clustering process can be conveyed on available licensed channels, e.g., with channel hopping [129]. Control message can be served by ISM band or other reserved channels which are exclusively used for transmitting control messages.

communication can be conducted on one or multiple licensed channels. Due to the assumed $0/1$ state of connectivity solely based on distance between CR users, the CRNcan be represented by a connectivity graph $\mathcal{G}(I, \mathcal{E})$, where $\mathcal{E} = \{(i, j, v)|i, j \in \mathcal{N} \wedge v \in V_i \wedge v \in V_j\}$ is wireless link between any secondary node i and its neighbour j with licensed channel v. Due to relatively low primary user dynamics, time index is omitted here.

For secondary node i in CRN, its neighborhood Nb_i consists of all the secondary users locating within its transmission range (links are assumed to be reciprocal), regardless whether common licensed channels exist or not. In the rest of this chapter, *channel* only refers to the licensed spectrum except when control channel is particularly mentioned.

Clustering

A cluster C is composed with one cluster head and cluster members, which satisfies the following conditions:

- Cluster head H_C is able to communicate with any cluster member directly, i.e., for any cluster member $i \in C$, there is $i \in Nb_{H_C}$.
- There exists as least one common licensed channel for the cluster, i.e., $\cap_{i \in C} V_i \neq \emptyset$.

Cluster head coordinates the activities of cluster members, i.e., notifies all the members to evade a channel if the channel is sensed by one cluster member to be occupied by primary users, or notify the members to use a different channel for payload communication. Cluster is denoted as C_i when its cluster head is i. We refer to the common channels within a cluster C by the term *inner common channels* (ICC) and denote this set of channels by set K_C. $K_C = \cap_{i \in C_i} V_i$, and $k_C = |K_C|$ is the number of common channels for cluster C. As the CR users are potentially mobile, clustering is performed with some periodicity, but obviously not more often than spectrum sensing.

4.4 Distributed Coordination Framework: Clustering Algorithm

In this section, we present the new clustering scheme named ROSS (RObust Spectrum Sharing). It is based on the local sensing results V_i of all CR users i and utilizes local similarity of the available channels to form clusters. ROSS consists of two cascaded phases: *cluster formation* and *membership clarification*. We will describe both phases sequentially.

4.4.1 Phase I - Cluster Formation

After spectrum sensing and communication with neighbours, every CR node is aware of the channel availabilities on itself and all its neighbours. We propose two metrics for each CR node to characterize the channel availability between it and its neighborhood.

Symbol	Description
$\mathcal{P}$, $\mathcal{N}$	complete collection of primary and secondary users
$\mathcal{F}$	set of non-overlapping channels in the scenario
Nb_i	node i' neighborhood
C	a cluster
V_i	set of available channels on CR node i
V_C	set of available common channels of cluster C
V_{C_i}	set of available common channels of cluster C whose cluster head is i
C_i	a cluster whose cluster head is i
	there is an exception: in Section 4.5, C_i is ith cluster among the legitimate clusters.
H_C	cluster head of a cluster C
δ	desired cluster size
S_i	set of claiming clusters, each of which includes
	debatable node i after phase I
K_{C_i}	set of common channels within cluster C_i
k_{C_i}	number of common channels of cluster C_i

Table 4.1 Notations in robust clutering problem

Individual connection degree D_i: $D_i = \sum_{j \in Nb_i} |V_i \cap V_j|$, which denotes the sum of the pairwise common channels of node i, and is an indicator of node i's adhesive property to the CRN.

Social connection degree G_i: $G_i = |\bigcap_{j \in Nb_i} V_j|$, which is the number of common channels in Nb_i. G_i represents the ability of i's neighborhood to form a robust cluster. Figure 4.1 illustrates an example CRN where the corresponding individual and social connection degrees are specified for each node.

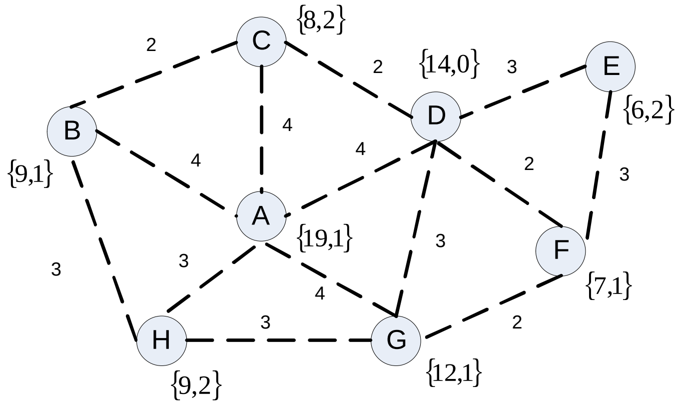


Figure 4.1 Connectivity graph and the connectivity vector $\{D_i, G_i\}$ on each node. The available channels sensed by each CR node are: $V_A = \{1,2,3,4,5,6,10\}, V_B = \{1,2,3,5,7\}, V_C = \{1,3,4,10\}, V_D = \{1,2,3,5\}, V_E = \{2,3,5,7\}, V_F = \{2,4,5,6,7\}, V_G = \{1,2,3,4,8\}, V_H = \{1,2,5,8\}$. Dashed lines indicates two end nodes are within transmission range of each other. Each edge is labelled by the number of common channels between the two ends.

The algorithm of phase I can be sketched like this: cluster heads are determined firstly, accordingly clusters are formed with cluster head's neighbourhood.

Determining Cluster Heads

In this phase, each CR node decides whether it is cluster head by comparing relevant metrics with its neighbours. Briefly speaking, the CR node which has the biggest *individual connection degree* in its neighbourhood excluding already decided cluster heads becomes cluster, i.e., CR node i becomes cluster head if $D_i < D_k, \forall k \in Nb_i \setminus CHs$ (CHs donate the cluster heads existing in Nb_i). If there is another CR node j in its neighborhood has the same *individual connection degree*, i.e., $D_j = D_i$, furthermore $D_j < D_k, \forall k \in Nb_j \setminus \{CHs \cup i\}$, then the node out of $\{i, j\}$ with higher *social connective degree* becomes cluster head, and the other one becomes member of it. If $G_i = G_j$ as well, node ID is used to break the tie, i.e., the one with smaller node ID takes precedence and becomes cluster head.

The pseudo code of phase I of clustering is in Algorithm 2.

Initial Cluster Formation

After deciding itself being cluster head, CR node broadcasts to notify its neighbours on control channel, meanwhile, i's initial cluster is formed immediately, which is i's neighborhood except for those nodes which have become cluster heads, i.e., $C_i = (Nb_i \setminus CHs) \cup i$. It is possible that the formed cluster doesn't poses inner common channel, this can be handled in the following way. As smaller cluster size increases the number of common channels within the cluster, certain nodes are eliminated until there is at least one common channel. The elimination of nodes is performed according to an ascending list of nodes sorted by their number of common channels with the cluster head, which means, the cluster member which has the least common channels with the cluster head will be excluded first. If there are nodes having the same number of common channels with cluster head, the node whose elimination brings in more common channels will be excluded. If this criterion meets a tie, the tie will be broken by deleting the node with smaller ID. It is possible that the cluster head excludes all its neighbours and resulting itself to be the cluster. Figure 4.1 depicts an example how CR nodes decide cluster heads. Node B and H have same individual connection degree, $D_B = D_H$, but as $G_H = 2 > G_B = 1$, node H becomes cluster head. In Figure 4.1, the cluster C_H is $\{H, B, A, G\}$.

As to the nodes eliminated in this procedure, they become either cluster heads or get included into other clusters later on, which is addressed in the following.

After receiving the notification from a cluster head, a CR node is aware it is one member in a cluster, then the CR user changes its individual connection degree to be a big positive value M (can be regarded as a positive infinite value), which is bigger than all the possible individual connectivity degrees in the CR network. Then this CR user broadcasts this new individual connection degree to all its neighbours. If a CR node i is associated to multiple clusters, D_i is still set to M. When the cluster member is excluded from the cluster, its individual connection degree is restored to the original value which is further broadcast to its neighbours. The purpose of manipulation on individual connection degree is to make the CR nodes out side this cluster possible to become cluster heads, so that every CR node either becomes cluster head or a member of at least one cluster. The final states of all the CR users in the CRN are described in the following theorem.

Lemma 1. *Every node in CRN will be included into at least one cluster in phase I in finite steps.*

Algorithm 2: Cluster head determination and cluster formation

Input: Unclustered CR node i which is aware of D_j and G_j, $j \in Nb_i$, and the ID of CRs which have be decided to be cluster heads, ID_{CH}, $CH \in Nb_i$. Empty sets $\tau_1, \tau_2, \tau_3, \tau_4, \tau_5$

Result: Whether or not i is cluster head

for *CR node* $j \in Nb_i \setminus CHs$ **do**
  if $D_i == D_j$ **then**
    $\tau_1 \leftarrow j$
  else
    if $D_j < D_i$ **then**
      $\tau_2 \leftarrow j$
    end
  end
end
if $\tau_2 \neq \emptyset$ **then**
  i is not CH; break;
else if τ_1 *is* $\emptyset$ **then**
  i is CH; break;
else
  /* $\tau_1 \neq \emptyset, \tau_1 == \emptyset$ */
  for $\forall k \in \tau_1$ **do**
    if $\nexists m \in Nb_k \setminus CHs$, *such that* $D_m < D_k$ **then**
      $\tau_3 \leftarrow k$
    end
  end
  if τ_3 *is* $\emptyset$ **then**
    i is CH;break;
  else
    for $\forall n \in \tau_3$ **do**
      if $G_n > G_I$ **then**
        $\tau_4 \leftarrow n$
      else
        if $G_n == G_i$ **then**
          $\tau_5 \leftarrow n$
        end
      end
    end
    if $\tau_4 \neq \emptyset$ **then**
      i is not CH;break;
    else if τ_4 *is* $\emptyset$ *and* $\tau_5 \neq \emptyset$ **then**
      if $ID_i < ID_r, \forall r \in \tau_5$ **then**
        i is CH;break;
      end
    else
      i is CH;break; /* τ_4 and τ_5 are $\emptyset$ */
    end
  end
end
if i *is cluster head* **then**
  $D_j, j \in Nb_i \setminus CHs$ is changed as a big positive value M;
end

Proof. To see this, assume there are some nodes not assigned to any cluster and node α is one of them. As node α is not contained in any cluster, there must be at least one node $\beta \in Nb_\alpha$, with $D_\beta < D_\alpha$. Thus, node β has at least one neighbouring node γ with $D_\gamma < D_\beta$, and this series of nodes with monotonically decreasing D_i might continue but finally ceases because the total number of nodes is limited. Now we find the last node ω in this series, because ω is the end node and does not have neighbouring nodes with smaller connectivity degree D, so ω will become a cluster head and embrace all its one-hop neighbours, including the node before it in the node series (here we assume that every new formed cluster has common channels). After that, the node recruited into cluster will set its connectivity degree D to M, which enables the node further down in the list to become a cluster head. In this way, all the nodes in the series are included in at least one cluster in an inverse sequence. This clearly contradicts the initial assumption and proves the claim stated above. The proof implicitly shows that, within $|I|$ steps, all nodes will become a part of certain clusters and so phase I converges. □

According to Lemma 1, we can assign reasonable amount of time for phase I to complete. The pseudo code for cluster head to obtain at least one common channel is shown in Algorithm 3.

Cluster Size Control in Dense CRN

In the introduction section, we have stated that cluster size should be given consideration to justify the pursuing of robust clusters, here we illustrate the pressing necessity to control cluster size when CRN becomes dense via theoretical analysis and simulation, and provide solution to it.

Assume CR nodes and primary users are evenly distributed and primary users occupy the licensed channels randomly, i.e., both CR nodes density and channel availability in the CRN is homogeneous. Based on Algorithm 2, cluster heads are the CR nodes which poses the biggest individual connection degree in their neighborhood, and they are surrounded by CR nodes. In contrast, CR nodes residing on edge are unlikely to become cluster heads as their neighbourhoods are only half the nodes locating away from edge. The clusters formed are the neighborhood of cluster heads, which is decided by the transmission range and network density. When this CRN becomes extremely dense, assume one cluster is formed by CR node i, based on the rule for cluster head selection Algorithm 2, the nearest cluster head generated could locate just outside the neighborhood or transmission range of i, which is as Figure 4.2 shows. In the figure, black dots represent cluster heads, the circles denotes the transmission ranges of those cluster heads. Cluster members are not shown in the figure. Let l be the length of side of simulation plan square, and r be CR's transmission radius. Based on the aforementioned analysis and geometry illustration as Figure 4.2, we give an estimate on the maximum number of generated clusters as l^2/r^2.

Now we show the estimation is valid with simulation. We distribute CR users and primary users randomly on a square plan, and set $r = 10, l = 50$. Network density is increased by adding more CR users. For each network scale, simulation is run for 50 times. Figure 4.3 shows the number of formed clusters. With the increase of CR users in the network, network density increases linearly (see the right hand side Y axis, which indicates the number of neighbours.), and the number of formed clusters also increases and approaches

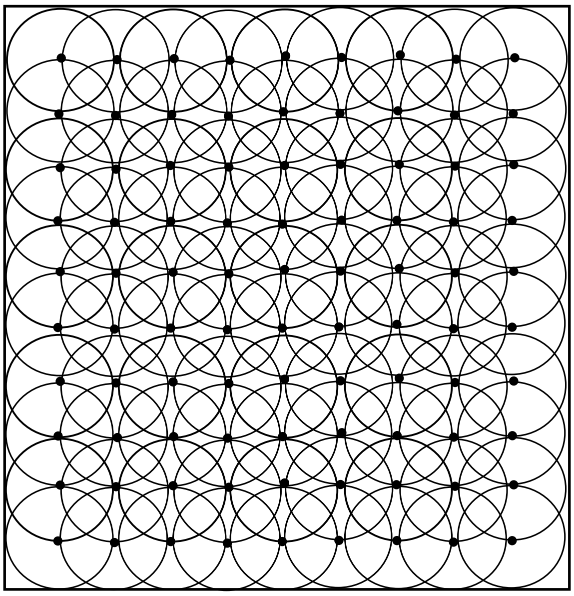


Figure 4.2 Clusters formation in extremely dense CRN. Black dots are cluster heads, cluster members are not drawn.

to the the upper bound of 25 which complies with the estimation. The confidence rate is 95% in the figure.

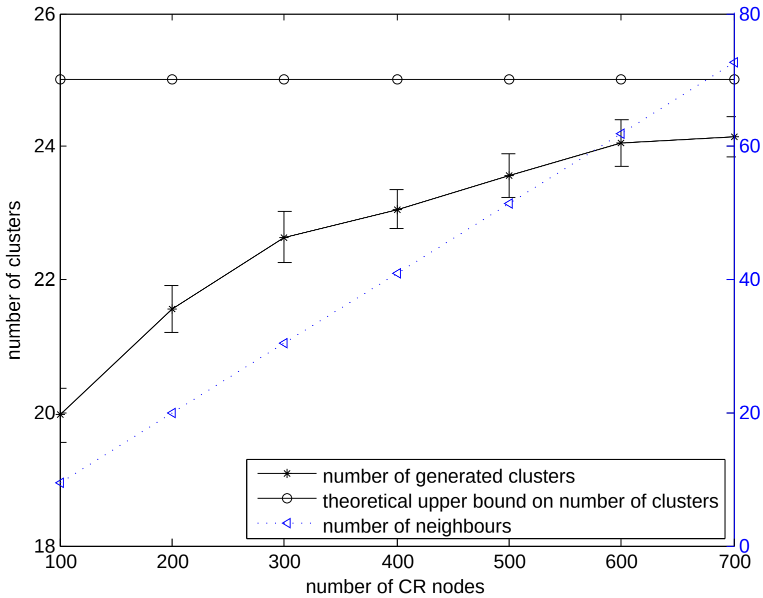


Figure 4.3 Number of clusters formed

Both the analysis and simulation show that with the increase of network density, the cluster size also increases. In case of dense network where cluster size is big, there will be heavy burden on cluster heads to manage their clusters, which is a challenge for resource limited cluster heads, besides [xxxxx]. As a result, certain measures are needed to prevent the network size to increase with the increasing network density. This task falls on cluster head. To control cluster size, cluster heads prune their cluster members if sizes are greater than the desired size δ. Given desired size as δ, cluster head excludes members sequentially, whose absence leads to the maximum increase of common channels within the cluster. This process ends when the size of resultant cluster is at most δ and at least one CCC is available. This procedure is similar with guaranteeing CCC available to be available in cluster, thus the algorithm is also given in Algorithm 3.

Algorithm 3: ICC guarantee and cluster size control by cluster head

Input: Initial cluster formed, empty sets $\mathcal{T}_1, \mathcal{T}_1$

Output: cluster has at least CCC, and satisfies the requirement on cluster size

`/* When available CCC is to be guaranteed, execute line 1, when cluster size control is conducted, execute line 2 */`

1 **while** $V_C = \emptyset$ **do**
2 **while** $|C| > \delta + 1$ **do**
3   calculate $\lambda = \min_{i \in C, i \neq H_C}(|K_{H_C} \cap K_i|)$;
4   **for** *each* $i \in C \setminus H_C$ **do**
5   **if** $|V_{H_C} \cap V_i| == \lambda$ **then**
6             $\mathcal{T}_1 \leftarrow i$
7   **end**
8   **end**
9   **if** $|\mathcal{T}_1| == 1$ **then**
10   delete node i from C;
11   break;
12   **else**
13   calculate $\mu = \mathrm{Max}_{i \in \mathcal{T}_1}(|\cap_{j \in C \setminus i} V_j| - |\cap_{j \in C} V_j|)$;
14   **for** *each* $i \in \mathcal{T}_1$ **do**
15   **if** $|\cap_{j \in C \setminus i} V_j| - |\cap_{j \in C} V_j| == \mu$ **then**
16                 $\mathcal{T}_2 \leftarrow i$
17   **end**
18   **end**
19   **if** $|\mathcal{T}_2| == 1$ **then**
20   delete node i from C;
21   break;
22   **else**
23   delete $i \in \mathcal{T}_2$, which has the highest ID;
24   **end**
25   **end**
26 **end**

4.4.2 Phase II - Membership Clarification

After applying ROSS phase I on the example in Figure 4.1, we get the clusters shown in Figure 4.4. We notice there are several nodes, i.e., A, B, D, are included into more than one cluster. We refer these nodes as *debatable nodes* as their cluster affiliations are not clear, and the clusters which include debatable node i are called *claiming clusters* of node i, and are represented as S_i. Actually, debatable nodes extensively exist in CRN with larger scale. Figure 4.5 shows the percentage of debatable nodes increases with the scaling of CRN network.

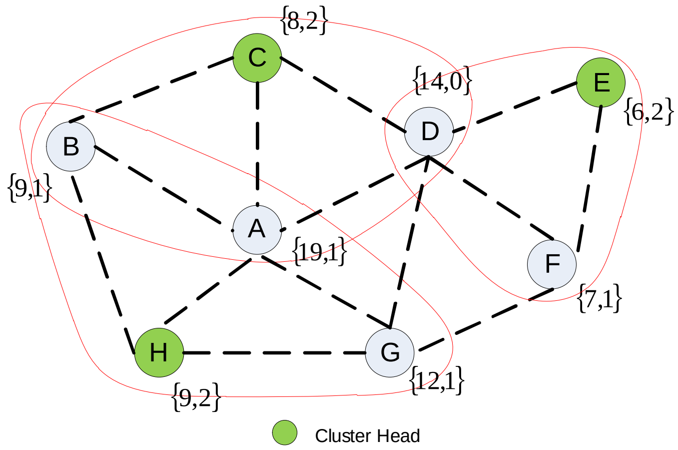


Figure 4.4 Clusters formation after the first phase of ROSS. Some nodes remain debatable nodes after the first phase.

Debatable nodes should be exclusively associated with one cluster and removed from the other claiming clusters, this procedure is called cluster membership clarification. We will introduce the solution for cluster membership clarification in the following.

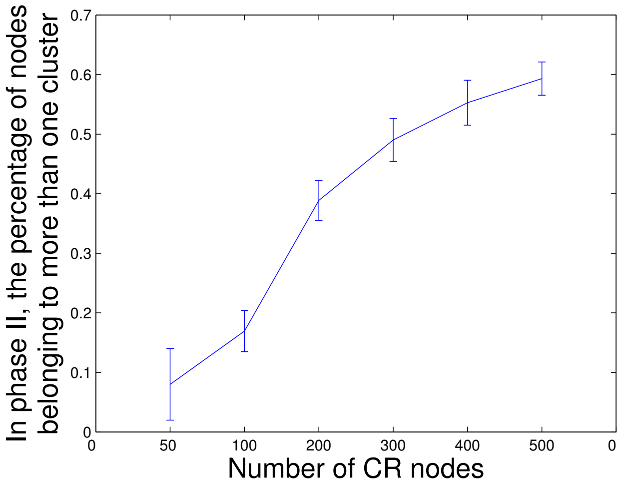


Figure 4.5 Clusters formation after the first phase of ROSS. Some nodes remain debatable nodes after the first phase.

Distributed Greedy Algorithm (DGA)

After Phase I, debatable nodes, e.g., i needs to decide which cluster $C \in S_i$ to stay, and leaves the others. The principle for debatable node i to choose one claiming cluster is to result in the greatest increase of common channels in all its claiming clusters. Node i communicates with all the cluster heads whose clusters are in S_i, and is aware of the vector of common channels of the claiming clusters, then i is able to calculate how many more common channels in one certain claiming cluster if i leaves that cluster. Based on this calculation, i decides in which claiming cluster to stay and leaves the other claiming clusters. If there exists one cluster $C \in S_i$, by leaving from which the clusters in S_i obtain the minimum increased common channels than leaving any other claiming clusters, then

i chooses to stay in cluster C. When there comes a tie in terms of the increase of common channels among multiple claiming clusters, i chooses to stay in the cluster whose cluster head shares more common channels with i. In case there are multiple claiming clusters demonstrating the same on the aforementioned metrics, node i chooses to stay in the smallest claiming cluster. IDs of cluster heads will be used to break tie if the previous rule doesn't decide on the unique cluster to stay.

Algorithm for debatable node i to decide which claiming cluster to stay is described as Algorithm 4. To conduct Algorithm 4, debatable node i needs to know the necessary information about its claiming clusters, i.e., V_C, V_{H_C}, $|C|$,$C \in S_i$, which are respectively the set of available channels in C, the set of available channels on C' cluster head H_C, and C' cluster size. Node i decides which cluster to stay based on Algorithm 4, then notifies all its claiming clusters, and retrieves the updated information of the necessary information V_C, V_{H_C}, $|C|$, where $C \in S_i$.

This procedure raises the concern on infinite chain effect that debatable nodes update their choices based on other debatable nodes' choices, and never cease. Assume debatable node i locates in one cluster $C \in S_i$, and C could have more than one debatable node except for i. Let i our of C's debatable nodes to make decision on the cluster to stay first. Then the choices of those debatable nodes except for i change C's membership, which possibly further triggers node i to alter its previous decision. Thus, we must answer this question raised when implementing ROSS-DGA. In the following we show that the process of membership clarification can be converted to a congestion game, and a equilibrium state is reached after a finite number of best response updates.

Bridging ROSS-DGA with Congestion Game

In this part, we illustrate that when debatable nodes decide on the exclusive clusters to stay, in particular, the To formulate the problem of membership clarification for the debatable nodes in the context of a game, we look at the problem from a different perspective. In the new perspective, the debatable nodes are regarded as isolated and don't belong to any cluster, which means the clusters they used to belong to become their neighbouring clusters. Then as to each debatable node, the previous problem to decide which clusters to leave becomes a new problem that which cluster to join. In this new problem, debatable node i (note now $i \notin S_i$) chooses one cluster C out of S_i to join if the decrement of common channels in cluster C is the smallest in S_i, and the decrement of number of ICC in cluster C is $\sum_{C \in S_i} \Delta|K_C| = \sum_{C \in S_i}(|K_C| - |K_{C \cup i}|)$. The relation between debatable nodes and claiming clusters is shown in Figure 4.6.

In the following, the debatable nodes constitute the players, and the we show that the decision of debatable nodes to clarify their membership can be mapped to the behaviour of the players in a *player-specific singleton congestion game* when proper cost function is given.

The game to be constructed can be represented by a 4-tuple $\Gamma = (\mathcal{P}, \mathcal{R}, (\sum_i)_{i \in \mathcal{N}}, \Delta|K_C^i|)$, where elements in Γ are given as below,

- $\mathcal{P}$, the set of players of the game, which are the debatable nodes after phase I in our clustering problem.

Algorithm 4: Debatable node i decides its affiliation, chooses one claiming cluster to stay and leaves all the other claiming clusters

Input: all claiming clusters $C \in S_i$
Output: one cluster C

```
calculate λ = Min_{C∈S_i}(|K_{C\i}| − |K_C|);
define set 𝒞_1;
for each C ∈ S_i do
    if |K_{C\i}| − |K_C| == λ then
        𝒞_1 ← C
    end
    /* metric is the increase of CCCs due to i′ departing */
end
if |𝒞_1| == 1 then
    choose cluster C;
    break;
else
    calculate μ = Max_{C∈𝒞_1}(V_{H_C} ∩ V_i);
    define set 𝒞_2;
    for each C ∈ 𝒞_1 do
        if V_{H_C} ∩ V_i == μ then
            𝒞_2 ← C
        end
        /* metric is the number of common channels between i
        and cluster head of demanding cluster */
    end
    if |𝒞_2| == 1 then
        choose cluster C;
        break;
    else
        calculate ν = min_{C∈𝒞_2} |C|;
        define set 𝒞_3;
        for each C ∈ 𝒞_2 do
            if |C| == ν then
                𝒞_3 ← C
            end
                                        /* metric is cluster size */
        end
        if |𝒞_3| == 1 then
            choose cluster C;
            break;
        else
            choose the C ∈ 𝒞_3, which has the highest ID;
        end
    end
end
Node i notifies H_C which is cluster head of C of its affiliation decision, cluster C
then accepts it.
```

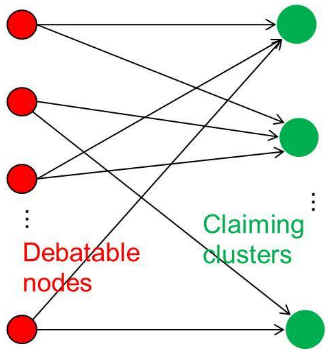


Figure 4.6 debatable nodes and claiming clusters

- $\mathcal{R} = \cup S_i, i \in \mathcal{P}$, denotes the set of resources for players to choose, S_i is the set of claiming clusters of node i. $\mathcal{R}$ is the set of claiming clusters after phase I in our clustering problem.

- As to the strategy space $\sum_i$ of player $i \in \mathcal{N}$, there is $\sum_i \subseteq 2^{[S_i]}$. As one debatable node is supposed to choose one claiming cluster in our problem, thus only one resource is allocated for i, accordingly this congestion game is a singleton game.

- The utility (cost) function $f(C)$ of resource $C \in R$, (or to say $f(r)$ of resource $r \in \mathcal{R}$) is $\Delta|K_C^i|$ which represents the decrement of ICCs in cluster C caused by debatable node i' joining in it. As to cluster $C \in S_i$, the decrement of ICCs caused by enrolment of debatable nodes is $\sum_{i:C \in S_i, i \to C} \Delta|K_C^i|$. $i \to C$ means i joins in cluster C. Obviously this function is non-decreasing with respect to the number of nodes joining in cluster C.

  The utility function is not purely decided by the number of players (debatable nodes) as that in a canonical congestion game, as in this game the channel availability on debatable nodes is different. Given two same sized groups of debatable nodes, when the nodes are not completely the same (neither are the channel availabilities on these nodes), the cost happened on one claiming cluster could be different if the two groups of debatable nodes join in that cluster respectively. Hence, this game is called player specific. In this game, every player greedily updates its strategy (choosing one claiming cluster to join) if joining in a different claiming cluster minimizes the decrement of ICCs $\sum_{i:C \in S_i} \Delta|K_C^i|$, player's strategy in the game is exactly the same with the behaviour of debatable node in membership clarification phase, which is described by Algorithm 4.

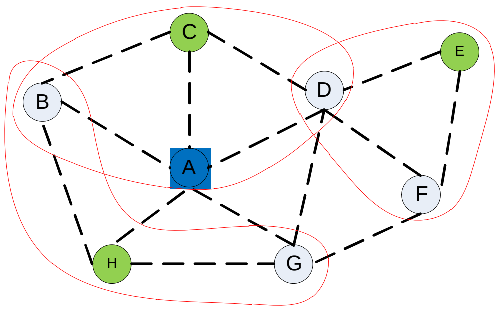
As to singleton congestion game, there exists pure equilibria which can be reached with greedy update [14].

Based on above model and analysis, phase II converges is Algorithm 4 is run by debatable nodes.

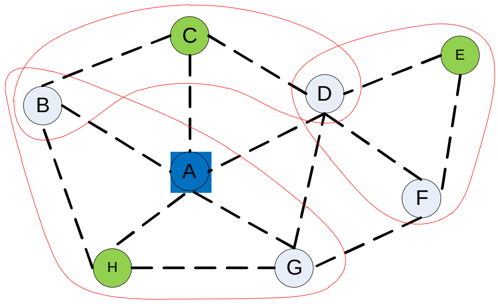
Distributed Fast Algorithm (DFA)

The complexity of DGA is quite large recalling that the formation of clusters takes at most $|I|$. Here we propose a faster algorithm DFA which is especially suitable for CRN where channel availability might change dynamically and re-clustering is possible. In DFA, each debatable node executes only one iteration of Algorithm 4 (by setting 'the current value' in Line 14 to zero). Every cluster includes all its debatable nodes, thus the membership is static and debatable nodes can make decisions simultaneously without considering the change of membership of its claiming clusters. For example, for node A in Figure 4.4, the membership of cluster $C_C, C_H \in S_A$ are $\{A, B, C, D\}$ and $\{A, B, H, G\}$ respectively.

The two possible strategies of node A's clarification is illustrated in Figure 4.7. In Figure 4.7(a), node A staying in C_C and leaving C_H brings 2 more ICC in S_A, as it is more than that brought by another strategy showed in 4.7(b), A's membership is clear. After the decisions made similarly by the other debatable nodes B and D, the final clusters formed are shown in Figure 4.8.



(a) Node A stays in cluster C_C, quits C_H, $\Delta|K_{C_C}| + \Delta|K_{C_H}| = 2$



(b) Node A stays in cluster C_H, quits C_C, $\Delta|K_{C_C}| + \Delta|K_{C_H}| = 1$

Figure 4.7 Membership clarification: possible cluster formations decided by node A's different choices

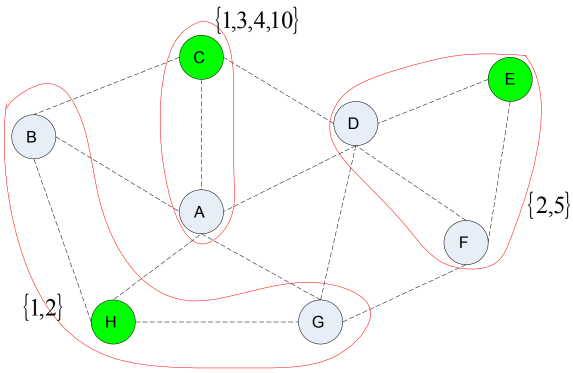


Figure 4.8 Final formation of clusters, common channels for each cluster is shown.

4.5 Centralized Clustering Scheme

The centralized clustering scheme aims to form clusters with certain sizes, meanwhile the total number of common channels of all clusters is maximized. In the following, we refer this problem as *centralized clustering* for short, and the problem definition is as follows,

Definition 1. *Centralized clustering in CRN.*

Given a cognitive radio network $\mathcal{N}$ where nodes are indexed from 1 to N sequentially. Based on certain correlation, certain secondary users constitute one cluster C. $1 \leq |C| \leqslant k$ where $|C|$ is size of cluster C and k is positive integer. We name the collection of such clusters as $\mathcal{S} = \{C_1, C_2, \ldots, C_{|\mathcal{S}|}\}$ (the subscript i is the unique index of cluster in $\mathcal{S}$, not the ID of cluster head of relevant cluster), $\mathcal{S}$ has following properties: $\bigcup_{1 \leq i \leq l} C_i = N$ and $V_{C_i} \neq \emptyset$ for any i which satisfies $1 \leq i \leq l$.

Following condition distinguish the centralized clustering problem discussed in this thesis. The number of common channels is denoted as f which is $|V_C|$ if $|V_C| > 1$, and $f = 0$ if $|V_C| = 1$. The question of this problem is to find a subcollection $\mathcal{S}' \subseteq \mathcal{S}$, so that $\bigcup_{C_j \in \mathcal{S}'} C_j = N$, and $C_j' \cap C_j = \emptyset$ for $C_j', C_j \in \mathcal{S}'$, so that $\sum_{C \in \mathcal{S}'} f$ is maximized. The decision version of centralized clustering in CRN is to ask whether exist $\mathcal{S}' \subseteq \mathcal{S}$, so that $\sum_{C \in \mathcal{S}'} f \geqslant \lambda$ where λ is a real number.

In the following part of this section, we will discuss the complexity of centralized clustering problem and provide solution for it. We put the definition of weighted k-set packing problem here as it will be used in the analysis on the complexity of our problem.

Definition 2. *Weighted k-set packing.*

Given a set $\mathcal{G}$ which contains finite number of positive integers, and a collection of set $\mathcal{Q} = \{s_1, s_2, \cdots, s_m\}$, where for each element $s_r, 1 \leq r \leq m$, there is $s_r \subseteq \mathcal{G}$, $1 \leq |s_r| \leq k$, and s_r has an associated weight which is positive real number. The question is whether exists a collection $\mathcal{S} \subseteq \mathcal{Q}$, where $\mathcal{S}$ contains only disjoint sets and the total weight of sets in $\mathcal{S}$ is greater than λ. Weighted k-set packing is NP-hard when $k \geqslant 3$. [49]

Theorem 4.5.1. *CRN clustering problem is NP-hard, when the maximum size of clusters $k \geqslant 3$.*

Proof. To see centralized clustering problem is NP-hard, we reduce the NP-hard problem *weighted k-set packing* to it.

To complete the reduction, we need to conduct following two steps:

- step 1: Show there exists a polynomial algorithm σ, by which any instance (e.g., $\mathcal{S}$) of a weighted k-set packing can be transformed to instance $\sigma(\mathcal{S})$ for centralized clustering.
- step 2: Show that $\mathcal{S}$ is a *yes* instance of weighted k-set packing if and only if $\sigma(\mathcal{S})$ is an *yes* instance for CRN clustering problem.

We continue using the notation introduced in problem definition. Let set $\mathcal{G}$ contains N positive integer numbers which are indexed from 1 to N sequentially. Assume one instance $\mathcal{S}$ of weighted k-set packing is a collection of disjoint sets $\mathcal{Q} = \{s_1, s_2, \cdots s_m\}$, each set is composed by certain amount of elements in $\mathcal{G}$. ω indicates the weight for each set s, $\omega : \mathcal{S} \to \mathbb{Z}^+$.

The polynomial algorithm σ consists of three transformations.

- In the first transformation, for each set s_i of instance $\mathcal{S}$, the elements are duplicated, for instance, given $s_i = \{1, 4, 6\}$, the dummy set s'_i is $\{1, 1, 4, 4, 6, 6\}$. By doing this, we obtain the dummy sets and constitute the dummy instance $\mathcal{S}'$ based on $\mathcal{S}$. The purpose of this transformation is to eliminate the single element set in $\mathcal{S}$. The weight of set is unchanged after this transformation, i.e., $\omega(s_i) = \omega(s'_i)$. After this transmission, there is no set with only one element. This transformation requires $\sum_{s_i \in \mathcal{S}} |s_i|$ steps.

- In the immediate following second transformation, we transform the dummy instance $\mathcal{S}'$ to an instance for CRN clustering problem. Given an instance $\mathcal{S}'$, we retrieve all the elements which appear in it, and map each of those elements into one CR node, i.e., each integer corresponds to one CR node, particularly, that integer becomes the CR node's ID. As to duplicated elements, we also map them into a CR node, thus there exist CR nodes with the same ID. As a result, these CR nodes constitute a collection of CR nodes, but note that they have not constituted one CRN yet as there are not connections drawn among them. Connections in CRN under this context is decided by physical conditions, which says the corresponding CR nodes have common channels and close enough to communicate with each other. This transformation requires $2 \cdot \sum_{s_i \in \mathcal{S}} |s_i|$ steps.

- Mere isolated nodes don't constitute network, thus we add connections in CRN based on the sets in $\mathcal{S}'$ sequentially. For each set $s' \in \mathcal{S}'$, we add connection between two CR nodes if their IDs are in s'. There is also connection between the CR node and its dummy node. The number of common channels of the CR nodes equals to the weight of set s'. No connection exists between two CR nodes if their IDs don't appear in one set in $\mathcal{Q}$. Afterwards, the CR node whose ID doesn't appear in any set in $\mathcal{S}'$ becomes single node clusters, according to the definition of clustering problem in CRN, the number of common channels is 0. This procedure requires $\sum_{s'_i \in \mathcal{S}'} |s_i|$ steps to map sets in $\mathcal{S}'$ into CRN and connections, and at most N steps to complement the single node clusters in CRN.

  The number of common channels of cluster f is non-decreasing function of cluster size, while, the weight of set in weighted k-set packing problem doesn't have this property. In weighted k-set packing, the weight of a set with smaller size could be larger than a set with more elements. But this difference doesn't hinder the transformation and we use an example to explain. Assume two sets in $\mathcal{S}$ are $s_1 = \{1, 2\}$ and $s_2 = \{1, 2, 3, 4\}$, their weights are 3 and 5 respectively. Their dummy sets are $s'_1 = \{1, 1, 2, 2\}$ and $s'_2 = \{1, 1, 2, 2, 3, 3, 4, 4\}$ and their new weights are 3 and 5 as before. The connections mapped to CRN are contradictory to reality, as the number of common channels of CR node group $\{1,1,2,2\}$ can only be smaller than that of $\{1,1,2,2,3,3,4,4\}$. We let this contradiction in the process of mapping happen because it will be eliminated later: no matter one instance $\mathcal{S}$ for weighted k-set packing results in *yes* or *no*, at most only one set of s_1' and s_2' is chosen, then we can safely delete the connections based on the deleted set from the CRN, and the contradiction is eliminated.

We have crossed the hurdle of finding one polynomial algorithm σ to transform instance of weighted k-set packing to an instance for clustering in CRN. Now we look into the step 2 in reduction.

When the instance $\mathcal{S}$ for weighted k-set packing contains one solution, i.e., there is a group of sets in $\mathcal{S}$, whose sum weights is greater than λ, then in the CRN which is mapped from $\mathcal{S}'$, the sum number of common channels of the clusters which correspond to the selected sets in $\mathcal{S}$ and $\mathcal{S}'$, is greater than λ.

When there is no solution out of set $\mathcal{G}$ for weighted k-set packing, let's assume the maximum sum of weights of all instances is $\sum_{s_i\in\mathcal{S}}\omega(s_i)=\delta<\lambda$. The dummy set of each $s_i\in\mathcal{S}$ is mapped to cluster of CR nodes. Definition of CRN clustering regulates that the number of common channels is 0 when the cluster has only one node. As to $|s_i|=1$, the mapped cluster has two nodes, with one of them is the dummy CR node. Then number of common channels is on longer 0 but equals to the weight of corresponding set s_i. Then the sum number of common channels of the clusters in CRN is $\delta<\lambda$, thus, there is no clustering solution for the mapped CRN.

After proving weighted k-set packing can be reduced to centralized clustering in CRN, we can say the latter problem is NP-hard. □

4.5.1 The Optimization Problem

As there is no efficient algorithm to solve clustering problem in CRN, we adopt binary linear programming to solve the problem. Note that binary linear programming is in NP-complete.

Given a CRN N and desired cluster size δ, we get a collection of clusters G, where clusters satisfy the conditions of clusters in Section 4.3, and the sizes of clusters are $1,2,\ldots,\delta$. Note that the legitimate clusters include the singleton ones, which guarantees the partition of any network is feasible. With $n=|N|, g=|G|$, we construct a $g\times n$ matrix Q_{gxn}. Each element $q_{ij}=|k_{C_i}|$ if $j\in C_i$, and $q_{ij}=0$ if $j\notin C_i$. In other words, Each non-zero element q_{ij} denotes the number of common channel of the cluster i where node j resides.

We also have one $G\times N$ binary matrix X, the element of the matrix is binary variable $x_{ij}, i=1,\ldots,G, j=1,\ldots,N$. $x_{ij}=1$ denotes cluster i is one partition chosen by the clustering scheme, $x_{ij}=0$ means this partition is not adopted.

$$\begin{array}{ll}\min\limits_{x_{ij}} & \Sigma_{j=1}^{g}\Sigma_{i=1}^{n}(-x_{ij}q_{ij}+w_i*\texttt{cost}(\delta))\\ \text{subject to} & \Sigma_{i=1}^{g}x_{ij}=1, j=1,\ldots,n\\ & \Sigma_{j=1}^{n}x_{ij}=\delta*(1-w_i), j=1,\ldots,g\\ & x_{ij}\text{ and }w_j\text{ are binary variables.}\\ & i\in\{1,2,\cdots g\},\quad j\in\{1,2,\cdots n\}\end{array}$$

$$
Q = \begin{array}{cc}
 & \begin{array}{cccccccc} 1 & 2 & 3 & \cdots & j & \cdots & n-1 & n \end{array} \\
\begin{array}{c} 1 \\ 2 \\ \vdots \\ i \\ \vdots \\ \vdots \\ g \end{array} &
\begin{pmatrix}
k_1 & k_1 & 0 & \cdots & \cdots & \cdots & 0 & 0 \\
k_2 & 0 & k_2 & \cdots & \cdots & \cdots & 0 & 0 \\
\vdots & & & \vdots & & \vdots & & \\
0 & k_i & 0 & \cdots & \cdots & \cdots & k_i & 0 \\
\vdots & & & \vdots & \cdots & \cdots & & \vdots \\
\vdots & 0 & 0 & \cdots & \cdots & \cdots & k_{i'} & 0 \\
k_g & & & \vdots & \cdots & \cdots & & \vdots
\end{pmatrix}
\end{array}
$$

Figure 4.9 Matrix Q,

As the resultant clusters are with certain desired sizes, we try to maximize the sum of products of cluster size and number of common channels in the objective function. The second item of objective function denotes the *punishment* for choosing the cluster whose size is not δ. We design `cost` (δ) as follows,

$$
\texttt{cost}\,(\delta) = \begin{cases} 0 & \text{if } |C_i| = \delta \\ \alpha_1 & \text{if } |C_i| = \delta - 1 \\ \alpha_2 & \text{if } |C_i| = \delta - 2 \\ \cdots & \end{cases}
$$

where $\alpha_i > 0$ and increases with i getting larger. Choice of α_i affects the resultant clusters.

Constraint 3.2 restricts that node j resides in exactly one cluster. In constraint 3.3, w_j is an auxiliary binary variable, $w_j = 0$ denotes cluster j is chosen in the solution. When $w_i = 1$, ith cluster is not chosen according to constrain 3.3, then the objective function suffers certain *loss*.

This is a linear binary optimization problem, which is solved by function $bintprog$ provided in MATLAB.

Take CRN in Figure 4.1 for example. As $|N| = 8$, we let the cluster size δ to be either 2 or 3 so that the partition of network is possible. A collection of clusters G is built, where the clusters satisfy the conditions for cluster in Section 4.3 and the sizes of clusters are 1, 2 and 3. $G = \{\{A\}, \{B\}, \ldots, \{B, C\}, \{B, A\}, \{B, H\}, \cdots, \{B, A, C\}, \{B, H, C\}, \{A, D, C\}, \cdots\}$, and $G = 38$.

The clustering result of binary linear programming is $\{\{D, E, F\}, \{A, C, G\}, \{H, G\}\}$, the number of common channels is $\{2, 3, 3\}$. The solution from ROSS is $\{\{B, H, G\}, \{C, A\}, \{D, E, F\}\}$, the number of common channels is $\{2, 4, 2\}$. By applying SOC, the clustering result is $\{A, B, C, D, G\}, \{E, F\}, \{H\}$.

The final clusterings of the example CRN by SOC and linear programming are as follows,

As to the average number of common channel, the results of ROSS, LP and SOC are 2.66, 2.66, and 3 respectively. Note there is one singleton cluster C_H generated. When the singleton cluster $\{E\}$ is excluded, the average number of common channels of SOC drops to 2.5.

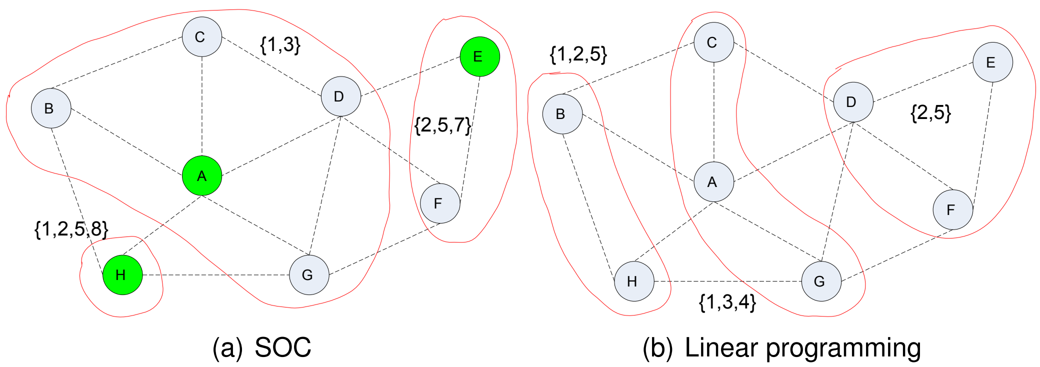


Figure 4.10 Final clustering of the example CRN

4.6 Performance Evaluation

In this section, we evaluate the performances of the two variants of ROSS, i.e., ROSS-DGA and ROSS-DFA, besides, the cluster size control scheme is also evaluated when the desired cluster size is smaller than the average neighbourhood size. We choose SOC as comparison scheme. To the best of our knowledge, SOC [71] is the only work emphasizing on the robustness of clustering structure from all previous work on clustering in CRN. The authors of [71] compared SOC with other schemes based on the average number of common channels within each cluster, on which SOC outperforms other schemes by 50%-100%. This is because the schemes except for SOC are designed either for ad hoc network without consideration of channel availability [28], or for CRN but just considering basic connection among CR nodes [132]. Hence, we only compare the two versions of our scheme ROSS-DGA and ROSS-DFA with SOC to show the merits of ROSS, and also compare with the centralized scheme to see the gap with the global optima. We will investigate the following metrics:

- Average number of common channels per un-singleton cluster.
  - SOC adopts the average number of common channel over all clusters, i.e., including the singleton clusters. As we try to look into the robustness of clusters of CRs, we exclude those singleton clusters.
- Number of unclustered CRs with moderate and vigorous intensity of PRs'activities.
  - This is the straight forward metric on robustness of clusters. We investigate how many clusters survives when we increase the intensity of PRs' activity.
- Cluster sizes
  - Specific clusters size is pursued in many applications due to energy preservation and the system design [60]. We will present the distribution of CRs residing in the formed clusters, and the number of generated clusters through multiple simulations.
- Number of clusters
  - Homogeneous clusters size is pursued.

- Amount of control messages involved.

The simulation is conducted with C++. Certain number of CR and PR nodes are deployed within a squire whose edge is 100 m. We adopt the round disk model [xxxx] to simulate transmission. Transmission ranges of CR and PR node are 10 and 30 respectively. As to CRs, the CR node residing within another CR node's transmission range is seen as neighbour of that CR node. If CR node locating within one PR node's transmission range, the CR node is not allowed to use the channel which is being used by that PR. The number of licensed channels in simulation is 10, each PR is operating on each channel with probability of 50%.

There are two parts of simulation, in the first part, we investigate the gap between the distributed schemes with the centralized scheme. As there is no polynomial time solution available to solve the centralized problem, we adopt a small network to compare the performances of the ROSS, SOC and the centralized solution. In the second part, we increase the network scale and change network density to thoroughly compare the two distributed schemes.

4.6.1 Centralized Schemes vs. Decentralized Schemes

Coinciding with the system model in Section 4.3, 10 primary users and 20 CR users are dropped randomly (with uniform distribution) within some area of size A^2, where we set the transmission ranges of primary and CR users to $A/3$. There are $P = 10$ available channels. With this setting, the average number of neighbours of one CR user is around 5. Each primary user randomly occupies one channel, and CR users are assumed to be able to sense the existence of primary users and identify available channels. When clustering scheme is executed, around 7 channels are available on each CR node. All primary and CR users are assumed to be static during the process of clustering. Performance results are averaged over 50 randomly generated topologies with equal parameters. The desired cluster size is 3. The confidence interval shown in figure corresponds to 95% confidence level.

Number of Common Channels

We first have a look at the average number of common channels per cluster, which is used in [76] as the sole criterion for clustering robustness. Figure 4.11 shows the average number of common channel of non-singleton clusters, as the singleton clusters (in other words unclustered nodes) don't execute any functionalities of clusters, which are described in Section 4.1. As to schemes, centralized schemes outperform distributed schemes on number of common channels. SOC achieves the most number of CCC than variants of ROSS. SOC is liable to group the neighbouring CRs which share the most abundant spectrum together, no matter how many of them are, thus the number of CCC of the formed clusters is higher, but this method leaves considerable number of CRs which have less spectrum not in any clusters. As to variants of ROSS, the procedure of debatable nodes greedily looking for better affiliation improves the number of CCC, thus ROSS-DGA with and without size control outperform ROSS-DFA and its size control version respectively. We also notice that, the size control feature doesn't affect the number of CCC for both ROSS-DGA and ROSS-DFA.

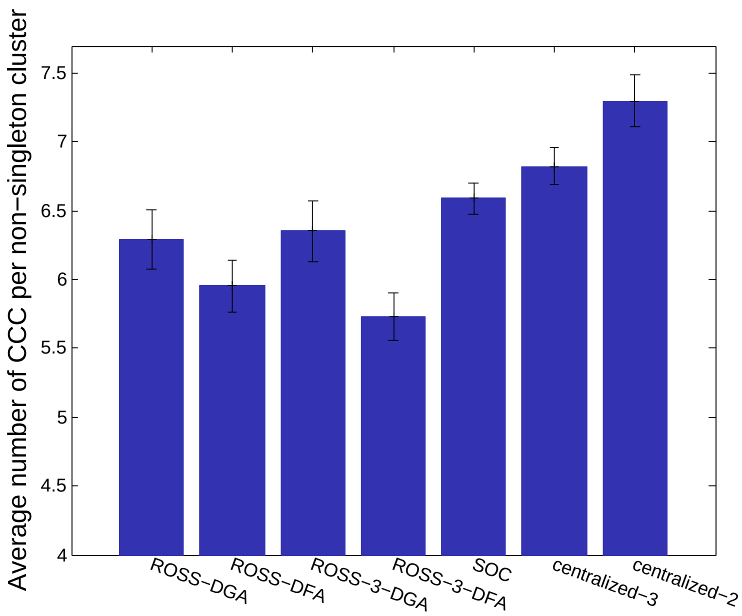


Figure 4.11 Number of common channels for non-singleton clusters, the numbers in the names of schemes annotate the desired cluster size.

Survival Rate of Clusters with Increasing PR Users

We investigate the robustness of the formed clusters when they co-exist with varying intensity of PRs' activities. After the clusters are formed under the influence of the initial 10 PRs, extra 100 PRs are sequentially added into the network. The transmission range and channel occupancy of the new PR is the same with the previous ones, i.e., transmission range is $A/3$, and one channel out of 10 is randomly chosen to operate. As to one cluster, if there is no common channels available for all members because of the new added PRs, the cluster destroyed, and the former cluster member CRs become unclustered CRs.

Figure 4.12 shows the number of unclustered CRs with the increase of PRs, which indicates the vulnerability of clusters under varying surrounding of licensed spectrum.

We obtain three conclusions corresponding to three comparisons shown in this figure,

- Centralized scheme with cluster size of 2 produces the most robust clusters, and SOC results in the most vulnerable clusters. Centralized scheme with cluster size of 3 achieves less unclustered CRs than variants of ROSS when the number of PRs is 10$\sim$30, when number of PUs is 30$\sim$60, same amount of unclustered CRs are generated with variants of ROSS. When there are 75 and more new PRs, centralized scheme with cluster size of 3 results in more unclustered CR nodes than variants of ROSS. Size control feature makes both ROSS-DGA and ROSS-DFA outperform themselves without size control when number of new PRs is greater than 50.

  The reason that centralized scheme with cluster size of 3 does not completely excel variants of ROSS is due to the favourable achievement of it: the uniformly sized clusters. As distributed schemes, variants of ROSS generate considerable amount of smaller clusters which are more likely to survive when PRs' activities become intense. The comparison on cluster sizes will be given in details in 4.6.1.

- ROSS with size control is better than the other two distributed schemes. The size control decreases the clusters size and makes the clusters more robust when under PRs' activity.

- Greedy algorithm improves survival rate. ROSS-DGA improves the survival rate of ROSS-DFA, so does ROSS-DGA with size control against ROSS-DFA with size control. This comply with the observation on number of CCC in section 4.6.1. As the debatable CRs greedily update their affiliation with demanding clusters, and the metric for updating is the maximum increase of CCCs of the demanding clusters, the average number of common channels is improved (shown in Figure 4.11), then the robustness of clusters is enhanced. Meanwhile, sizes of more clusters become smaller also contributes more robustness.

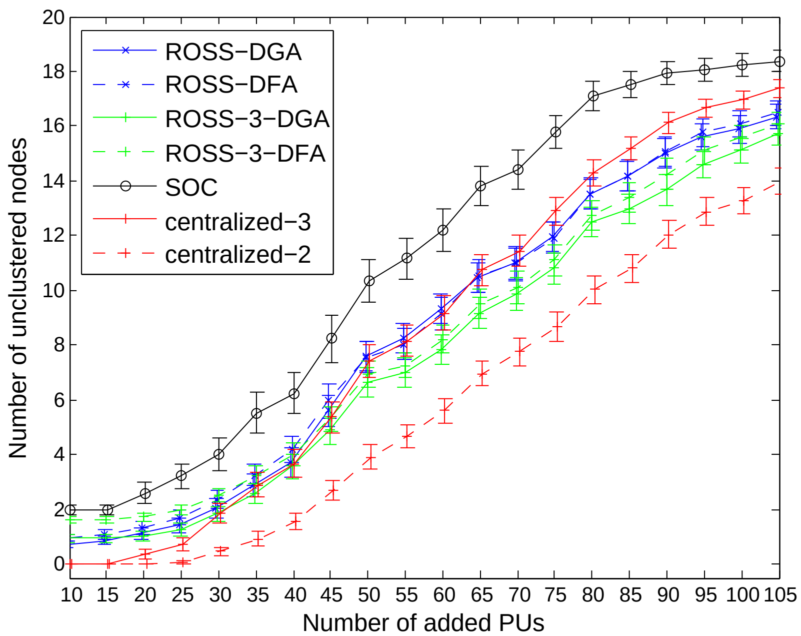


Figure 4.12 Number of CRs which are not included in any clusters

Cluster Size Control

Figure 4.13 shows the number of CRs residing in certain sized clusters. The centralized schemes are able to form clusters which strictly satisfy the requirement on cluster sizes. When the desired size is 2, each generated cluster has two members. When the desired size is 3, in average only 3 CRs are formed into 2 node clusters. When ROSS-3-DFA is applied, most number of CRs are in 3 node clusters, nevertheless, slightly less nodes are found in 2 node and 4 node clusters, there are also considerable number of singleton clusters. ROSS-3-DGA decreases the clusters sizes and results in more 2 node clusters, the second most CRs are found in 3 node clusters. ROSS-DGA and ROSS-DFA generate rather even distribution of nodes with different sizes, whereas SOC results in more CRs unclustered or clusters of large sizes. Figure 4.13 shows distributed clustering schemes are not able to control cluster sizes perfectly, but ROSS-DGA and ROSS-DFA eliminate the clusters whose size diverges largely with the desired one, i.e., single node clusters and clusters with size of 13 and 14. Particularly, size control enable both ROSS-DGA and

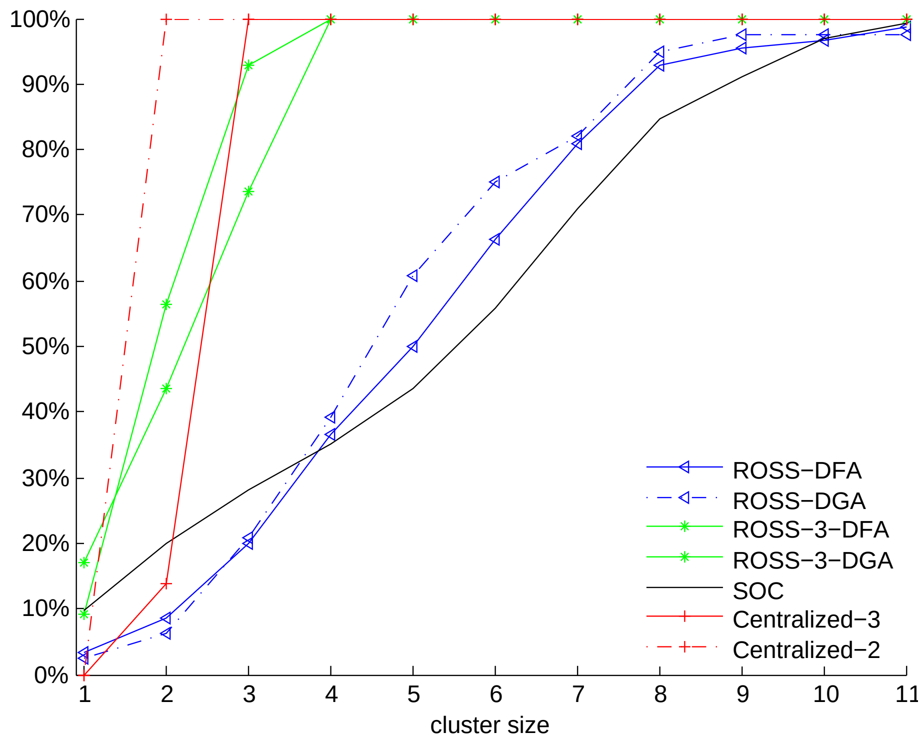


Figure 4.13 Distribution of CRs residing in clusters with different sizes, as to ROSS with size control feature, the desired cluster size is 3. The average number of neighbours is 4.838.

ROSS-DFA to achieve clusters whose sizes demonstrate certain homogeneity, i.e., cluster sizes vary from 1 to 4. But there are considerable number of single node clusters, which is due to the cluster pruning discussed in section 45.

Control Signalling Overhead

As to any variants of ROSS, there are two phases, in the first phase, clusters are formed, in the second phase, cluster membership is decided so that each node only resides in one cluster. Control message exchanges between CR nodes are involved in both phases.

In this section we compare the amount of control messages involved for clustering in different schemes, e.g., centralized scheme, ROC, ROSS-DGA, ROSS-DFA and those with size control feature. In order to highlight the amount of control signalling only for clustering, we omit the control messages used for neighbourhood discovery, which are regarded the same for all schemes, and only compare the number of control messages brought in by the features of the schemes. The control message here refers both broadcast and unicast.

As to variants of ROSS, in the first phase, after each node broadcasts their new knowledge on spectrum robustness, cluster is automatically formed by cluster head which is decided from consensus by comparing the spectrum robustness with neighbours, then the cluster head broadcasts message containing its ID and the available channels in its cluster. As to ROSS with size control feature, there are same amount of cluster heads with ROSS without enabling size control feature, and the cluster head broadcasts the available channels of the pruned cluster. Afterwards in the second phase, membership clarification of debatable nodes is conducted. Debatable node informs the cluster which it going to stay and the cluster head broadcasts message about its new cluster. As to SOC, each node needs to maintain one cluster, the final clusters are formed after three rounds of comparisons and cluster mergers, while as to ROSS, only debatable nodes need to communicate with cluster heads to clarify their membership.

Worst case protocol complexities. We assume that the protocols execute synchronously. We compare the Time Complexity (TC), defined as the number of steps required to perform a protocol operation, and the Communication Complexity (CC), defined as the number of broadcast in performing the operation.

The complexity parameters are the number of nodes n in network, number of clusters h.

The quantitative analysis of amount of control overhead and the size of messages are illustrated in Table 4.2,

Scheme	Number of broadcast	Content of message
ROSS-DGA, ROSS-x-DGA	$h+2*m^2c$ (upper bound)	ID_{H_C} and V_C for $h+m^2c$ times, notification to join in one cluster for m^2c times
ROSS-DFA, ROSS-x-DFA	$h+2m$ (upper bound)	ID_{H_C} and V_C for $h+m$ times, notification to join in one cluster for m times
SOC	$3*n$	$\{V_i\}, i \in M \subseteq Nb_i$
Centralized	n	$\{C\}$

Table 4.2 Singalling overhead. Notations: n-number of CR nodes in CRN, h-number of cluster heads, m-number of debatable nodes, c-number of demanding clusters, δ-desired cluster size

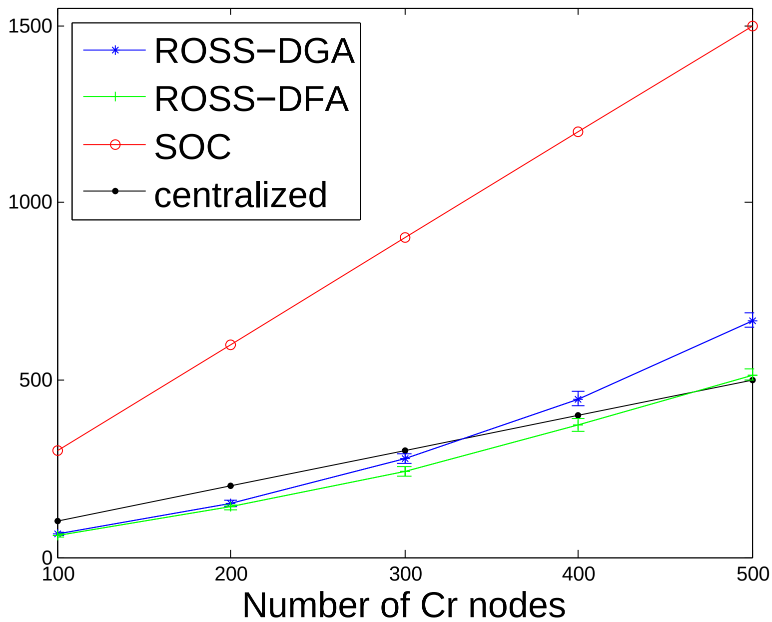


Figure 4.14 Number of control messages

4.6.2 Comparison between Distributed Schemes

In this part we investigate the performances of distributed schemes in CRN with different network scales and densities. The transmission range for CR is $A/10$ whereas $A/5$ for

PR. The number of PR is 30, we investigate the CRN where number of CR is 100, 200 and 300, and the average number of neighbours of each CR is 9.5, 20, and 31.

Number of CCC per Non-singleton Clusters

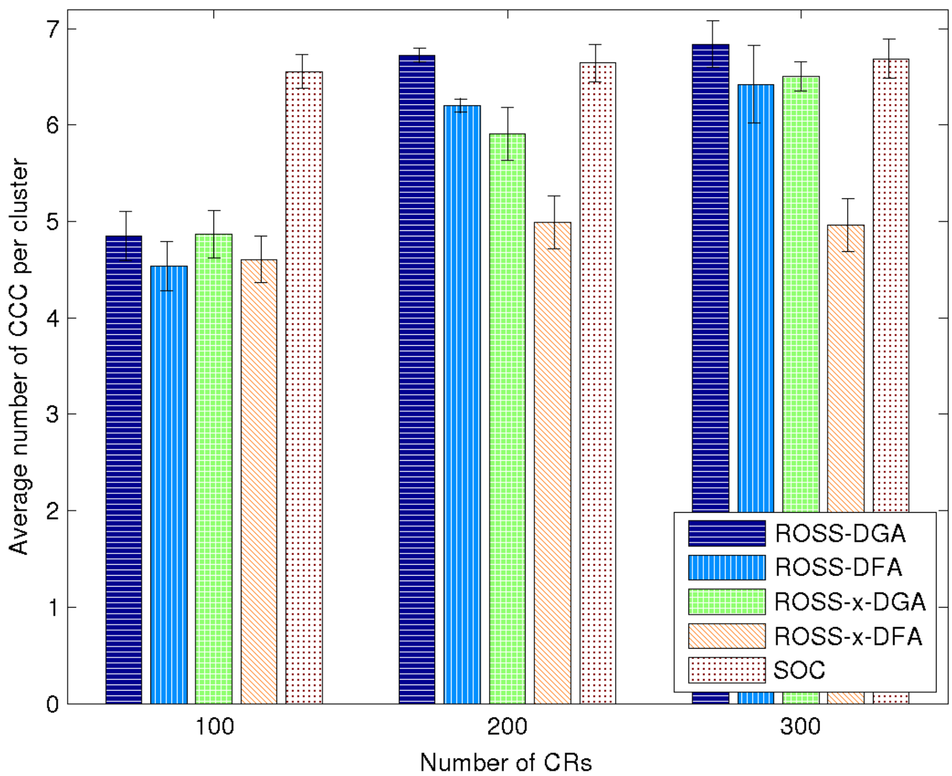


Figure 4.15 Number of common channels for non-singleton clusters. As to ROSS with size control feature, we adopt $x = 6$ when $N = 100$, $x = 12$ when $N = 200$, $x = 21$ when $N = 300$, which is around $2/3$ of the number of average neighbours

Figure 4.15 shows the Figure 4.15 illustrates the average number of CCC of the non-singleton clusters. It shows when $N = 100$, variants of ROSS have 30% less CCC than SOC, but this gap is decreased when N is 200 and 300. This means SOC performs better on average number of CCC per non-singleton clusters when network density is small, which is already observed in section 4.6.1. When the network becomes more dense, ROSS-DGA achieves even more CCC than SOC, and ROSS-DFA and ROSS-x-DGA visibly increase their performances on CCC.

Survival Rate of Clusters with Increasing PR Users

With the increase of PRs in the network, clusters become broken as no CCC available within the clusters. In this part of simulation, we add 290 more PRs randomly in CRN with interval of 10 to evaluate the robustness of clusters. Figure 4.16 shows the increasing tread of the number of singleton clusters with the increase of PRs. SOC generates around 10 more singleton clusters than the variants of ROSS, which accounts for 10% of the whole network. The confidence intervals of the variants of ROSS are not shown in the figure as they overlap, and we only show the average values. It can be seen that greedy algorithms result in slightly less singleton clusters than their counterparts.

Figure 4.17 shows a more dense CRN where $N = 300$. SOC noticeably causes more singleton clusters than ROSS variants, except for ROSS-3-DFA when PRs are few. The reason is ROSS-3-DFA only conduct cluster membership once, which leaves large number of singleton clusters, while, in ROSS-3-DGA increase the size of smaller clusters through debatable nodes' repeated updates.

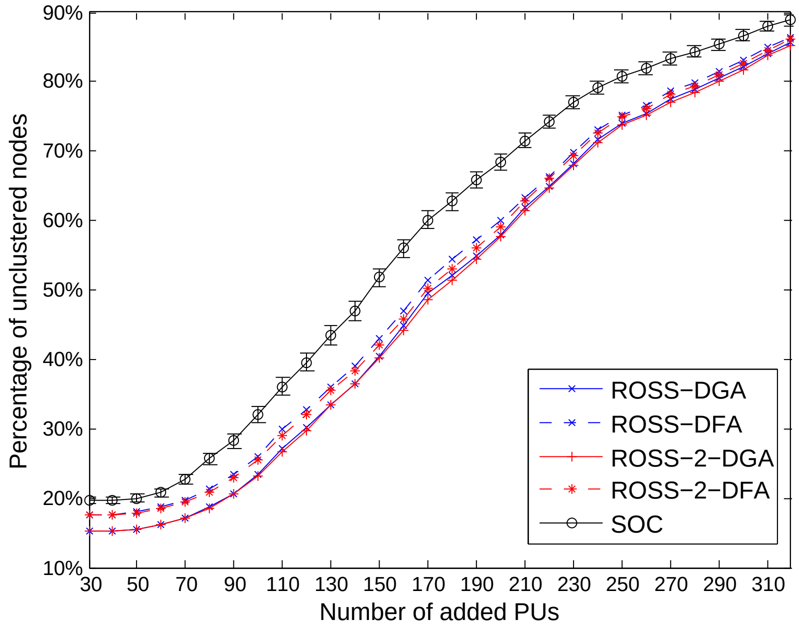


Figure 4.16 Number of CRs which are not included in any clusters, $N = 100$

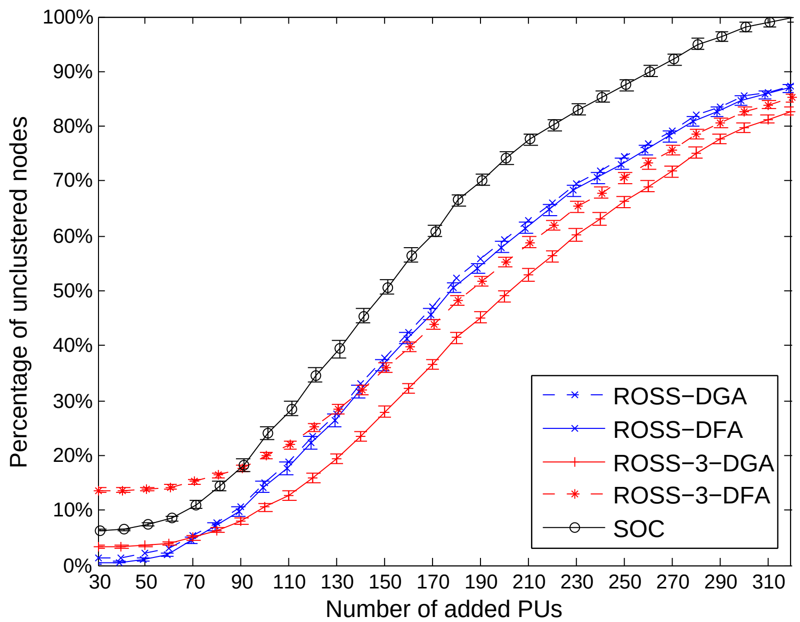


Figure 4.17 Number of CRs which are not included in any clusters, $N = 300$

From the Figure 4.16 and 4.17, we can see greedy versions of ROSS is more robust than their counterpart variant of ROSS. When the network is more dense, the improvement on cluster sizes and robustness by the greedy search is more obvious.

Cluster Size Control

The number of formed clusters is shown as Fig. 4.18.

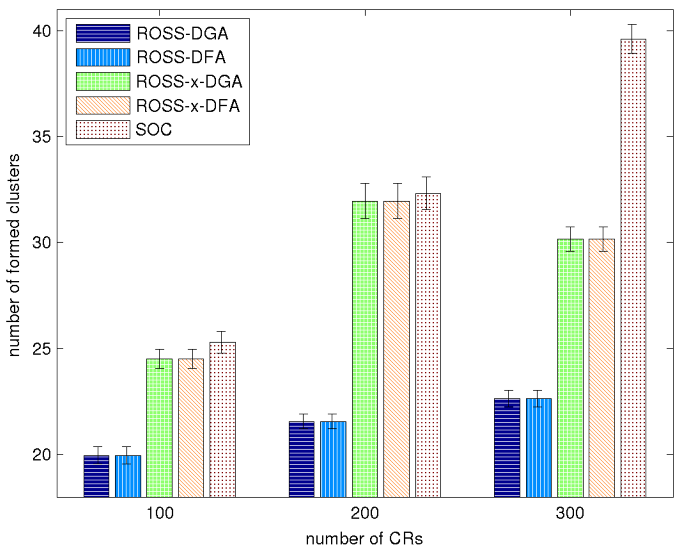


Figure 4.18 Number of formed clusters

When the network becomes denser, more clusters are generated by SOC compared with ROSS variants. To know the generated clusters better, we depict the cluster sizes with with cumulative distribution.

Cluster size analysis is made when the number of PRs is 30.

We see in Figure **??**, when variants of ROSS are applied, most CRs are included into clusters with size of 2, thereinto, ROSS-2-DGA achieves the some homogeneous result, i.e., , there is no cluster whose size is greater than 3, and the number of CRs in 2 node cluster is greater than that resulted from ROSS-2-DFA. This is due to in the phase that debatable nodes clarify their membership, greedy search not only increases the number of CCC of relevant clusters, but also lets debatable nodes stay in smaller cluster, as shown in algorithm 4. SOC doesn't have size control feature thus the cluster sizes diverge greatly. In a more dense network with 300 CRs, where desired size is 3, 94% of CRs are integrated into 2 or 3 node clusters by ROSS-3-DGA, as to ROSS-3-DFA, 13% CRs constitute singleton clusters, and 27% CRs are within 4 node clusters. Cluster size spans over a large range for schemes which don't have cluster size control mechanism. As to ROSS-DGA, ROSS-DFA and SOC, 95% of CRs stay in clusters whose sizes are smaller than 8, 9 and 14 respectively.

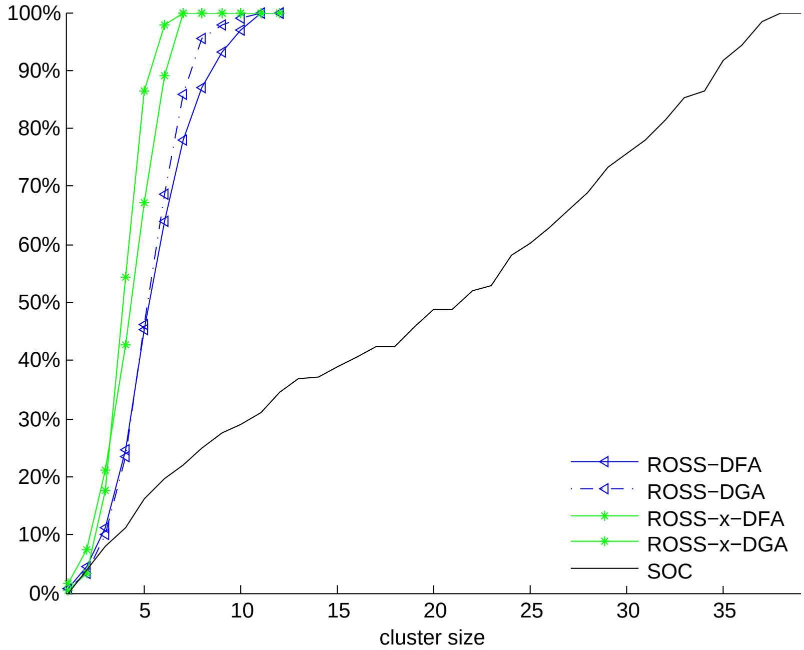


Figure 4.19 100 CRs, 30 PRs, the average number of neighbours is 9.5.

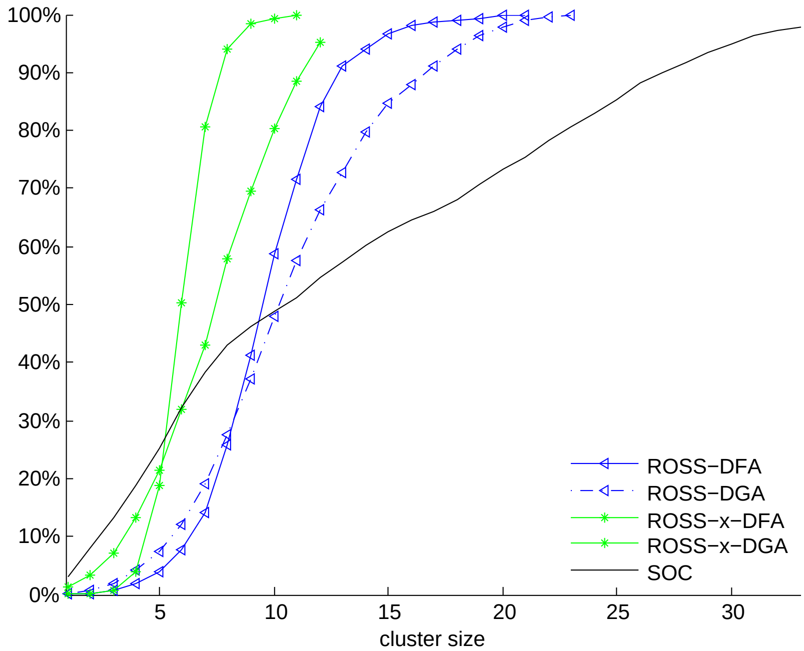


Figure 4.20 200 CRs, 30 PRs, the average number of neighbours is 20

4.7 Conclusions and Future Work

We investigate extensively the robust clustering problem in CRN, which is important to form clusters which maintains unbroken to the greatest extent possible under primary users' activity. We prove the NP hardness of the problem and one distributed and light weighted clustering scheme ROSS-DGA is proposed. The clusters resulted from ROSS-DGA and its faster version ROSS-DFA are less vulnerable compared with other distributed clustering schemes, and demonstrates similar survival rate with centralized scheme under primary users' influence. An light weighted cluster size control mechanism

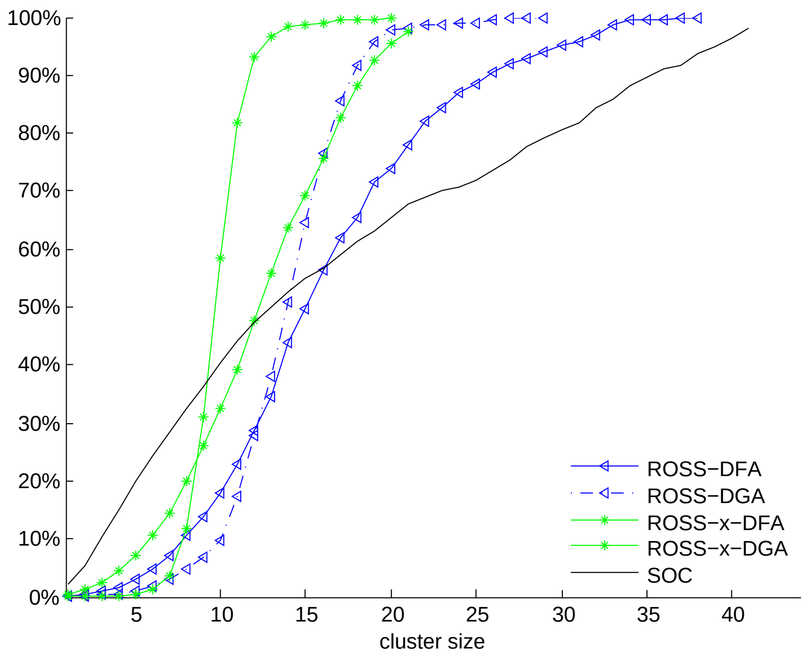


Figure 4.21 300 CRs, 30 PRs, the average number of neighbours is 30

is contained in both ROSS-DGA and ROSS-DFA, which is advantageous for cooperative sensing and network operation with clusters. Furthermore, considerable less control messages are generated when compared with other clustering schemes.

The drawback of this scheme is it does not form big clusters, which is attributed to that ROSS forms cluster based on cluster head's neighbourhood, and does not absorb CR nodes outside of the neighbourhood. Big clusters could be demanded when the network density is low.

5

SPECTRUM AWARE VIRTUAL COORDINATE ASSIGNMENT AND ROUTING IN MULTIHOP COGNITIVE RADIO NETWORK

5.1 Introduction

Cognitive radio technology is promising to solve the significant shortage of spectrum, which is due to proliferation of wireless devices. According to the definition of FCC (Federal Communications Commission in U.S.), cognitive radio is a device which is able to sense, measure, or learn its environment and accordingly tune its radio operating parameters (like center frequency, bandwidth and transmit power) on the fly, i.e. during operation. In this chapter cognitive radio equipment is also called secondary user. Together with these features secondary users are allowed to reuse licensed spectrum which is authorized to so called licensed users. The cognitive radio devices are capable of vacating a spectrum band if the licensed users reappears in order not to cause harmful interference to them.

Since primary users' activity demonstrates different patterns [65], the availability of licensed spectrum exhibits different dynamics accordingly. In certain scenarios the licensed spectrum occupancy stays available for fairly long time, e.g., TV white space [84]. In that case the licensed spectrum occupancy can be seen as static during a long period of time. In other scenarios primary users' states change frequently, but measurements [116, 91] show that the percentage of time that licensed spectrum is occupied at a specific location or during a certain period of time doesn't change, i.e. in city down town during the work time, the duty cycle of spectrum occupancy by cellular network is stable.

To fully exploit the potential of the secondary spectrum, it is crucial to investigate routing in dynamic spectrum environment. The dynamic availability of spectrum causes frequent break down of links between secondary users, and leads to prevalent topology changes, which makes spectrum aware routing difficult but essential [35].

Recent measurement in [91] shows the spectrum occupancy doesn't have significant spatial correlations between different locations. It follows that licensed spectrum is used by primary users heavily in some areas, whereas in the other areas licensed spectrum is available over longer timespan for secondary users to use. It is obvious to see that a routing path is better to go through the areas where primary users occupation is lower, as this alleviates or avoids the burden to cope with the changing or totally occupied spectrum when forwarding packets potentially with latency requirements. Geographic routing is a natural choice to realize this geography sensitive routing path. Geographic routing is light weight regarding the determination of next hop, and achieves high scalability in various wireless networks [13]. Merely knowing the geographic locations of its neighbours and the destination, a node is able to locally choose the next hop which has the smallest distance to the destination. However, in CRN dynamic link state renders geographic routing unsuccessful since packets are forwarded to the destination along the shortest path rather than avoiding areas heavily influenced by primary users.

To enable geographic routing in CRN, in this chapter we propose SAViC, spectrum aware virtual coordinates for secondary users in multi-channel multi-hop CRN. The virtual coordinate is independent of real geographic position, and has been proposed to represent the properties of the media like, link quality [21] or hop numbers [33]. Following this line of thought, our proposed virtual coordinate represents the spectrum occupancy of primary users. On top of this, we propose the geographic routing scheme which decides the next hop with Euclidean distance metric, and detours the areas affected by primary users, or cuts through the area with lower spectrum occupancy. With SAViC, geographic routing imposes little computation on deciding the next hop, and requires less communication cost transmitting packet to next hop. As to our knowledge, this is the first work integrating the spectrum usage by primary users into network coordinates in order to support geographic routing in CRN, which carries meanings especially for those resource restricted devices which want to work with licensed frequency band. The remainder of the chapter is organized as follows, after reviewing related work in Section II, system model is introduced in Section III. Assignment of SAViC is explained in Section IV, followed by opportunistic access during transmission in Section V. Section VI gives performance evaluation, concluding remarks are given in the last section.

5.2 RELATED WORK

When secondary users are static and primary users' operation activity is known, i.e., primary users occupy a certain channel for long time, or they occupy a channel with fixed probability, then centralized routing schemes for CRN can be designed[90]. But as centralized scheme requires sensing result from each secondary user in the network, thus suffers from any change of channel state of secondary users [11], besides, one centralized controller is needed to calculate the routing path on the basis of collected information from the network [90, 92]. Considerable amount of distributed schemes are proposed to cope with routing in CRN where spectrum state is usually considered to be rapid changing. [32] proposes CAODV (Cognitive Ad-hoc On-demand Distance Vector) and let each CR node explore all channels and store route for each available channel. CAODV requires frequent message exchange between secondary users to maintain the up to date connections on each channel due to PU's activities, which is a burden for secondary user when primary users' activity is intense. [103] improving the DSR scheme (Dynamic Source Routing) by letting RREQ messages record spectrum availability, link quality and congestion possibility along routing paths, but it also suffers from frequently changing channel state.

To cope with the rapid change of channel state, some routing schemes abandon routing table and let the transmitter decide the next hop for each single packet based on spectrum state between transmitter and neighbours. When there is packet to send, secondary user evaluates channel availability based on the statistics of sensing history [78], or the prediction on channel availability in the forthcoming time slot [77], then secondary user chooses the favoured channel and next hop node to send out the packet. Distance to the destination is also a consideration for choosing next hop. Such per-packet forwarding paradigm reacts swiftly on the fast changing channel state, but it requires more powerful computation power on secondary users. Firstly, that scheme produces high computation complexity on determining the channel and next hop node, secondly, specifically designed MAC mechanism and large amount of control messages are needed to coordinate the communication between the sender and the potential next hop nodes, these aspects make it uneconomic for many networks, e.g, wireless sensor networks operating with licensed spectrum [106]. Furthermore, as this kind of routing paradigm emphasizes on finding the maximal transmission opportunity of secondary spectrum, the selection on preferred channel decreases the scope of next hop neighbours, thus it may yield route which does not reach the destination [65, 101].

Chowdhury et al. [40] proposes *SEARCH* which is a valuable attempt to avoid the primary users' influences on routing path on the basis of geographic routing. In *SEARCH*, the source node launches geographic routing on each channel, and every routing path bypasses the nodes where corresponding channel is unavailable. Paths on different channels will merge on the nodes where path circumvent happens, if such change of path and switch of channel lead to shorter time needed to send packets to destination. After receiving the routing message on each channel, the destination decides the shortest path and sends back notifications along the chosen path. The routing path is blocked when one primary user locating along it changes its state from OFF to ON, thus source node needs to periodically launch route request to update the routing path which may have been invalid. *SEARCH* adopts routing table and doesn't involve frequent overhead exchanges.

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We propose a routing paradigm in CRN. Geographic routing is applied in the CRN network which is assigned with spectrum aware virtual coordinates. The dynamic availability of spectrum leads to prevalent topology changes, which makes spectrum aware routing difficult but essential. Routing schemes are proposed in [11, 32, 103] for CRN where primary users change their operating parameters infrequently. Highly dynamic primary users impose great challenge on routing, as is discussed in [92], where the statistics of primary users' activity is utilized in routing decision. A class of packet forwarding strategies for dynamic spectrum CRN is proposed in [78, 77]. Whenever a secondary user needs to forward a packet, it chooses channel and hop jointly based on channel's statistical characteristics observed beforehand. Forwarding decision is made for each single packet, which requires complex computations, large amount of control overhead, and customized media access control mechanisms. The solution provided by Chowdhury et al.[40] improves geographic routing in multiple channel CRN by introducing circumventing mechanism, i.e., when the next hop chosen based on geographic routing metric (e.g., Euclidean distance) is affected by primary user, the routing packet chooses a neighbour of that node free from primary user's affection so as to avoid the primary user affected area. Such routing is conducted on all channels, afterwards a path merge process is undertaken and one path with alternating channel is finally formed with consideration of end to end delay.

As the decision of the next hop is largely decided by the channel availability on the time point of decision, the node chosen as next hop may not be able to work after a short while due to primary user's reappearance. Thus, this scheme works well when the primary user's activity is infrequent, but when it goes tense, the frequent invalidity of nodes due to lack of available spectrum seriously deteriorates routing performance.

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5.3 SYSTEM MODEL

We consider a CRN composed with secondary users which are randomly and statically deployed in a plane. There are orthogonal licensed channels denoted by set C, and secondary user is allowed to use any of them if no primary user is detected on that channel by the secondary user. One common control channel (CCC) in license-exempt band is available for all secondary users to exchange control messages. Only one licensed channel is used for payload transmission. Primary users are static, and they occupancy spectrum in a constant manner, e.g., the percentage of time that they access a certain channel is static in any period of time.

Proactive spectrum sensing is conducted locally and periodically as Figure 5.1 shows.

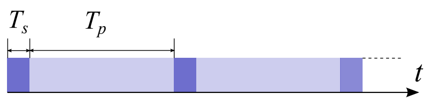


Figure 5.1 Sensing duration T_s and sensing period T_p

The sensing duration T_s includes both detection time in physical layer and the decision synchronisation time. Sensing period T_p is the time between two successive sensing durations. If the channel is sensed as busy[1] in sensing duration, which means at least one primary user in the vicinity is in ON state, we say the state of primary user is labelled as ON in the following sensing period T_p. If not a single primary user is sensed, primary users in vicinity in the following sensing period is said to be in state OFF. Secondary user senses each licensed channel for time T_{access} with round robin scheduling, and records statistics of ON/OFF states of that channel at its place.

5.4 Spectrum Aware Virtual Coordinates

In this section, we firstly introduce how spectrum aware virtual coordinate is assigned, then we introduce two normalized spectrum utilities on secondary user adopted in the

[1] Concrete sensing techniques are not discussed in this chapter.

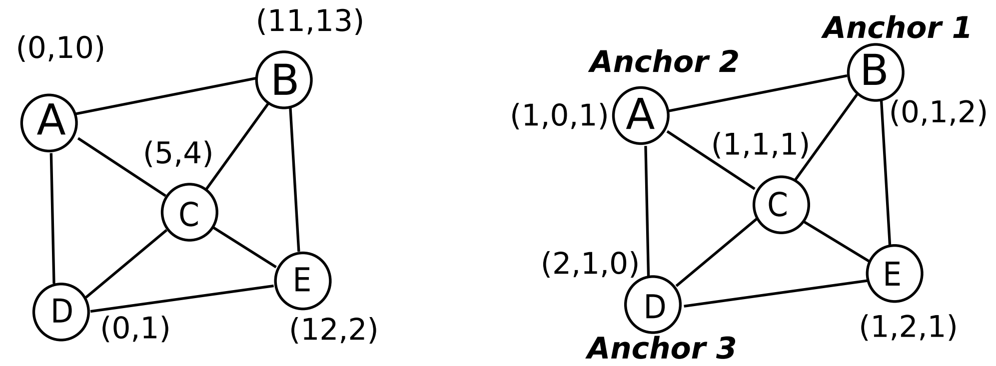


Figure 5.2 Left: nodes with physical locations, Right: nodes with doublet virtual coordinate, each element in the virtual coordinate is the number of hops away from corresponding anchor. Connecting lines denote the communication is possible.

virtual coordinate assignment process. One of them is called *normalized spectrum availability* which is on the basis of duty cycle of primary users' absence, the other is called *normalized longest blocking time* which as the name tells, is based on the lengths of time durations that primary users are detected.

Virtual coordinate has been proposed in sensor and ad hoc networks [33, 21]. In the left part of Figure 5.2, nodes are labelled with physical positions. The right hand side part shows the same network assigned triplet virtual coordinate for each node according to VCap [33], where each element of the coordinate denotes the minimal number of hops away from corresponding anchor. This kind of virtual ordinate belongs to tree based virtual coordinates, and is obtained based on anchors which locate at the edge of network. Anchor messages are broadcast from anchors, each of them contains a counter recording the number of hops travelled. The minimum counter of the arriving anchor messages constitutes the corresponding element of the virtual coordinate on the arrival node. Except for the hope numbers away from certain anchor node, virtual coordinate can also be composed with link quality [21] in wireless sensor networks. The hop based virtual coordinate is independent on actual physical position, but supports greedy geographic routing successfully [33, 21]. For example, when the source-destination is B and D, and Euclidean distance calculated with virtual coordinate is adopted in the routing decision, then the greedy geographic routing achieves the same routing path in both networks: $B \rightarrow C \rightarrow D$. This path is one with the shortest traversal distance.

In this chapter, we propose licensed spectrum aware virtual coordinate in CRN, which enables geographic routing to find the path with better available spectrum. Figure 5.3 shows one CRN where secondary users are assigned virtual coordinate according to anchor 1. The transmission opportunity of the nodes locating within primary users' transmission range, e.g., node A and C, is decreased due to sporadic spectrum, as a result, the cost for packet transmission, e.g., transmission delay and energy consumption, is increased. We integrate this obstacle caused by spectrum scarcity to transmission into virtual coordinate.

5.4.1 Assign Spectrum Aware Virtual Coordinate

As to SAViC, anchors broadcast anchor messages which flood over the network and result in virtual coordinate for each secondary user. Several anchors are needed to assign unique virtual coordinate for each secondary user. How to select anchors is out of the scope of

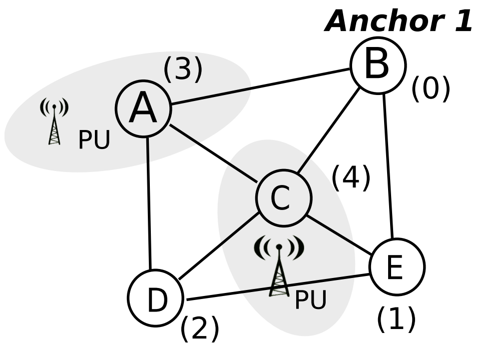


Figure 5.3 A network under primary users' influence assigned with SAViC, only anchor 1 is adopted. Flooding of anchor messages is not shown.

this chapter. In the following, we introduce how is virtual coordinate decided on each node with respect to anchors.

Each secondary user maintains its virtual coordinate which is one r-tuple where each element contained corresponds to one anchor, and the tuple length is r. The elements of virtual coordinate on each node is set as big positive value. An anchor message is generated on the anchor, which contains a $counter$ whose value is set as 0. The anchor message is broadcast on control channel. The influence of primary users on a secondary user is quantified as spectrum utility λ on that secondary user. The bigger value indicates heavier spectrum occupation by primary users. λ will be discussed in Section 5.4.2 and 5.4.3.

When a node i receives an anchor message from the tth anchor, i compares the tth element in its current virtual coordinate with the sum of the λ and $counter1$ which is contained in the arriving anchor message. If the sum is greater than the tth element in its current virtual coordinate, which indicates that the path traversed by this anchor message exposes to more active primary users, node i drops the anchor message. If the sum is smaller than the tth element in its current virtual coordinate, the node set the tth element as the sum and updates $counter1$ contained in the anchor message before forwarding it. This process is presented as Algorithm 5. The process ceases within a period of time.

Lemma 2. *As to one anchor, the number of times for each node to forward anchor message is bounded by g, where g is the number of one hop neighbours of anchor.*

Lemma 3. *The counter value of one anchor message is increased when it is forwarded.*

Proof. This is proved by the lines 18-20 in Algorithm 5. □

Lemma 4. *One anchor message affiliated with one anchor accesses the one secondary user at most twice.*

Proof. Assume one node is accessed by the same anchor message for two times. When the anchor message arrives at the secondary user, let's say i, for the first time, there is vc $> counter + \lambda$, and both of the vc and counter in the anchor message are updated to be $counter + \lambda$. After being forwarded, the anchor message travels at least one other secondary user before arriving i, and the counter is greater than the counter value when it is forwarded from i according to Lemma 3, which means, current counter value is greater than λ_i, and the anchor message is dropped. Thus, this anchor message accesses secondary user i for at most two times. □

Theorem 5.4.1. *The number of anchor message corresponding to one anchor is bound by $2 * g * n$, where n is the number of secondary users.*

Proof. This is proved by Lemma 2 and 4. □

According to Theorem 5.4.1, every secondary users obtains virtual coordinate which respects to all anchors after a finite time duration.

Algorithm 5: Secondary user i obtains one element vc_i in its VC with respect to an anchor

Input: $vc_i = M$, M is one big positive number

if *i is anchor* **then**
  $vc_i = 0$;
  set $counter1 = \lambda_i$ in anchor message;
  broadcast anchor message;
end
if *receive anchor message* **then**
  if $counter + \lambda_i \geqslant vc_i$ **then**
    drop anchor message;
  else
    $vc_i = counter + \lambda_i$;
    set $counter = vc_i$ in anchor message;
    broadcast anchor message;
  end
end

5.4.2 Normalized Spectrum Availability on Secondary User

Based on the statistics of primary user's ON/OFF states in time duration $T_{assement}$ which contains multiple T_s, secondary user i characterizes the likelihood that one licensed channel, say k, is available at its own position with *duty cycle*, which is

$$\gamma_i^k = \frac{\Delta_{\text{OFF}}}{\Delta_{\text{OFF}} + \Delta_{\text{ON}}}, \tag{5.1}$$

where Δ_{OFF} is the number of sensing periods when channel k is sensed as OFF in $T_{assement}$. To implement SAViC whose resultant Euclidean distance between two nodes reflects both influence from primary users and distance in terms of hops, we need to design a normalized quantified spectrum availability λ_i.

Single licensed channel

When there is only one licensed channel in CRN (the superscript of channel λ is omitted), the normalized spectrum availability on node i is proposed as,

$$\lambda_i = -\ln \gamma_i + c \cdot \gamma_i \tag{5.2}$$

With Formula 5.2, when one anchor message which originates from anchor X is forwarded from node a to b without being dropped, the distance based on virtual coordinate reflects both the spectrum availability and geographic distance in terms of hops between the two nodes. Based on Algorithm 5 and Formula 5.2, the distance in dimension X is,

$$\begin{aligned} |x_b - x_a| &= \sum_{i \in P_{(a,b]}} (-\ln \gamma_i + c \cdot \gamma_i) \\ &= -\ln(\prod_{i \in P_{(a,b]}} \gamma_i) + c \cdot \sum_{i \in P_{(a,b]}} \gamma_i \end{aligned} \tag{5.3}$$

here x_a and x_b are virtual coordinates of node a and b in dimension X respectively. $P_{(a,b]} = (\cdots, b)$ denotes the list of nodes after a and till b, which forward the same anchor message.

The reason to choose the form of Formula 5.2 is as follows. As Formula 5.3 shows, the first item is logarithm of the product of consecutive spectrum availability likelihood of the nodes in $P_{(a,b]}$. The product is the likelihood that one message travels from node a to b without hampered by primary users, which is an important property we want to integrated into our virtual coordinate system. The fist item will be infinity when the spectrum is occupied by primary users during all the time, where $\gamma = 0$. In this case, infinity can be replaced with a large positive value which results in a large λ. The second item denotes number of hops, which can be seen clearly when $\gamma_i = 0$ for node $i \in P_{(a,b]}$.

As λ_i needs to be monotonically decreasing with respect to γ_i, so that the less spectrum availability results in bigger cost for communication, thus there should be

$$\frac{\partial \lambda_i}{\partial \gamma_i} = c - \frac{1}{\gamma_i} < 0 \tag{5.4}$$

hence the tuning parameter c should be smaller than 1. In the simulation part, we choose $c = 0.2$ so that λ visibly reflects the changes of γ when γ is not too small, as Figure 5.4 shows.

Multiple licensed channels

When multiple licensed channels are allowed to use without interfering primary users, one node can switch to an another channel which is at present available to send or forward packet, then the normalized channel availability is,

$$\gamma_i = 1 - \prod_{k=1}^{|C|} (1 - \gamma_i^k) \tag{5.5}$$

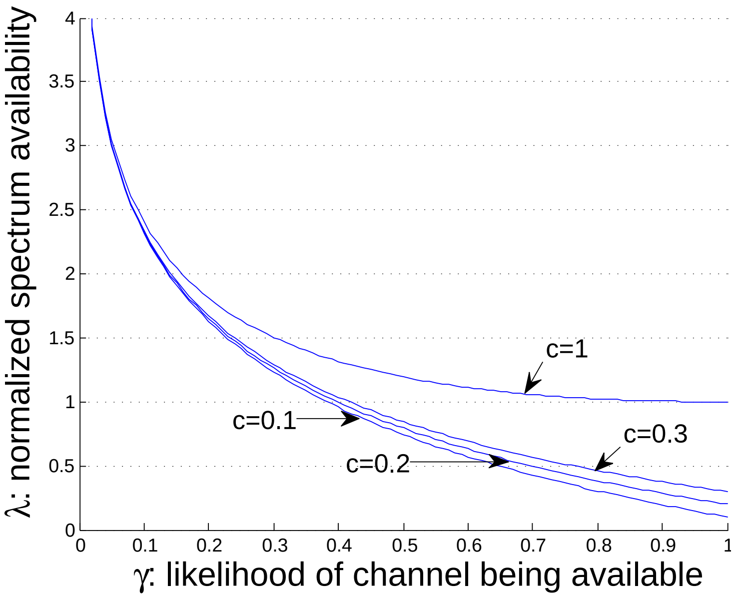


Figure 5.4 Normalized spectrum availability with respect to the likelihood of spectrum being available one a node

Based on Formula 5.2, the normalized spectrum availability on node i when multiple secondary channels are available is,

$$\begin{aligned}\lambda_i &= -\ln \gamma_i + c \cdot \gamma_i \\ &= -\ln(1 - \prod_{k=1}^{|C|}(1-\gamma_i^k)) + c \cdot (1 - \prod_{k=1}^{|C|}(1-\gamma_i^k))\end{aligned} \tag{5.6}$$

5.4.3 Normalized Longest Blocking Time on Secondary Users

Channel utility introduced in previous subsection characterizes the likelihood that secondary user is allowed to forward packets, but it fails to reflect the availability of spectrum in a finer granularity of time. For instance, in the period of time T_{access} to access the spectrum availability, one channel which frequently changes between state ON and OFF due to primary users' violent operation may have the same likelihood of available spectrum with the channel where primary user sojourns on state ON for long time. This difference has direct consequence on delay when the likelihood of spectrum availability on PU affected secondary nodes is homogeneous.

Let T_{ON}^k be the length of time period that channel k is not available, there is $T_{ON}^k = n \cdot (T_s + T_p)$, where n is the number of consecutive sensing duration that channel k is sensed as busy. T_{ON}^k is recorded within T_{access}, and we use $\tau^k = \overline{T_{ON}^k}$ to denote the average value of the time duration that channel k is occupied by primary user, which is the maximum time period that secondary user is blocked from sending/forwarding.

Single licensed channel

In single licensed channel scenario, the normalized maximum blocking time on node i is (superscript k is omitted),

$$\lambda_i = f(\tau_i) = \gamma_i \cdot \tau_i + b \cdot e^{-\gamma_i \cdot \tau_i} \tag{5.7}$$

The first item is the product of blocking time and the duty cycle of available spectrum, note that we assume the duty cycle is identical for any PU affected secondary user and thus can be regarded as constant. As to the secondary users which locate out of any primary user's transmission range, there is $\tau_i = 0$, then $\lambda_i = b$, λ_i denotes hop count in this case. This is the reason that the second item is needed.

Same with the analysis in section 5.4.2, when one anchor message travels through path $P_{(a,b]}$, the distance on the corresponding coordinate dimension is the sum of the normalized longest blocking time, which is the function of the sum of maximum blocking time on the cascaded nodes on the trajectory of anchor message,

$$\begin{aligned} |x_b - x_a| &= \sum_{i \in P_{(a,b]}} (\gamma_i \cdot \tau_i + b \cdot e^{-\gamma_i \cdot \tau_i}) \\ &= \gamma_i \cdot \sum_{i \in P_{(a,b]}} \tau_i + b \cdot e^{-\gamma_i \cdot \sum_{i \in P_{(a,b]}} \tau_i} \end{aligned} \tag{5.8}$$

Normalized longest blocking time λ is monotonically increasing with τ_i, which requires

$$\begin{aligned} \frac{\partial \lambda_i}{\partial \tau_i} = \gamma_i - \gamma_i \cdot b \cdot e^{-\tau_i \cdot \gamma_i} &> 0 \\ b &< e^{\gamma_i \cdot \tau_i} \end{aligned} \tag{5.9}$$

then we set the tuning parameter b as 1.

Multiple licensed channels

In multiple licensed channel scenario, τ_i equals to the smallest maximum blocking time over all secondary channels on node i,

$$\tau_i = \min \tau_i^x, x \in C \tag{5.10}$$

The normalized maximum blocking time on node i is as Formula 5.7 shows.

In remainder of this chapter, the virtual coordinate based on normalized spectrum utility is referred as *spectrum availability based VC*, and The virtual coordinate based on normalized maximum blocking time is denoted as *blocking time based VC* out of convenience.

When λ on secondary nodes is identical, the resultant SAViC appears to be similar with hop based virtual coordinate. In reality, as the measurement shows in [91], heterogeneity of spectrum usage by primary users is very normal, besides, the two kinds of virtual coordinates make it easier to find out such heterogeneity. [91] also shows within certain frequency band, primary users' activity is stable for hours, e.g., cellular network. When primary user's operation pattern changes, e.g., occupy spectrum with increased duty cycle, then SAViC needs to be reimplemented.

5.5 Geographic Routing and Opportunistic Spectrum Access

Although spectrum aware virtual coordinate is the main concern of this chapter, we also introduce the geographic routing to be used as it affects the routing result directly. With geographic routing, packet sender/forwarder chooses the neighbour which has smaller Euclidean distance to the destination. The distance between node i and destination d is $\sqrt{(x_d - x_i)^2 + (y_d - y_i)^2 + (z_d - z_i)^2}$, when virtual coordinate can be denoted as $\{x, y, z\}$. A trivial improvement on greedy geographic routing is implemented in network layer to mitigate the dead end problem. When routing protocol reaches dead end node u which is closest to destination, u adds its ID to the packet as taboo before forwarding the packet to v which is closest to the destination in its neighborhood. The packet will not be sent to the nodes whose IDs appear to be taboos.

Buffer is implemented on each node, where packets stay temporally when no unoccupied licensed spectrum is available. Secondary user resends buffered packet every period of time, and drops it if there is still no available channel after trying for 10 times.

In multiple channel CRN, after one node deciding on the next hop via geographic routing, which channel to use needs to be answered. This problem involves considerations from many aspects, such as minimizing channel switch cost [101], mitigating co-channel interferences [73] etc.. We adopt a lightweight heuristic method in this chapter. When there is packet to send and the next hop is decided, packet sender chooses the channel in descending sequence with channel's metric, i.e., likelihood of channel availability, or blocking time. The sender chooses the channel with the best metric, then conducts spectrum sensing in the immediately following sensing duration to determine the channel's usability. If the channel is sensed as free to use, sender transmits *request_channel_x* to the next hop on the control channel, when it receives the answering message *channel_x_available* from that node, it starts communication on channel x in the following sensing period. If the channel is sensed to be busy before or among the transmission, or it receives *channel_x_unavailable* message from next hop node, the sender moves to the channel with the second best metric, and conduct the same procedure as described above.

5.6 Performance Evaluation

In this section, we present the performance of geographic routing together with SAViC. Both virtual coordinates based on metrics of spectrum availability and blocking time respectively are evaluated. Prior to that, the set-up of simulation is introduced.

5.6.1 Simulation Setup

In this section, we introduce the deployment of the primary users to generate various spectrum availability in the network, then introduce the important parameters in simulation. Different from [33] where simulation is conducted without considering any activities in MAC and physical layer, simulation in this chapter deploys a wireless environment which is close to reality, e.g., interferences and channel shadowing are involved.

Primary Users

Measurements [83, 51] show that the sufficiently accurate statistic model of spectrum occupancy can be given by a Markovian process. In simulation, primary user alternates state between ON and OFF as a two-state discrete time Markov chain (2TDMC). The probability that it changes from one state to the other, or stays in the same state is called transition probability. Transition probability further decides the stationary probability of 2DTMC, which represents the percentage of time that primary user is in state ON or OFF in a long run. The relationship between stationary probability $\Pi = \{\pi_{\text{ON}}, \pi_{\text{OFF}}\}$ and duty cycle γ is,

$$\lim_{T_{assement} \to \infty} \gamma = \pi_{\text{OFF}} \tag{5.11}$$

Transition probability also decides the continuous sojourning time of primary user on a certain state, which affects the longest blocking time sensed by secondary users. Hence, by adjusting transition probability, we can let primary user operate with desired intensity, i.e. stationary probability for being in state OFF, or continuous sojourning time of being on state ON. We denote stationary probability of state OFF as P_{OFF}, and the maximal blocking time as T. In the following, we only use P_{OFF} and T to define primary user's dynamics, and omit mentioning the transition probability. The time unite of the DTMC for primary user to follow is 0.1s.

As spectrum availability based and longest blocking time based virtual coordinates are designed for CRN which is influence by certain primary user activity, we design two primary user distributions. As a result, we design two categories of primary user settings to evaluate the routing performance assisted by the two categories of virtual coordinate respectively.

- As to spectrum availability based virtual coordinate, two primary users are located in the CRN which can not affect all the nodes in CRN, as shown in Figure 5.6(a).
- For blocking time based virtual coordinate, network is evenly covered by primary users which have the same duty cycle, but some primary users have different blocking time with the others, as Figure 5.9 shows.

When multiple channel scenario is to be investigated, existing primary users simply start to work with current and additional channels, and there is no new primary users appear.

Parameter Setting

Simulation is conducted with INET framework provided by OMNeT++ simulator [113], which comprises both generation of SAViC and following geographic routing. Secondary users are randomly distributed in a square area and 6 nodes which locate at the edge are deployed as anchors.

5.6.2 Success Rate of Geographic Routing on Finding Path

We evaluate SAViC's reachability, i.e. given the virtual coordinate of destination, geographic routing forwards packet from source to the node with the desired virtual coordinate. The comparisons are real geographic location, and hop based virtual coordinate according to VCap [33]. We deploy 6 anchors and then there is no duplicated virtual coordinate among the resultant virtual coordinate system.

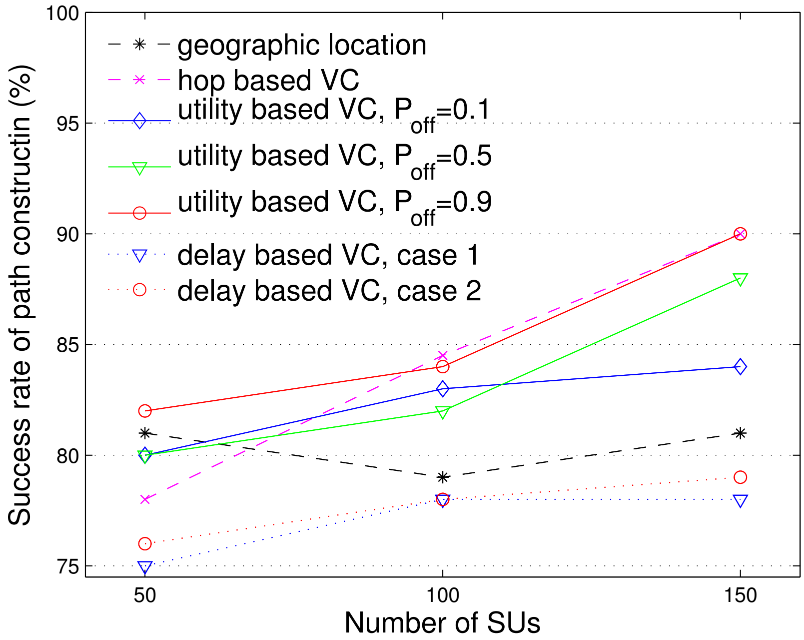


Figure 5.5 Reachability of different virtual coordinates, the average number of neighbors is 6, 12, and 14

In order to evaluate the effectiveness of coordinates to support geographic routing, we design different configurations of primary users. As to duty cycle based VC, two primary users are randomly deployed in the network. As to delay based VC, we configure 9 primary users to evenly cover the network, among of them, 4 primary users have different maximal blocking time with the rest. Under one configuration of primary users, 1000 random CRN is generated and in each CRN one far departed pair of source and destination is chosen to test.

Figure 5.5 shows, spectrum availability based virtual coordinate supports geographic routing to achieve similar reachability with hop based virtual coordinate[2], which is better than that with real geographic location. Blocking time based virtual coordinate performs a little bit worse than other coordinates. In summary, after integrating the primary user's influence, SAViC supports geographic routing to achieve comparable success rate of path construction with conventional virtual coordinate and real geographic location.

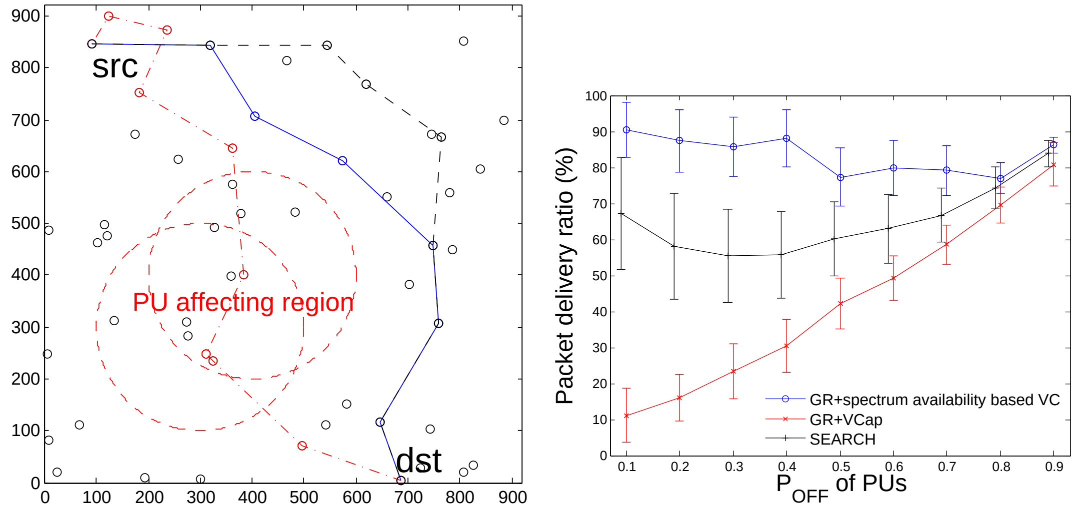
5.6.3 Routing Performance

We sequentially present the routing performance of SAViC based on spectrum availability and blocking time respectively. In more details, spectrum availability SAViC is compared with hop based virtual coordinate VCap and *SEARCH*. The reason to choose *SEARCH* [40] is it is on the basis of geographic routing and utilizes routing table in the interval of updates, thus it requires less computation ability and overhead exchanges. The time interval for *SEARCH* to update routing tables of the nodes on routing path is 5s. Both single and multiple licensed channel scenarios are investigated for the three solutions.

[2]The numerical result of hop based virtual coordinate coincides with the simulation result presented in [33] under the same network density

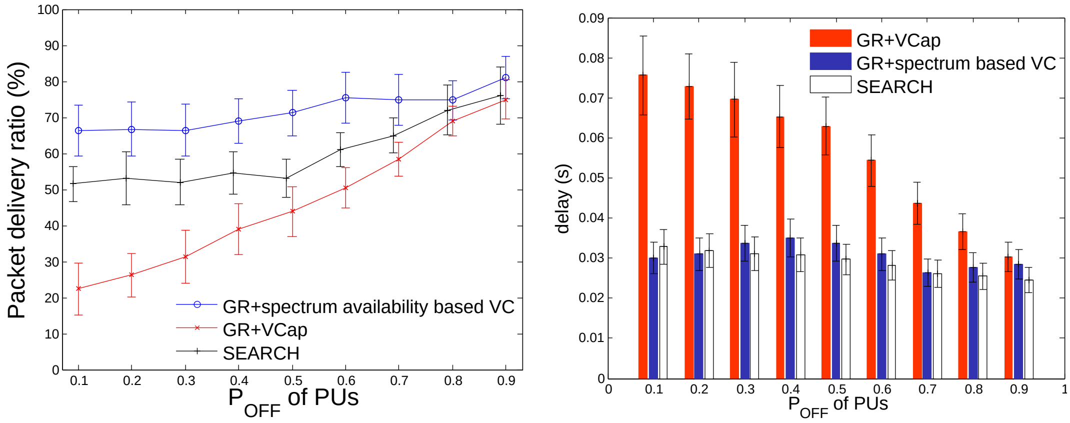
Duty Cycle Based Virtual Coordinate

We start by looking into the performance of SAViC in single channel scenario.



(a) Routing paths (b) PDR over 50 random CRN network, PU's location is fixed as shown in Figure 5.6(a)

Figure 5.6 Routing paths and corresponding PDR



(a) PDR (b) Delay

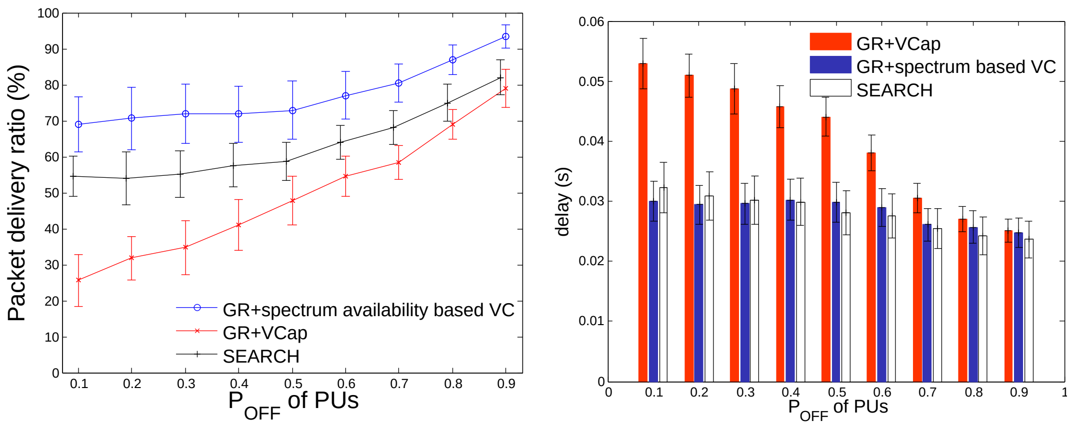
Figure 5.7 Packet delivery ratio with single secondary channel, over 50 randomly located CR nodes and PUs

We start with a case study, two primary users locate at the centers of dashed cycles as shown in Figure 5.6(a). VC based on spectrum availability and VCap (hop is its metric) are assigned to secondary users separately. The red dashed path in Figure 5.6(a) is formed by geographic routing with VCap, which cuts across the primary users' affecting area and thus suffers great packet loss. The black dash and blue solid paths are formed with spectrum availability based virtual coordinate, the two paths are formed when primary user's working intensities P_{OFF} is 0.1 and 0.9 respectively. These two paths vividly illustrate that utility based virtual coordinate successfully integrates the spectrum scarcity in CRN network, and decomposes a large part of routing decision. The paths of SEARCH is not drawn here as the routing path is possible to change after path update. We keep the primary users in the middle of the network, for each activity intensity, 50 CRNs where secondary users are randomly located are generated. Figure 5.6(b) shows the PDR of spectrum availability based virtual coordinate is high except for a minor decline when P_{OFF} is between 0.5 and 0.8, which is contradictory to the monotonically increasing trend of hop based virtual coordinate. This can be explained by the path snapshot in Figure 5.6(a). When channel is sensed to be scarce (primary users access channel intensively), path generated is far away from the affected area and circumvents completely. When primary users become less intensive, routing path moves closer to that area. In other words, the weaker dynamics of primary users attracts path and result in packet drop. When P_{OFF} approaches to 1, spectrum availability based virtual coordinate becomes actual hop based virtual coordinate as the link metric in formula 5.2 becomes zero.

The paradox that more licensed spectrum leads to worse PDR can also be observed on *SEARCH*, whose PDR curve declines first and increases later on. When channel is heavily utilized by primary users, the routing request is more likely to encounter operating primary user, then a node out of the primary user affecting area is chosen as next hop, so that the path experiences less packet loss (with the price of more hops). When primary users become less intense, routing request is more likely to traverse the affected areas, as a result, the routing path experiences packet loss due to the primary users in that area before next route update.

Figure 5.7(a) shows the PDR when both primary and secondary users' locations are random. SAViC's performance deteriorates because the source and destination may be influenced by primary users, so that a path completely detour the primary users' area is impossible. where geographic routing has no means to detour the affected areas. In figure 5.7(b), SAViC and SEARCH achieve lower delay although forwarding more packets, which means SAViC is effective to facilitate geographic routing to avoid PU affecting areas.

Now we introduce the routing performance in multiple channel scenario, where two licensed channels available, but only one is allowed for payload transmission.



(a) PDR over 50 CRNs where SUs and PUs are randomly located (b) PDR over 50 CRNs where SUs and PUs are randomly located

Figure 5.8 Packet delivery ratio with multiple secondary channel scenario

In this part of simulation, we follow the setting of single channel scenario, except that secondary users have at most two licensed channels.

Thanks to the second channel, the packet delivery radio is increased as shown in Figure 5.8(a), and delay is decreased as depicted in Figure 5.6(a). SAViC still outperform the other schemes especially in the aspect of PDR.

Longest Blocking time Based Virtual Coordinate

As discussed in section 5.4.3, spectrum availability based virtual coordinate doesn't reflect the sparsity or abundance of spectrum well when the likelihood of spectrum availability is homogeneous in CRN. A CRN working with single licensed channel in Figure 5.9 is used to show the fail of spectrum availability based virtual coordinate. Two items are used in the following to make the analysis tidy.

T_1	Maximal blocking time of primary users whose transmission ranges are solid cycles in Figure 5.9
T_2	Maximal blocking time of the other primary users

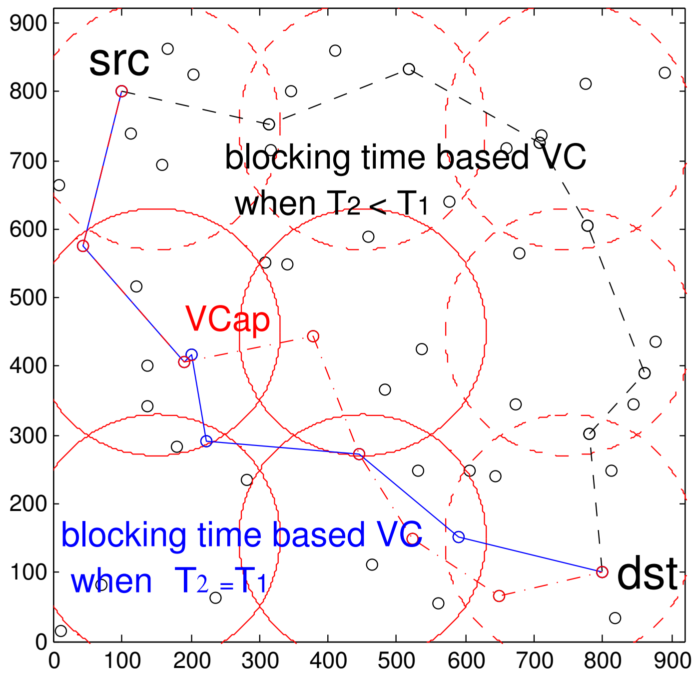
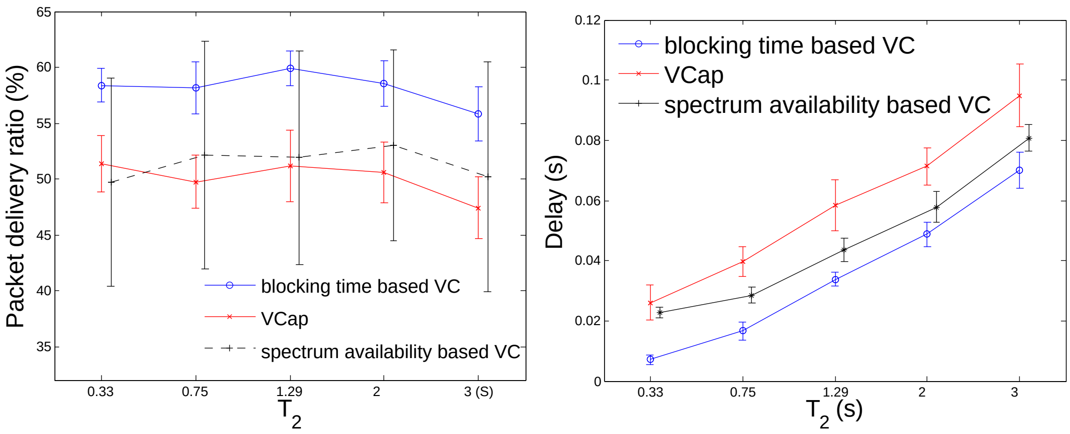


Figure 5.9 Routing paths in one network, $T_1 = 3s$. cycles denote the transmission range of primary uers.

In the network, 9 primary users evenly distributed, $P_{\text{OFF}} = 0.5$ for each of them. For the primary users denoted by the solid cycles, maximal blocking time $T_1 = 3s$, and $T_2 = 1s$ and $3s$ for the other primary users. When $T_2 < T_1$, the resultant routing path is in black and dashed, which goes through area where primary users have shorter maximal blocking time. When $T_2 = T_1$, the resultant routing path largely converges with the path with VCap.

The ineffectiveness of spectrum availability based virtual coordinate in case of identical P_{OFF} is observed in Figure 5.9. In this case a different characteristic, i.e., the longest blocking time, which shows the geographically diverse characteristics of spectrum can be used. In our simulation, $P_{\text{OFF}} = 0.9$ for all primary users, but they are diverse on sojourn time, i.e. T_1 of primary user is 3s, and T_2 is shorter. We randomize the location of secondary users in 50 networks, and present the performance of blocking time based virtual coordinate to show its superiority on decreased end to end delay and PDR. In this part of simulation, we don't show the result of *SEARCH*, as it performs as bad as geographic routing with hop based virtual coordinate. The reason is the widespread primary users seriously hamper the routing requests to arrive at destination, consequentially most paths for forwarding the packets can not be constructed successfully.



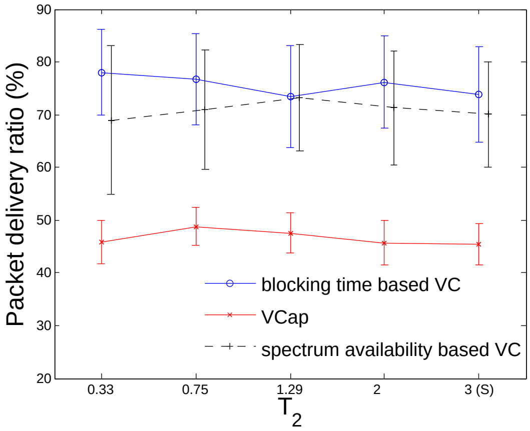
(a) Packet delivery ratio (b) Delay

Figure 5.10 Geographic routing in single secondary channel scenario, $P_{\text{OFF}} = 0.9$ for all primary users, $T_1 = 3s$, T_2 varies.

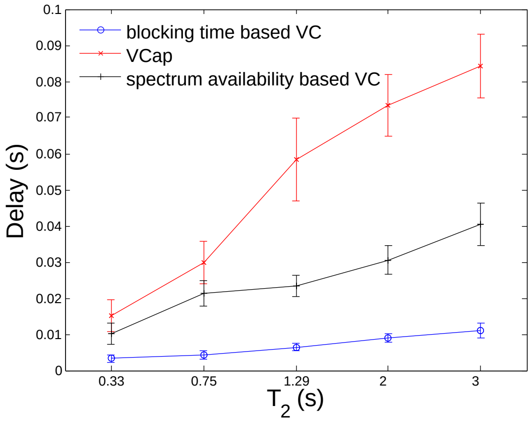
Figure 5.10(b) shows as T_2 increases from 0.33s to 3s, the delay of successfully delivered packets also increases for both blocking time based virtual coordinate and VCap, but a constant gap exists in between. Whereas, the delay of spectrum availability based virtual coordinate is random as respect to sojourn time, the reason is the routing metric in this scenario doesn't involve blocking time imposed by primary users.

The packet delivery ratio shown in Figure 5.10(a) is constant with both blocking time based virtual coordinate and VCap, because all the primary users have the same P_{OFF} which is 0.9. Particularly, blocking time based virtual coordinate achieves higher packet delivery ratio than the other two virtual ordinates, the reason is when the former is applied, less packets are dropped from buffer as the time of being blocked is shorter for the secondary users on the path.

Now we have a look at the CRN with two licensed channels. As to performance of delay, because of the second available channel, blocking time based virtual coordinate achieves very delay, in contrast, spectrum availability based virtual coordinate still demonstrates obvious randomness, as is shown in Figure 5.11(b). Compare Figure 5.11(a) and 5.10(a), we can see the packet delivery ratio in two channel network is obviously higher than that in single channel network, as the second channel provides extra transmission opportunities. Blocking time based virtual coordinate achieves up to 10% better performance than that with spectrum availability based VC, the reason is packets in buffer have greater likelihood to be sent out before getting dropped.



(a) Packet delivery ratio



(b) Delay

Figure 5.11 Geographic routing in two secondary channel scenario, $P_{\text{OFF}} = 0.9$ for all primary users, $T_1 = 3s$, T_2 varies.

5.6.4 Sensitivity of SAViC to Estimation Errors

In this Section, we evaluate the performance of SAViC in the presence of erroneous estimates about the primary user activity. In order to induce a particular amount of errors, we artificially add errors to duty cycle of primary user activity by directly modifying the implementation of 2 state markov chain. By doing this a real life scenario is built, where estimation errors are expected. The simulation is conducted with the same configuration with Figure 5.6(a). Figure 5.12 shows even the errors are significant, i.e., DC is modified by 25% to 100%, the corresponding performance varies only at most 13%.

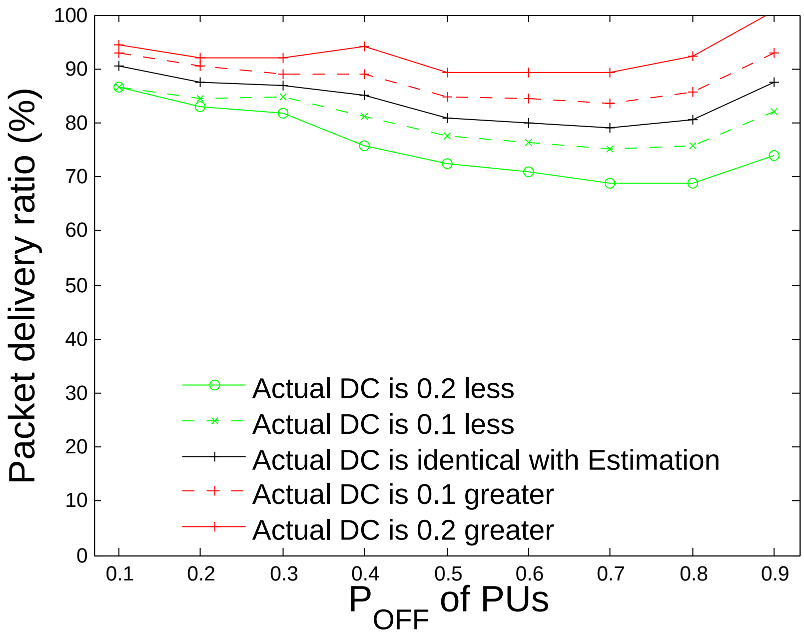


Figure 5.12 In the setting of Figure 5.6(a), perofrmance of DC based virtual coordinate is not affected greatly by the erroneous estimation

5.7 CONCLUSION

The proposed virtual coordinate SAViC reshapes the topology of cognitive radio network based on sensing results of spectrum availability. As SAViC adjusts the distance between nodes based on the communication obstruction caused by primary users, the virtual coordinate comprises a part of the routing decision, so that geographic routing is able to detour the areas seriously affected by primary user. Geographic routing with SAViC greatly simplifies the computation and communication burden on each secondary user involved in routing in CRN. Together with SAViC, geographic routing achieves better performances than other geographic routing designed for CRN through extensive simulation. This paradigm of routing is especially suitable for CRN network where the resource limited CR nodes can only support geographic routing. This work emphasises on avoiding primary users' influence with geographic routing, and doesn't consider the interference issue among the secondary users, which should be addressed in the future work.

6

Conclusion

Cognitive radio network lays a foundation for the In this dissertation, we solve a series of problems residing from layer 1 to layer 3 in the OSI model [2] of CRN with distributed solutions.

- We solve the power and spectrum allocation problem in IEEE 802.22 networks. This work mainly lies in layer 1, after deciding the maximal transmission power on each secondary cellular base station, we formulate the distributed spectrum allocation problem in TV white space scenario (a special CRN where primary user is TV station which operates according to a slow and pre-decided schedule) into a canonical congestion game, then propose distributed algorithm corresponding to the behaviour of player in the game.

- When the availability of spectrum is considered to have the same probability due to licensed users' activity, and local operation is needed, i.e., for cooperative sensing, unlicensed users need to form clusters and the clusters should be robust against the primary users' activity. A distributed clustering scheme for CRN is proposed. The process of finalizing cluster membership is innovatively formulated into a congestion game, then as long as cluster head is decided, clusters which have clear membership are formed quickly by applying the light-weighted distributed scheme derived from the game. This problem can be regarded to lie in layer 2.

- In layer 3, we propose a lighted weighted routing scheme for CRN. Spectrum aware virtual coordinate is proposed, thus light weighted geographic routing can be used to decide the next hop.

Many further efforts can be done on the basis of the work in this thesis. As to channel and power allocation in IEEE 802.22 network, cooperation can be brought to improve performance. As a light weight clustering scheme which can cope with mobility of both spectrum and users, ROSS can be used to support routing and resource allocation.

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