Abstract

Due to the proprietary spectrum allocation paradigm and the boom of wireless communications, spectrum scarcity has become an increasingly pressing problem. Cognitive Radio 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 for spectrum utilization in many aspects, such as deciding the spectrum which is available and suitable for communication, deciding the maximum transmission power to avoid harmful interference at primary users, delivering service, etc.

Due to the propagation path attenuation of spectrum, the available spectrum or resources at cognitive radio users are dependant on their locations, which are usually different from place to place. Furthermore, the available spectrum varies due to primary users' activities. Thus, a secondary user is suitable to make decisions autonomously and only based on the local information, as it is easier for a secondary user to know the updated spectrum availability on it. In this thesis, we design distributed algorithms to solve the problems imposed on cognitive radio networks (CRNs), and show the advantages of distributed solutions over centralized schemes in CRNs. In the process of algorithm design, we employ game theory to guarantee the dynamics within CRN to converge into Nash equilibrium.

The concrete problems solved in this thesis reside from physical layer up to network layer in CRNs. On physical layer, We propose method to let secondary users choose channel and power in a network, whose architecture is compatible with the regulation on the TV database access. 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 enlightened by the player behaviours in the game. Power allocation is then conducted on the channel decided before. On MAC layer, a distributed clustering scheme for cognitive radio ad hoc network (CRAHN) is proposed. CRAHN adopts cluster structure to obtain more accurate sensing result, or to facilitate network management. In order to resistant the compulsory evacuation of channel due to primary users' random appearance, the formed clusters should poses more common channels within them, and should be able to control their clusters sizes. The negotiation among neighbouring secondary users to form clusters with above characteristics is formulated into a congestion game, then a lightweight distributed scheme is derived. On network layer, we propose a lightweight geographic routing scheme which works with spectrum aware virtual coordinate for CRN. The spectrum aware virtual coordinate integrates the spectrum availability between any pair of neighbouring secondary users, in particular, the distance between two secondary users is longer when the available spectrum is more scare in between them. Except for the last problem, we also propose centralized schemes to give bounds on the performance. We

compare distributed and centralized schemes in the aspects of singling overhead and time complexity, and analysis the strength and weakness of the two in different CRN scenarios.

Acknowledgments.

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

Reprints were made with permission from the publishers.

Contents

1

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* [137], 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 [103]. 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 [129]. Open spectrum access [93] 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 band) 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 [71].

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 [66]. 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 [7], 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 [137], and call this spectrum usage policy as *hierarchical access model*, where licensed users are called primary users (PUs), 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 (CR) is firstly proposed by Mitola III who defines the concept of CR in his dissertation [87] 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 [4] 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. [84] proposes discrete Markov chain and adjusts duty circle models to describe the availability of licensed spectrum for GSM on 900/1800 MHz. [121] 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 [70]. 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 [76]. 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.) [76], channel switching delay [22], and channel holding time, i.e., the expected time duration that the primary users don't occupy the channel before any one occupies again.

1.3 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 [28]. 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].

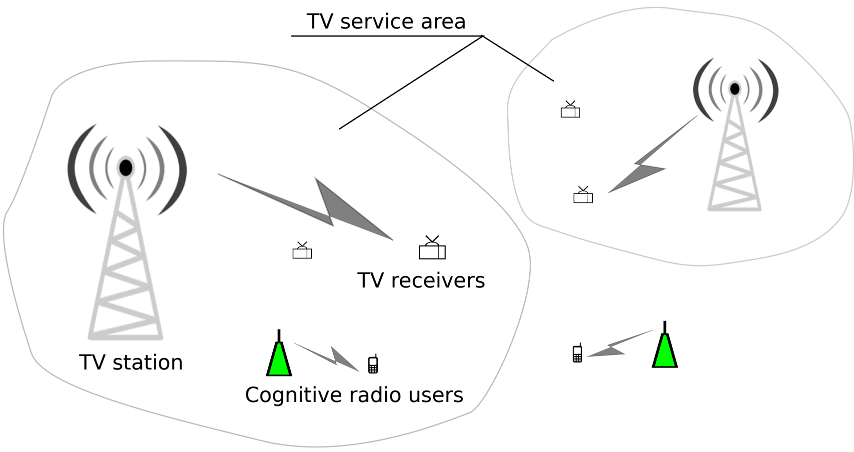


Figure 1.1 The concept of overlay spectrum usage in a TV service scenario. The hull shows the range of a TV service area, inside and out of which secondary users work on the licensed channels.

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 [131]. 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 [55]. 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 [135].

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 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.

1.4.1 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.

1.4.2 TV White Space

On November 4, 2008, FCC made far reaching changes on spectrum usage by opening the unused portion of the UHF TV space to unlicensed secondary users. *Unused portion* here denotes the TV spectrum which is not currently being used by TV stations, or that secondary users can use while the ongoing TV broadcasting on the same spectrum is not interfered. These Unused portion of TV spectrum is called TV White Space (TVWS). Locating within the VHF and UHF range, TVWS is highly desirable for wireless communications, because it has good properties on propagation, buildings penetration, and broadband payload capacity.

In the US, the requirements for secondary spectrum usage in the TV broadcast bands are given by FCC. Autonomous spectrum sensing is one approach for secondary users to decide the available TV spectrum. With sensing ability, every secondary user scans certain parts of the TV spectrum band and is able to detect TV transmission even from a very distant place such that those channels can be ruled out for usage. However, to real prevent any interference with ongoing TV broadcasts, the sensing algorithm becomes quite complex. Moreover, it is required to be conservative when deciding the available TV channels leading to an underestimation of available TV channels and causing inefficiencies [54]. Considering the slow change of TV spectrum usage, along with the fact that the spectrum usage by TV stations is scheduled, the geolocation approach together with central database becomes more appealing in TVWS utilization scenario. FCC adopts this solution as the main way, and 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. FCC regulates portable secondary users to operate from channel 21 (512 MHz) to 51 (698 MHz), with the exception of channel 37. As to fixed secondary usage, the allowed spectrum band is from TV channel 2 (54 MHz) to TV channel 51, with TV channels 3, 4 and 37 being prohibited. Thus, the available TV spectrum is about 600 MHz wide. Compared to conventional unlicensed ISM bands in the 2.4 GHz and 5 GHz band, all together TVWS has more to offer.

While the TV spectrum is free to use under the above mentioned conditions, it might also be 'polluted' by primary TV stations due to the coexistence with them. [56] analyzes the capacity possibly provided by exploiting free TV channels. Complying with the rigid regulation of FCC, TV white space brings hundreds of kilobits/sec per square kilometre for secondary users when the communicating secondary pair is about 1 km apart. The research shows that interference from TV stations and other co-channel secondary users heavily restricts the capacity. [29] further investigates the possible TVWS usage *within* TV service area (referred to as 'gray space'), where the secondary usage does not violate TV receivers. The authors propose another significant amount of TV spectrum, but the interference from TV broadcasters is stronger due to the secondary receivers being closer to TV broadcasters.

The potential applications supported by TVWS are the major driving force for TVWS communications technology. It is envisioned that TVWS can support high-data-rate backbone for fixed stations in Large Area Connectivity, short-range indoor connectivity, seamless connectivity for mobile stations and emergency related equipment. In the following, we give a brief introduction to the governing regulations and industrial standards issued for TVWS usage.

Co-Existence in TV White Space

Regulatory bodies in different countries have issued requirements on the occupancy of TVWS bands by secondary users respectively. The permissible channels regulated by

FCC have been briefly introduced above. Besides, FCC divides the devices operating in the TVWS (TV band devices, or TVBDs) into three categories: Fixed device, Mode I personal/portable device, and Mode II personal/portable device. Every category obeys distinct rules on transmission power, mandatory database access and so on. Fixed and Mode II devices are connected to the database directly (or indirectly by another fixed or Mode II TVBD), Fixed device accesses DB at least once per day, Mode II device has to access DB every 60 seconds, or when it changes location by more than 100 meters. The transmission power for Fixed TVBD is 4 W, and 100 mW for Mode II TVBD. Mode I TVBD operates only under the control of a fixed or Mode II TVBD, and accesses them for available channels every 60 seconds. There is also regulations on the antenna heights and other aspects. OFCOM (being the regulatory authority in UK) opens less TVWS for TVBD and categorizes White Space Devices (WSDs) into Master WSD and Slave WSD which are roughly equivalent to fixed/Mode II TVBD and Mode I TVBD, respectively. ECC (being the regulatory authority in Europe) also adopts Master and Slave structure while utilizing the geolocation and database solution to assign channels and corresponding operating parameters to TVBD. In both FCC and ECC regulations, the available channels are calculated based on the distance between primary and secondary systems together with some propagation model. Hence, the principle behind the notion of channel availability is the presumed received signal strength at potential TV receivers, which should be obviously below a certain level. FCC adopts a fixed transmit power level for secondary systems and assumes that the distance used (resulting from the propagation model) is sufficient to protect the TV receivers. ECC's restriction is more flexible on the transmission power which can be adjusted based on the distance between the secondary user and the TV receivers. For both regulations, TV receivers may become vulnerable when there are multiple secondary equipments transmitting simultaneously. [67] shows that even the regulations integrate an interference margin for multiple secondary users' transmitting, the TV receivers are still vulnerable.

Standardization on secondary usage of TVWS is very active. IEEE 802.19 is a family of IEEE 802 standards in Wireless Coexistence Working Group, among which, IEEE 802.19.1 is for wireless coexistence in TVWS. IEEE 802.11af is standards for WLAN operation in TVWS, IEEE 802.15.4m is for low rate (LR) WPAN operating in TVWS. IEEE 802.22 is for Wireless Regional Area Network (WRAN) using TVWS. As TV band is only 6 or 7 MHz while WLAN channel bandwidth is 40 MHz for state-of-the-art IEEE 802.11n amendment, IEEE 802.11af proposes channel aggregation mechanism for WLAN working with TVWS. Maximum transmit power and spectrum mask of Mode I should be approved by Mode II devices beforehand.

IEEE 802.22 has been the first IEEE standard for wireless regional area network (WRAN) working on TV white space. According to this standard, the system consists of a base station and customer premises equipment (or terminals for short), where terminals are associated with base stations, and are served by them. Recent standard published in Nov. 2010 mentions both, i.e. sensing ability as well as TVWS geolocation and database look-up as schemes for detecting primary systems. Self-coexistence mechanism is also proposed, which provides a TDMA like mechanism for WBSes to share TVWS. [59] proposes a distributed solution for power control and channel assignment in both down-link and up-link communication in a WRAN, but the investigated secondary network is composed with only one base station and multiple terminals.

1.5 Problem Statement

The

Adopting centralized or decentralized solutions is largely dependant on the network types and desired services to convey. As to secondary users working with TV white space, regulations and standards desire one centralized database, which can be used to conduct certain centralized solution to assign the resources. As to CRAHNs which consist of mobile autonomous secondary users and without any infrastructure, distributed scheme practically becomes the sole choice. Actually, the majority of the research in cognitive radio domain is carried out with distributed manner.

We proposes distributed solutions for a series of problems in cognitive radio networks. We investigate the differences between decentralized and centralized schemes in terms of several criterion, i.e., Performance, overhead and needed time.

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 [3] are addressed.

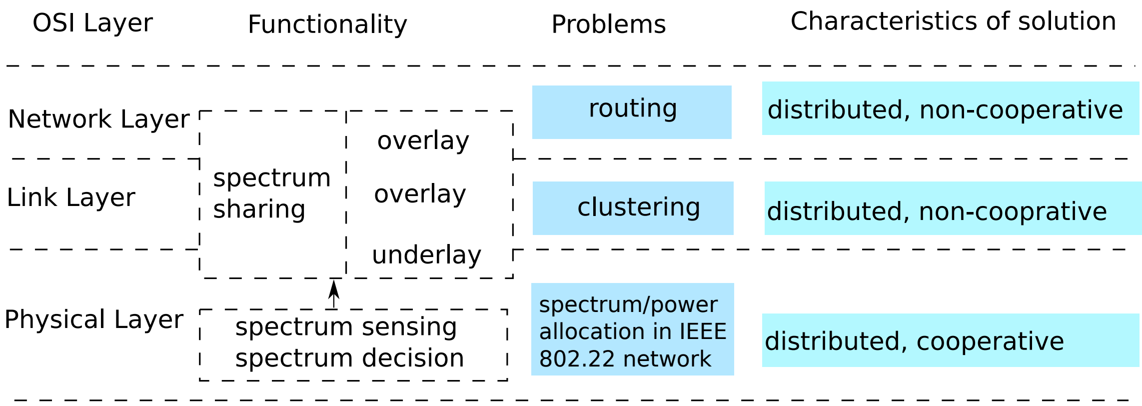


Figure 1.2 Spectrum management and the problems addressed in this thesis

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.

1.5.1 Channel and Power Allocation in IEEE 802.22 Network

There are several problems with the current regulations and standards proposing on the utilization of TVWS. Firstly, most of these proposals rely on the centralized database to manage the spectrum usage in a centralized manner. This paradigm is not suitable when the TVBD belong to different business bodies, i.e., operators. Thus, a centralized resource allocation is infeasible. Secondly, the current usage of TVWS is prudent, i.e., on working channel and transmission power as introduced in Section 1.4.2. These conservative measures on the transmission power restrict the full utilization of TV spectrum. Thirdly, as the transmission power of TVBD is restricted, the interference between TVBDs is not given consideration. In fact, as the interference caused between co-channel transmitters may not be symmetric, the solutions proposed for the channel assignment problems in conventional networks, e.g., ad hoc networks, or mesh networks can not be applied any more. Up to our knowledge, there is no work coping with co-existence between secondary base station with both primary TV broadcasters and other base stations.

In this thesis, we propose a solution for the joint power and channel allocation problem for the base stations in a WRAN network.

1.5.2 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 [75]. Secondly, cluster structure facilitates cooperative sensing and increases the sensing reliability [116]. Thirdly, cluster structure supports coordinated channel switching and simplifies routing in ad-hoc cognitive radio networks [112].

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 [24,64,126,136] 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. [81] targets large number of control channels within cluster, but it intriguers high complexity.

1.5.3 Geographic Routing in CRN with Spectrum Aware Virtual Coordinate

Recent measurement in [96] 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 [12]. 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.

1.5.4 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.

1.6 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 [71], and makes channel allocation problem not to fit into the congestion game model proposed in [80] 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 [73]. 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 [41, 82].

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.

1.7 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 [90, 120]. Game theory is a powerful mathematical tool for studying, modelling and analysing the interaction among rational decision makers which have potential conflicting objectives. When the network entities are seen to be self-interested rational, game theoretic approach can guide the behaviours of them, so as to achieve desirable collective behaviours and performance with respect to the system level objective. 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 [85].

  In communication system, a device is programmed to maximize 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 obtain 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 can be 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 the system will stabilize as the current CW is the optimal for every station. Such best response naturally defines an algorithm for Wi-Fi systems. Besides, outcome from game theory is robust [55].

- **Game theory is suitable to apply in cognitive radio network because of the properties of CRN.** Firstly, as only local information is needed to feed each user, 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. Distributed schemes usually lead to Nash equilibrium (NE), which is usually sub optimal. As comparison, although optimization is the common tool to pursue global optimality, when the information is not accurate or adequate enough, or the optimization itself is difficult to solve, the optimized results can be far from optimal.

  Secondly, combinatorial nature of communication problems makes game theory as one of a few choices [55]. Many problems in wireless communication involve integer variables, i.e., channel availability, 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 [92].

A game of normal form 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.
- $s = (s_i, \cdots, s_n)$ is vector of strategies and also is called as one strategy profile, which represents an instance of all players' choices. There is $s \in \mathcal{S}$.

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

- 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.

- $u_i : \mathcal{S} \to \mathbb{R}$ is the utility function of player i. $\mathcal{S}_{-i} = \prod_{i \in \mathcal{N} \setminus \{i\}} \mathcal{S}_i$ is the set of states of all the other players except for player i. As to each player i, its utility 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 utility 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. Actually, one player maximizes its utility is equivalent to that the player minimizes its cost, note that cost is the reversed utility.

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 Equilibrium

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,

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

s is also called strong dominant strategy, and when the $>$ can be written as $\geq$, s is called weak dominate strategy. 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 equilibrium, and mechanism design [65] is developed to design games which have dominate strategy equilibrium, 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/utility. Nash equilibrium successfully captures this property, and is the most discussed and pursued solution concept in game theory.

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 equilibrium is a Nash equilibrium, 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.

Being not unique and possibly sub-optimal, NE is still applied in extremely diverse applications due to the reasons discussed in the beginning of this section. Thus, when pursuing NE as solution, people should answer the question that, 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 concept, but it doesn't tell how to reach such a state. Hence, it is important to find an efficient algorithm to reach the equilibrium. The notion of *NP-completeness* is not an appropriate concept of complexity for *finding a Nash equilibrium* problem as NE always exists, nevertheless, theoretical scientists tell *finding a Nash equilibrium* problem is a combinatorial problem and is often very difficult (Chapter 2, [92]). Having said that, in some games, with the special strategy space structure, or players' special behaviours, efficient algorithms to reach NE exist.

Pareto Optimality

An strategy profile $\bar{s}$ is *Pareto optimality* (PO), if there does not exist profile s with $u_i(s) \geq u_i(\bar{s})$ for each $i \in N$, and meanwhile $u_i(s) > u_i(\bar{s})$ for at least one $i \in N$. PO 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, and the lack of stability.

[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 choose one strategy from theirs strategy sets, then 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 probability distribution. 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 [92].

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 a function only of its strategy s_i, but not the strategies chosen by all n players, then the maximization of its payoff or minimization of its cost becomes an optimization problem, and such game has n such optimization problems in total. Whereas as to a general 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 [119], congestion game is a game where players simultaneously allocate sets of resources to minimize their costs, and the cost of a resource is a function of congestion, which is the number of players choosing the resource. Congestion games 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 [52].

Now we give the formal definition of a congestion game. A congestion game [104] [119] 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 is an attractive game model which describes the problem where participants compete for limited resources in a non-cooperative manner, it has good property that Nash equilibrium can be achieved after finite steps of best response dynamic.

Example: Server Matching

We describe an exemplary congestion game *server matching* [72] to illustrate the extensive application of game theory in communication systems. Consider a number 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 is a monotonic increasing function of the *number of clients* attached to it. When clients try to choose one server which has the shortest latency, a congestion game is formed.

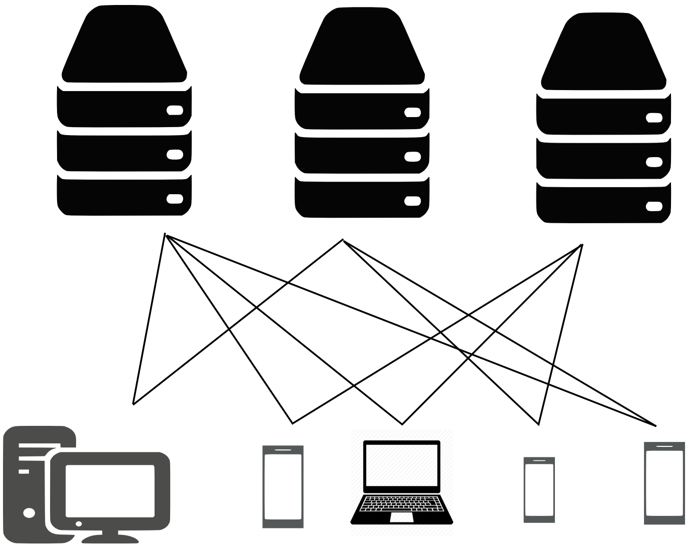


Figure 2.1 An example server matching, one server is possible strategy of the client at the other end of the connecting line

More formally, this corresponding congestion game is composed of players (the self-interested clients) and resources (servers), where players are allowed to choose one certain resources to use. There is cost (latency) generated on a resource for the players who use that resource, and the cost is monotonic increasing with the number of players using it. As congestion game permits convergence when every players in turn adopt the strategy which leads to a better utility. Thus in server matching problem, when clients in turn choose a permissible server with a smaller predicted latency, then after finite number of steps, no client has motivation to switch any more, and we reach a NE.

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, it is known [119] that, for every congestion game, every best response ends in finite steps. In the following, we introduce the sketch of the proof of this proposition, as the proof also reveals the number of steps needed to reach a Nash Equilibrium.

We first introduce Rosenthal's potential function $\phi(s) : \mathcal{S} \rightarrow Z$, where s is the strategy profile of all the players, let $s = s_1, s_2, \cdots, s_N$:

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

$n_r^i(s)$ 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, $\sum\limits_{r \in s_i} g_r(n_r^i(s))$ 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 [119], 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 $\sum\limits_{r \in s_N} g_r(n_r^N(s))$ 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 $\sum\limits_{r \in s_N} g_r(n_r^N(s))$ 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.

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

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, and every best response move made by a player decreases it at least by 1, 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 and transmission power are scarce, Meanwhile, new services raise new requirements for these resources. Resource allocation and its optimization are needed to accommodate the needs. Various optimization problems are formulated to improve radio resource usage in CRN [26, 128, 132]. Optimization can be conducted from either a global view or from individual perspectives.

Many wireless resource allocation problems are formulated as constrained optimization problems. Table 2.2 shows the commonly used parameters, objectives and constraints of some optimization problems in wireless communication. Part of the contents in Table 2.2 refers [55].

The solutions to optimization problems can be categorized by their properties, i.e., convex, linear, integer, or non-convex non-linear, etc. In this thesis, we make use of different

	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

solvers, i.e., Lindo, Gurobi, to solve the formulated optimization problems in different categories.

3

DISTRIBUTED CHANNEL AND POWER ALLOCATION IEEE 802.22 NETWORKS

3.1 Motivation

Secondary users working with 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 frequencies of TV bands enable broadband access over larger geographic ranges compared to higher frequency bands. Nevertheless, services on TV receivers need to be protected with so called interference margin [73] which should not be exceeded by the accumulated interference caused by all secondary users working on the the channel.

FCC and ECC have announced rules on the transmission power of secondary users working in TV white space in US and Europe respectively [8, 9]. FCC requires a minimum distance between secondary user and TV service area, besides, the transmission power for fixed secondary users is set as 4 W, which is a conservative setting. FCC believes with these prudent measures, the interference margin can not be exceeded by interference from secondary users. But it may not be the case when there are multiple secondary equipments transmitting at the same time, which is pointed in [67]. ECC requires the secondary users to adapt their maximum transmission power according to the distance away from the TV receivers.

FCC issued a memorandum [1, 8] in 2010, which removes the mandatory rigid sensing requirements, and prompts the usage of geolocations[1] of secondary users. FCC regulates a centralized database, which registers all the secondary users within one certain area.

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

[1]Geolocation means both geographic location and terrain.

Secondary users can access the database, and can only use the channels assigned by the database. Work [89] follows this rule to obviate spectrum sensing and only relies on the database of TV incumbents to determine the white space availability for secondary users. The authors of [89] demonstrate the feasibility of predicting the available TV spectrum accurately using sophisticated propagation models (Longley-Rice) and geolocations of secondary users. A central database contains the geolocations of all TV stations, then the database calculates the received signal strength index (RSSI) levels of TV UHF signals on all secondary users and accordingly determines the available TV spectrum for them. If RSSI of a channel is below a certain threshold, TV service is regarded not to exist, and the channel is seen available there. The calculated results on channel availability is very close to the measurement results. The work of [89] gives big impetus to the usage of database mode. As in TV white space, the accurate RSSI can be obtained with geolocations and suitable propagation model, given geolocation 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) on the TV receivers.

In this chapter, we investigate the usage of TV spectrum in a WRAN which complies with IEEE 802.22 network. The secondary users are assumed to be cellular systems consisting of base stations and associated terminals, all of which work on TV white spectrum. Some cellular networks, i.e., GSM or LTE network, work on licensed spectrum and 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 makes the problem of channel and power selection difficult. With the existence of central database, it is natural to utilize it as a central controller to assign channel and power usage for secondary users, but the secondary users may belong to different commercial groups and they may not content with the assigned resource. Hence, the spectrum sharing of the secondary users in IEEE 802.22 network should be decided in distributed manner and each secondary user takes care of its own interest, i.e., to maximize its preferred utility.

Given all the other WBSs' 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 obtain better SINR on its terminals and meanwhile maximize their coverage [59, 127]. Nevertheless, high transmission power causes significant co-channel interference to other secondary users operating on the same channel. Hence, a secondary cell has to balance its transmission power and the caused interference on other cells, meanwhile to choose working channel to decrease the experienced interference on its terminals. The goal of this chapter is to protect the primary users from harmful interferences, meanwhile to find a strategy for WBSs to choose channel and power level in order to acquire good SINR on end terminals.

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 should not be interfered by secondary systems. The secondary systems are IEEE 802.22 Wireless Regional Area Network base stations utilizing the TV spectrum with senseless mode [89]. WBSs locate within one area whereas TV areas locate around them. WBSs serve a set of end users/terminals. These secondary systems are distributed over a certain area A and is surrounded by multiple DTV service areas, as Fig. 3.1 shows. Denote the set of DTV stations by $\mathcal{K}$ and the collection of WBSs by $\mathcal{N}$ with $|\mathcal{N}| = N$. The set of TV white spectrum contains multiple channels which are denoted as $\mathcal{C}$, they are identical in terms of attenuation and fading. Let $c(i)$ denote the channel used by a WBS $i \in \mathcal{N}$.

When there are two WBSs work on the same channel, co-channel interference is caused on each, while, neighbouring channel interference is not considered. To simplify the analysis, we assume that each DTV station as well as each WBS utilizes exactly one channel.[2] 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 uses 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.

In the rest of the chapter, we use WBS and secondary base station interchangeably. There are interference measurement equipments deployed on the contours of TV service areas (as bold rectangles in Fig. 3.1), which represent the worst located TV receivers in the TV service areas. For these interference measurement devices, an interference threshold should not be violated by the noise generated by the secondary users. 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. WBSs 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 WBSs.

3.2.1 SINR on terminals

WBSs are interested in payload data communication with their associated terminals. As to performance metric for the QoS provisioning, we choose the signal to noise and interference ratio (SINR) on the terminals. SINR 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, as the interference caused by uplink communication is neglectable.

Given a WBS i, another WBS which works on the same channel is denoted as $\bar{i}$. As to a certain terminal m associated to WBS i, the path losses between m and the serving WBS i and interfering WBS $\bar{i}$ are denoted as h_{im} and $h_{\bar{i}m}$ respectively. The path loss is dependent on the distance between the corresponding equipments, e.g. $h_{im} = K \cdot d_{im}^{-\alpha}$, where α is the path loss exponent, d_{im} is the distance between i and m, K is a constant which models

[2]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.

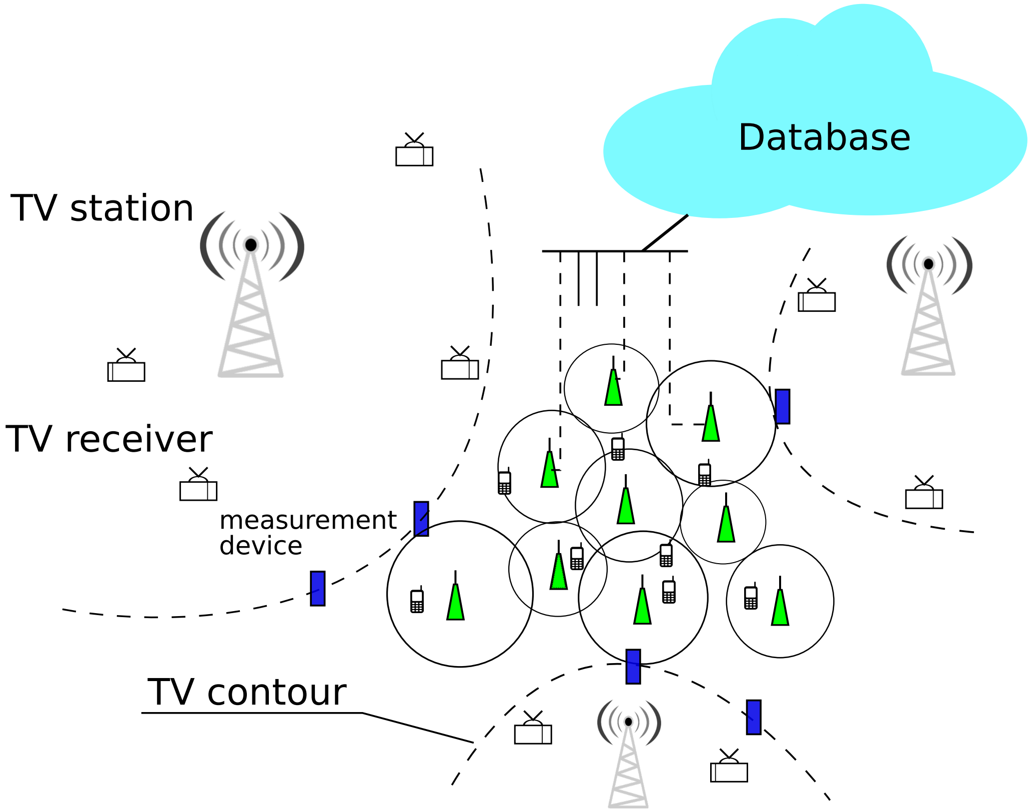


Figure 3.1 System model: WBS cells and DTV systems

the reference loss over a single unit of distance. N_0 denotes the thermal noise power. Shadowing without fading is considered in our model. The sum of all disturbing radio frequency effects (including interference) on terminal m (we assume the working channel is c) is as following,

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

where $P_{\bar{i}}^c$ denotes the transmit power of interfering WBS $\bar{i}$, $z_{\bar{i}m}$ models the zero-mean log-normally distributed shadow fading between $\bar{i}$ and m, and the standard deviation is σ_{SH}. Then we get the SINR on end terminal m,

$$\gamma_m = \frac{P_i^c \cdot h_{im} \cdot z_{im}}{f_m^c} \tag{3.2}$$

3.2.2 Problem Statement

Our goal is to design distributed solution for WBSs to choose channel and transmission power, so as to improve the SINR on their end terminals. Each WBS's utility is a function of certain form of the SINR on all its end terminals, i.e., the utility can be the average SINR at all its terminals. When adopting a function of SINR on all terminals as utility, as the terminals are mobile, and they are influenced by many factors, i.e., the type of service provided to the terminals, the utility may diverge from the real performance of the terminals. On the other hand, it is not appropriate to choose one [39] or more fixed terminals, and use their SINRs to represent the SINR for all the other terminals in that cell, because their location could diverge greatly with the locations of the other terminals.

As a result, we propose a metric *QuasiSINR* to represent WBS's performance, which is independent on the actual locations terminals.

QuasiSINR of WBS

QuasiSINR is an indication of SINR that a WBS can provide to its terminals. Given an auxiliary circle centering at WBS, quasiSINR of a WBS is the ratio between the weakest signal of interest and the summation of the strongest interference caused on the circle. Figure 3.2 illustrates how is quasiSINR calculated. The discussed WBS is denoted as i, and the rest WBSs are denoted as j, j' and j'' respectively. We assume all the WBSs work on the channel k, this co-channel interference is caused on each WBS. An auxiliary dashed circle centering at WBS i is shown, whose radius is δ.

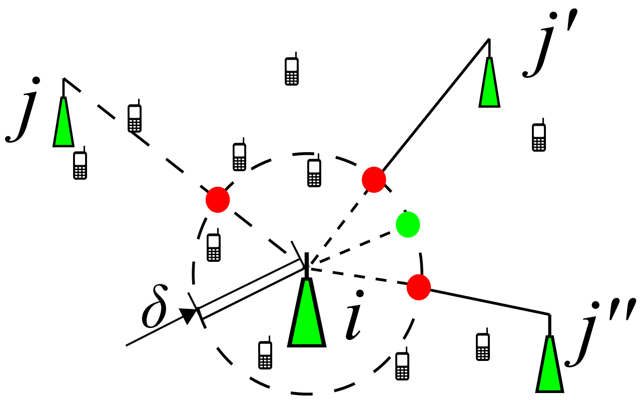


Figure 3.2 QuasiSINR is the ratio between the power of signal of interest on the green point with the co-channel interferences on the red points

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, $\tilde{P}_i$ is the power of the signal of interest received on the green dot

The interference on auxiliary circle 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, which is the crossing of the connecting line between WBS i and j and the auxiliary circle. The sum of interference on the intersections of auxiliary circle and connecting lines is,

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

In the following chapter, $\tilde{P}$ and $\tilde{f}$ represent the received power of interest and the strongest interference on the auxiliary circle. The quasiSINR of WBS i is,

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

We can adjust the radius of the auxiliary circle δ to let WBS foster better service to the 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 WBSs are independent on the individual end terminals. With quasiSINR, the channel and power allocation problem exclude the terminals and simplify the problem.

Calculation Instead of Measurement

According to our system model, every WBS is able to access the central database which stores all WBSs' geolocations i.e., working channel, transmission power, the characteristics of radio frequency environment such as parameters of attenuation and shadowing. To obtain quasiSINR, we don't need to measure the signal strength, but only need to calculate them based on Formula 3.6 using propagation model [67] and the information stored in central database. A WBS also knows the interference it causes on the auxiliary circles of other co-channel WBSs via accessing the 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 minimize the sum of inverted quasiSINR.

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

For a WBS, each channel in $\mathcal{C}$ receives different levels of interference from other WBSs working on it. In order to provide better service to its end users, WBS is liable to choose either the channel permitting higher transmission power or the channel which experiences 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

Firstly we introduce the solutions proposed on the utilization of TV white space, which includes regulations, proposed standards and recent research advances. Secondly we introduce the power and channel allocation schemes proposed for cognitive radio network, and explain the reasons why they are not suitable to solve our problem.

3.3.1 Utilization of TV white space

Some prototype applications which only rely on the TV database are proposed in cellular network [46, 101] and WiFi-like network [98] based on the FCC regulation.

Standardization activities are in progress on TVWS utilization, including IEEE 802.22 [2] for Wireless Regional Area Networks (WRAN), IEEE 802.11af [48] for WLAN, IEEE 802.15.4m [5] for 802.15.4 wireless networks in TVWS and 802.19.1 [6] for coexistence methods among local and Metropolitan Area Networks (MAN).

Scientific research on utilization of TVWS goes on in parallel with the regulatory agencies. Feng et al. [47] investigate the business model of TV spectrum utilization in database involved network structure, emphasis on the price policy of the channels approved by FCC. Spectrum sharing in TVWS is formulated as a series of optimization problems. The guarantee that TV receivers should not be affected by the aggregate interferences form TVBDs is one constraint. The objective can be maximizing TVBD's downlink transmission power [73], uplink transmission power [117], or best geographic distribution of TVBDs [133]. [30, 40, 50, 110, 130] emphasise on interference mitigation among TVBDs via spectrum allocation. Vehicular networks operating with TVWS assisted by TV database and cooperative sensing is discussed in [42]. Work [44] 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.

3.3.2 Resource Allocation in CRN

The proposed solutions can be divided into two categories, centralized and distributed, which will be introduced sequentially.

To implement centralized solutions, optimization problems are often formulated. In [60], the objective is to increase the number of supported terminals whose SINRs are above a threshold, and the constrains are to refrain the interference at the primary users within a certain margin. [25] minimizes the transmission power and meanwhile makes sure the SINR of terminal is above a threshold, but this work fails to consider the protection of primary users. A heuristic algorithm is proposed in [99], which considers the channel availability and transmission demand of each WBS. The aforementioned two schemes don't consider varying the transmission power.

As to decentralized schemes, in order to avoid or to alleviate co-channel interference between cells, and to allow arbitrary number of cells to work in IEEE 802.22 network, [61] proposes distributed inter-network spectrum sharing scheme, where contention decisions are made in a distributed way and the winner cells can use the shared channels. This work doesn't consider the role of transmission power in the co-channel interference. An distributed power allocation (single channel) scheme based on learning for secondary networks is given in [49], where penalty function involving the interference threshold on primary systems is used.

[59] 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 need to cope with the multiple cells in our problem. Joint channel-power selection for multiple transmission links (pairs) is investigated in [127]. The authors decompose the Lagrangian dual of the problem, then propose a distributed scheme based on the dual parameters. The scheme converges into 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. A distributed joint power and channel allocation is proposed in [94], each base station chooses optimal power level and channel to optimize its utility, which results in induced received interference and caused 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. Firstly, the paper doesn't provide means for base stations to obtain the needed information which is needed to calculate the utility function. Secondly, 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 a potential game, converge speed or the number of updates before convergence is a theoretic problem which is still unsolved. 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 indicate meaningful performance metrics, i.e., SINR on terminals, or the total transmission power consumption. In [39], Chen et al. investigate the channel allocation problem in the scenario of TV white space. The channel allocation problem is formulated into a potential game, individual WBS's utility is to maximize the capacity of one single static terminal.

Potential game is also adopted in work [43] to design algorithms, which mitigates the adjacent interference.

[74] adopts cooperation game to research the coexistence of femtocells. Each femtocell negotiates with neighbouring fremcells, and they form temporary coalition, but the goal of this solution is to allocate resource block in terms of time and transmission power.

Distributed algorithm based on Learning is proposed in [62] for LTE to allocate the the resource block in down link, which leads to correlated equilibrium, but slow converge hinters its application. [25] proposes both centralized and decentralized solutions. Two distributed schemes are proposed, joint channel and power allocation is formulated into a weighted potential game, as an alternative workaround, the problem is solved in two sequential phases.

3.4 Problem Decomposition and Corresponding Related Works

In the related works, the protection on primary users is taken care during the process where channel and power selection are conducted, but according to the current regulations and standards, there exists no communication means between the secondary users and the primary users. Besides, assuming such communication media is available, the communication overhead between primary users and second users is considerable. We decide the maximal transmission power for each WBS on each channel before dealing with channel and power allocation, and this work is conducted at the centralized database. As the database has global info of the network, it guarantees the primary users are not interfered when all the WBSs work on the same channel. By decompose the problem into two subproblems, the protection on the primary users from harmful interferences is excluded out of the latter consideration on channel and power allocation.

In summery, we solve the channel and power allocation in downlink communication in IEEE 802.22 network by solving three sequential sub problems:

- Firstly, given a set of secondary WBSs and their geo-locations, the maximum permitted transmit power on each channel for each WBS is determined, so that the interference margin can not be exceeded no matter how do WBSs utilize the spectrum and power resources. In other words, the dynamics in the secondary network is transparent to the primary system.
- Secondly, once the maximal transmit power is determined, each WBS chooses its operating channel, this subproblem is a channel allocation problem with different transmission power.
- Thirdly, transmission power is adjusted on the channel which is decided in the previous step.

The first subproblem is a centralized approach, the following two problems are solved with 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, the aggregate interference caused by WBSs at the contours of TV receivers should be within interference margin [73]. 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 requires 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 formed to satisfy the sufficient condition for every interference measuring device for the TV receivers.

3.4.2 Channel allocation with fixed transmission power level

After knowing the maximum transmission power on each channel, WBSs need to decide which channel to use so as to mitigate interference among WBSs and provide the best SINR for their end users. Here we assume WBSs' transmission power is the maximum permitted and fixed.

This problem lies in the category of *channel assignment problem*, which has been well investigated in many scenarios. Channel assignment problem tries to mitigate co-channel interference among users, which can be converted into colouring problem thus is NP hard [102]. Authors of [71] propose heuristic algorithms utilizing best response to improve its welfare, but the transmission power is assumed identical and path loss is deemed as symmetric, which renders this method problematic for our problem where transmission is non-identical and the path loss is asymmetric. [91] 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 burden for network in ad-hoc structure. [45, 124] investigate the channel allocation problem under game framework in same collision domain, the authors propose 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.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Mitigating co-channel interference via channel allocation has been attracting plenty of research efforts in the past decade, from multiple channel mesh network [102], Ad hoc network [71] up to cognitive radio network [63, 130]. Channel allocation problem is converted into colouring problem thus is NP hard [102], thus centralized optimization fails to produce. Authors of [71] 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 [130]. For the same purpose, no-regret learning [57, 63] is exploit to optimize the choice on channel. All the available channel allocation schemes are designed under the same assumption, that the transmission power levels are identical, and the attenuation between any pair is reciprocal.

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.

We name the our solution of channel and power allocation as DiCAPS (Distributed Channel Allocation and Power Selection), and call the solution to a sub-problem of it, i.e., channel allocation, as WhiteCat (White space Channel allocation).

3.5 The Maximum Permitted Transmission Power

The WBSs work in underlay manner with primary TV stations, the aggregate generated interference on each channel should not excess the threshold of the interference measuring devices. We adopt the interference model and the optimization methodology from the work of [73] to plan the maximum transmission power on each channel for WBSs. Having a global view of the propagation parameters, geolocations of WBSs and interference threshold at interference measuring devices, linear programming is implied in the database to calculate the maximum permitted power.

For WBS $i \in \mathcal{N}$, the maximum transmission power allowed on channel c is denoted as P_i^c. As to each channel $c \in \mathcal{C}$, the generated interference on each interference measuring device should be within a predefined interference margin I_{pt}^c. The interference margin in a slow fading environment is decided according to [105].

Then the maximum permitted transmission power on channel c for each WBS can be obtained by solving the following optimization problem,

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

P_{min}^c is the prudent transmission power by FCC, we set is as 4 W. P_{max}^c is the maximum transmission power. z is shadow fading as introduced in 3.2. Here we only consider the interference caused by WBSs, and omit the interferences from end terminals. Since WBSs' transmission power is higher and their altitude is higher [73], thus the downlink transmission contributes the major part of interference [14]. The first constraint indicates that the interference margin will not be exceeded even when all the WBSs work on the same channel.

Formula 3.8 will be solved for each channel $c \in \mathcal{C}$. After solving the $|\mathcal{C}|$ problems, the maximum permitted transmission power vector $\boldsymbol{P^c} = \{P_1, \cdots, P_{|\mathcal{N}|}\}, \forall c \in \mathcal{C}$ is obtained.

If implying linear programming to decide the maximal transmission power, the WBSs locating far from TV coverage cell border contribute more to the aggregate 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.

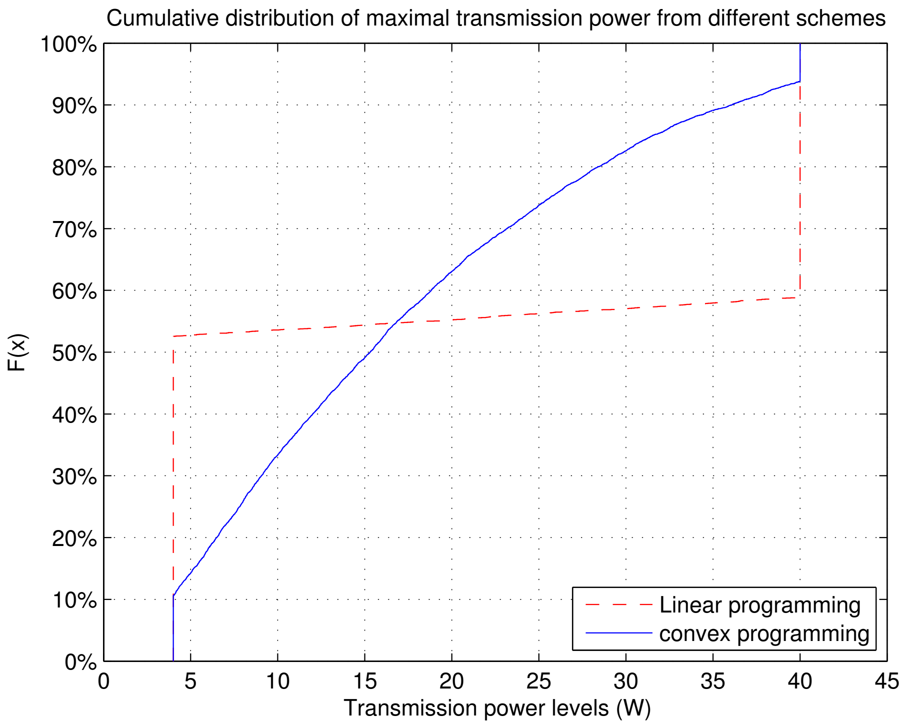


Figure 3.3 Distribution of maximal transmission power levels obtained from convex and linear programming respectively

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.

3.6 Channel Allocation with Fixed Transmission Power

First, we give the centralized solution, then the decentralized scheme is introduced.

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 [79] 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 (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.

Algorithm 1: Spectrum selection by node i

Input: d_{ij}: the distance between interfering WBS i to the auxiliary circle of WBS j 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

$c(i)$ 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 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:

- $\sum_{\substack{j\in\mathcal{N},j\neq i,\\ c(\sigma_j)=c(\sigma_i)}} \tilde{f}^c_{ji}, c \in \mathcal{C}$: the received interference on i' virtual measurement point from other WBSs j working on the same channel for $\forall c \in \mathcal{C}$.

- $\tilde{f}^c_{ij}$: the interference caused by i on j's virtual measurement point when i works on channel $\forall c \in \mathcal{C}$.

- P^c_j: 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 [89] which verifies the usage of geolocation 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 of its channel update. As the location of WBSs and TV stations and the transmission channel and power of TV stations are usually static (entries of TV station change averagely once in 2 days [89]), except for the channel usage in the network, the change of the other data stored in WBS is infrequent.

We refer [91] to decide the sequence for WBSs to update their channel. [91] 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 WBSs 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 [80] which 'reversely engineer' the distributed channel allocation schemes proposed in [23, 71].

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 [80]. 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 [119].

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

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

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,

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

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.

Gap 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. If we regard one WBS as multiple ones which locate at the same place, and each WBS works on one distinct 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 the other WBSs 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, WBSs 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 having the motivation to diverge from the power level being used (the maximal permitted power) if the other WBSs keep their transmission power unchanged.

We adopt the function form of utility proposed in [114].

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

This new utility is function of both its own transmission power and quasiSINR, thus one WBS doesn't need relevant information from other WBSs. 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. Every WBS keeps on minimizing its utility and finally all the WBSs achieve 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 jointly, the optimization problem 3.12 is not quadratic any more and becomes mixed integer non-linear problem, for which no efficient solution exists. 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

$$x_{jk} \cdot x_{ik} = \alpha_{ij}^k \tag{3.19}$$

$$\beta_{ij}^k = p_j^k \cdot \alpha_{ij}^k \tag{3.20}$$

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

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 locations of the WBSs, 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 [58, 108].

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 [94] as comparison. As introduced in section 3.3, [94] 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 [57] 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 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 locations of WBSs and TV contours are illustrated in Fig. 3.4. The other parameters are listed in Table 3.14efsimulationparameter.

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

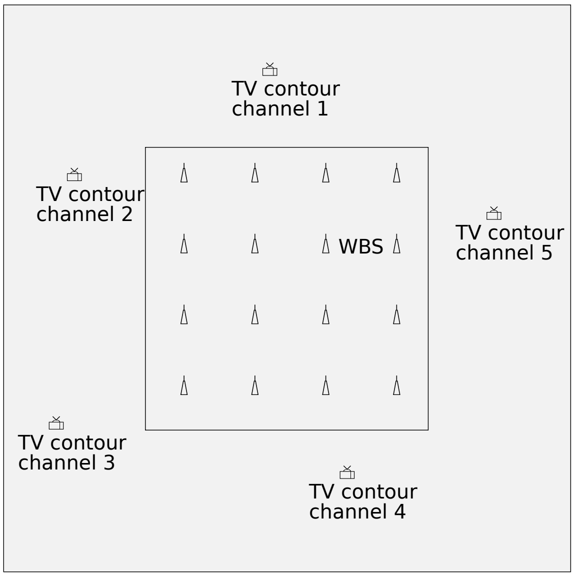


Figure 3.4 Layout of WBSs and TV contours

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*.

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 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' locations are 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

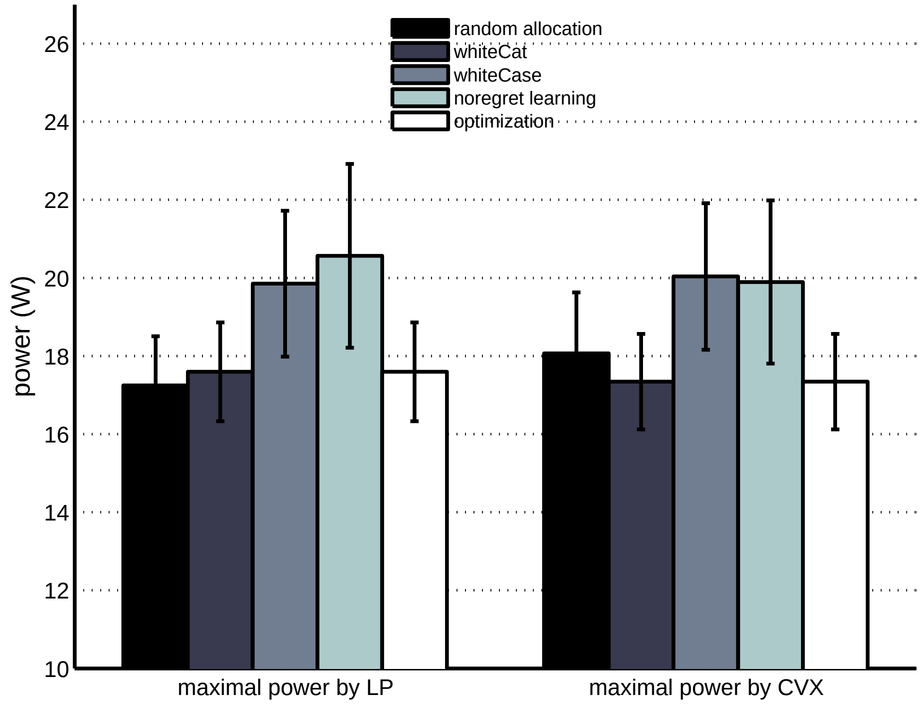


Figure 3.5 Power consumed by different distributed spectrum allocation schemes under different ways deciding the maximal transmission power map

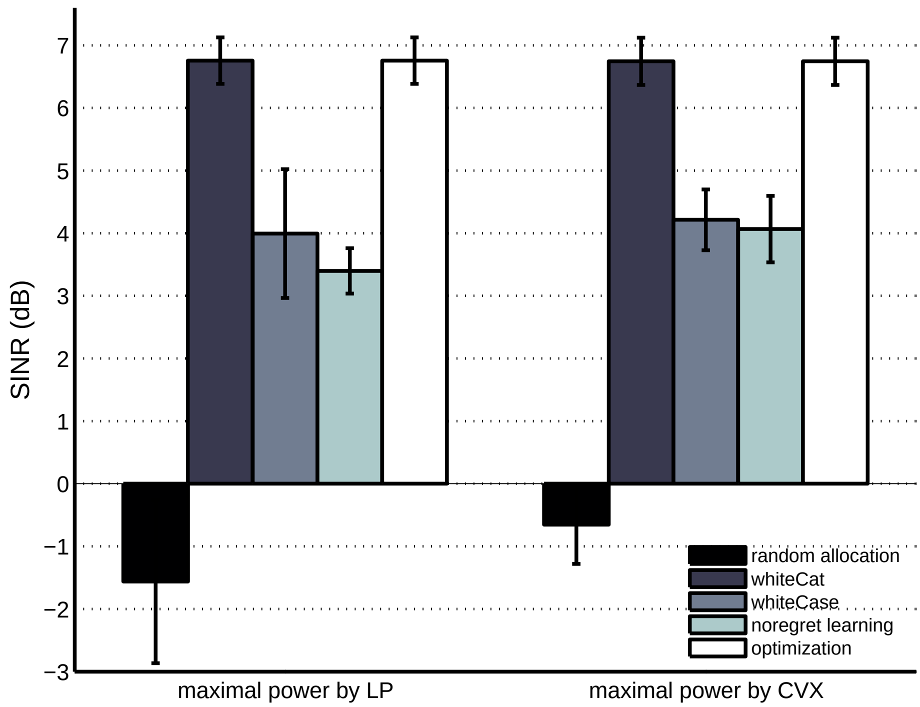


Figure 3.6 QuasiSINR achieved by different distributed spectrum allocation schemes under different ways deciding the maximal transmission power map

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

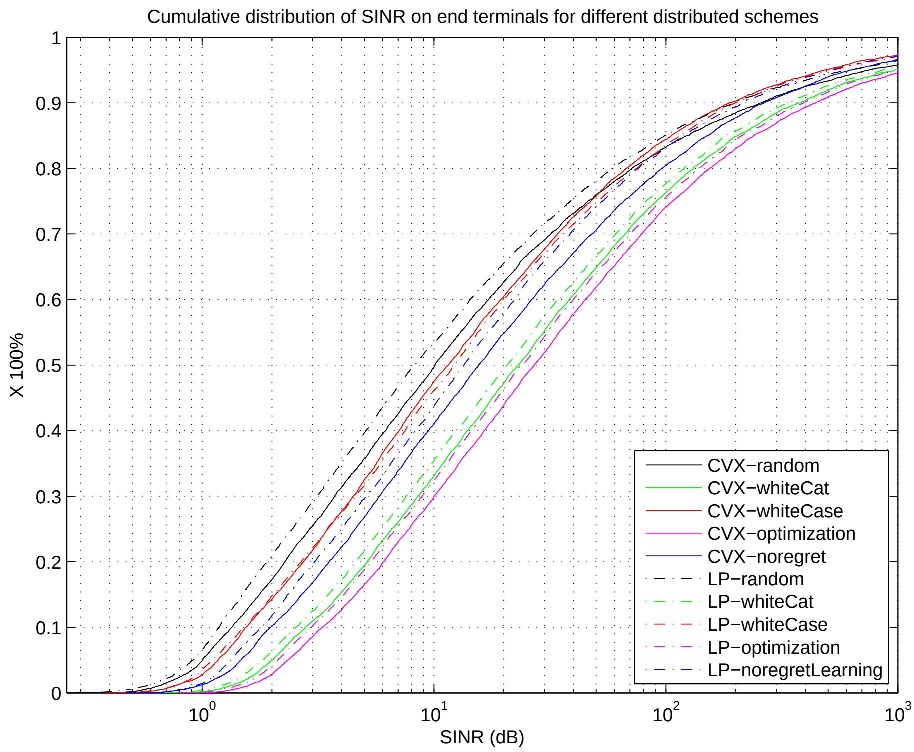


Figure 3.7 CDF of SINR on end users obtained by different CA schemes under different methods to decide the maximal transmission power map

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 WBSs, and trigger the procedure of distributed channel allocation.

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.

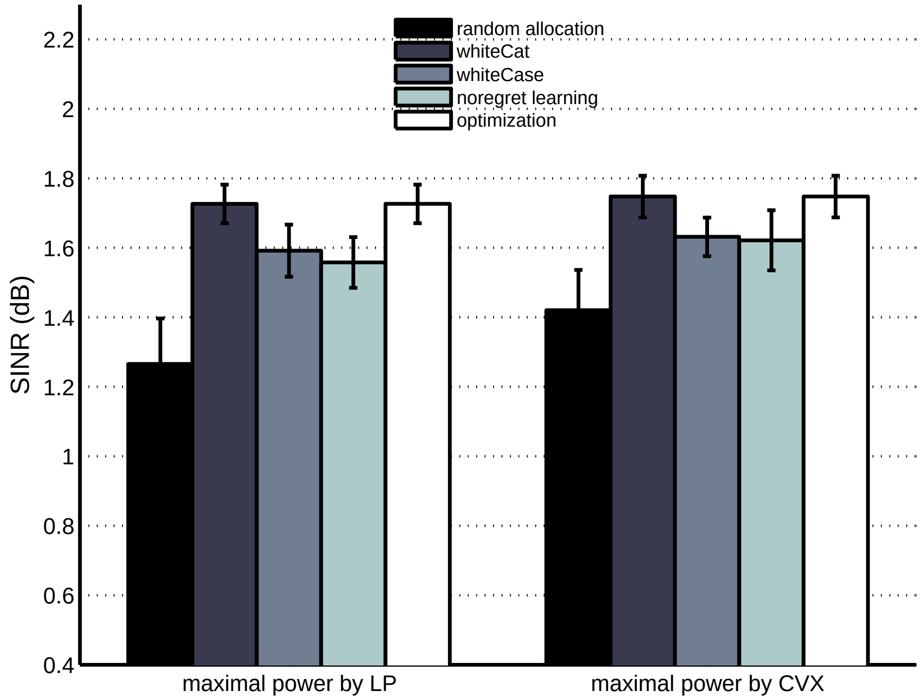


Figure 3.8 The average SINR of the 20% worst end terminals

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.

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.

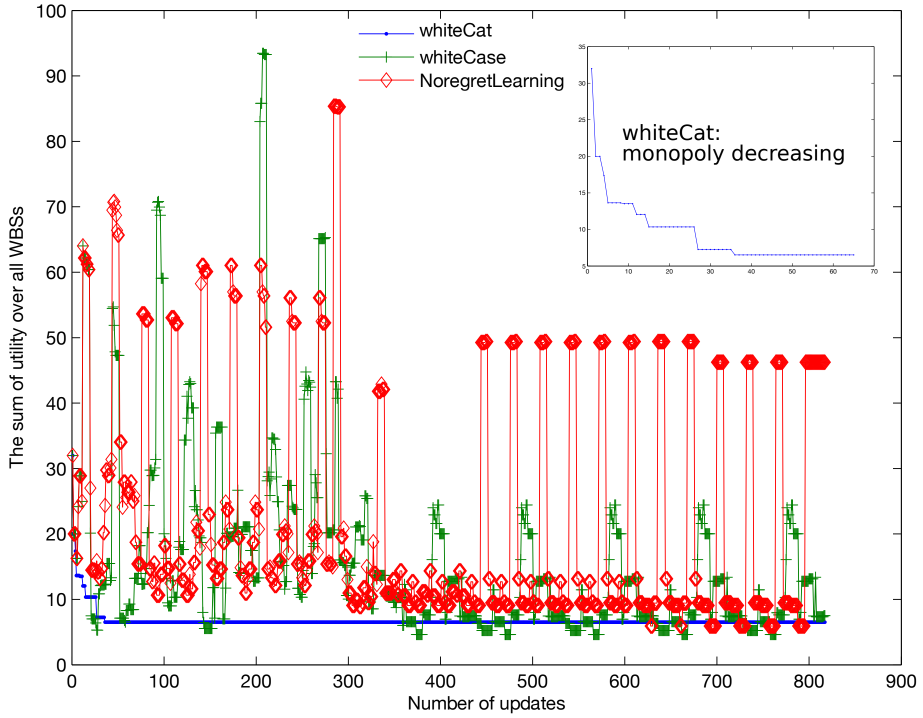


Figure 3.9 Convergence with three different schemes in one simulation instance

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

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 by executing two sequential distributed schemes. As comparisons, we implement two joint power channel allocation schemes. One is centralized optimization introduced in section 3.8.1, which is used as upper bound in the comparison. The other comparison is distributed joint power and channel allocation scheme [94] which is introduced in section 3.3. We need to point it out that, scheme proposed in [94] 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, .

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 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

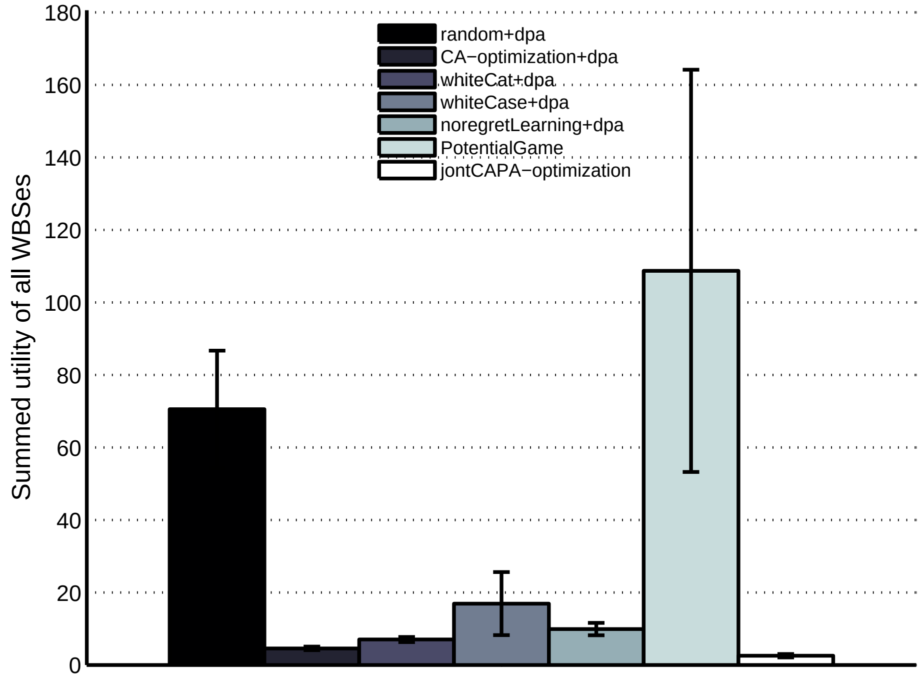


Figure 3.10 Summed utility of all WBSs, which is the objective in problem 3.7. dpa in legend represents *distributed power allocation*

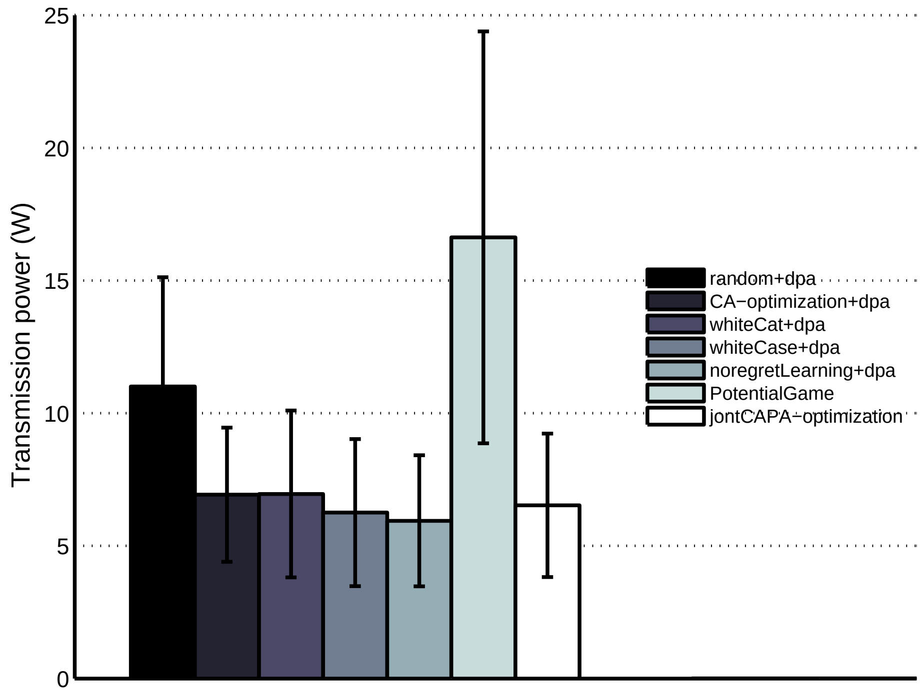


Figure 3.11 Average transmission power of one WBSs

problem of allowing base stations to set the transmit power arbitrarily within the maximum transmit power limit.

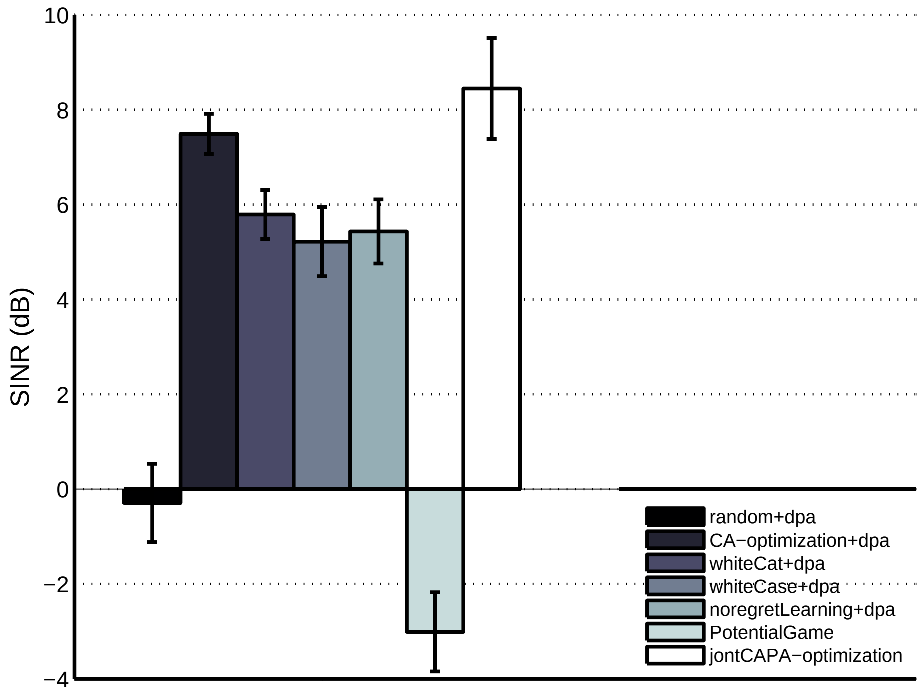


Figure 3.12 Average quasiSINR of a WBS

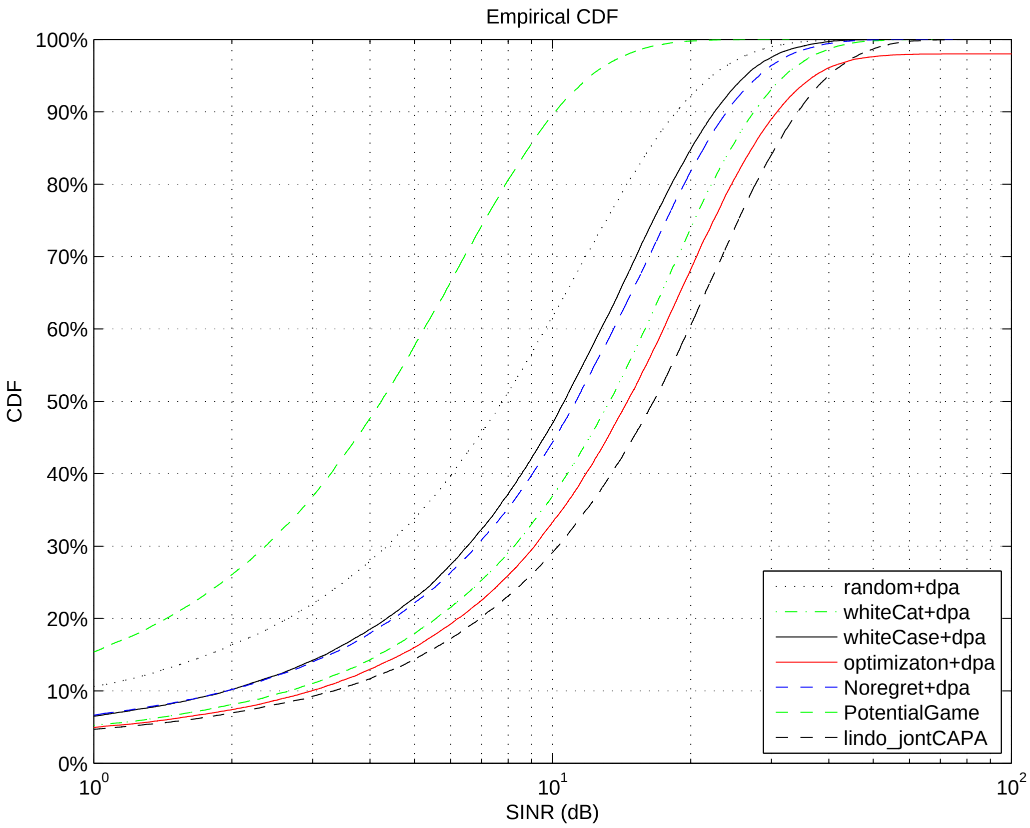


Figure 3.13 SINR on end users after channel and power allocation

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. $\square$

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,

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

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

CR is a promising technology to solve the spectrum scarcity problem [86]. 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 [106]. Cooperative spectrum sensing is able to effectively cope with noise uncertainty and channel fading, thus improves the sensing accuracy remarkably [18]. Clustering is regarded as an effective method used in cooperative spectrum sensing [116, 136]. 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 [122]. With cluster structure, the possibility that one CR node interferes neighbouring clusters after vacating the channel due to primary node appearance is reduced [100], as it can be notified by cluster head (CH) or other cluster members about the possible collision. Clustering algorithm has also proposed to support routing in cognitive ad-hoc networks [11].

[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 [75], 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 [19, 64], and it is also influence the accuracy of cooperative spectrum sensing [126]. 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 [27, 68, 78], wireless mesh networks [11], and wireless sensor networks [11] 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 [115, 125].

As to cognitive radio networks, clustering schemes are also proposed, which target different aspects. Work [126] improves spectrum sensing ability by grouping the CR users with potentially best detection performance into the same cluster. Clustering scheme [64] obtains the best cluster size which minimizes power consumption caused by communication within and among clusters. [64] 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. [123] 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 [24, 136], 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. [21] 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 [75, 81]. Authors [75, 81] 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 [21, 64].

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 [134]. 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 *common control channels* (CCC) 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.

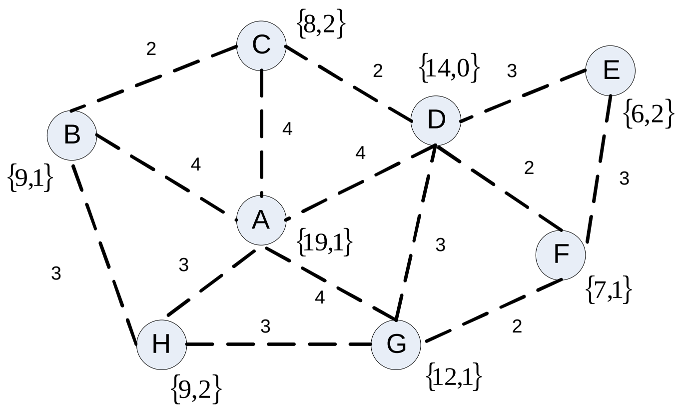


Figure 4.1 Connectivity graph and the connectivity vector $\{D_i, G_i\}$ on each node. The available channels sensed by each CR node are: $V_A = \{1,2,3,4,5,6,10\}, V_B = \{1,2,3,5,7\}, V_C = \{1,3,4,10\}, V_D = \{1,2,3,5\}, V_E = \{2,3,5,7\}, V_F = \{2,4,5,6,7\}, V_G = \{1,2,3,4,8\}, V_H = \{1,2,5,8\}$. 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. $\square$

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

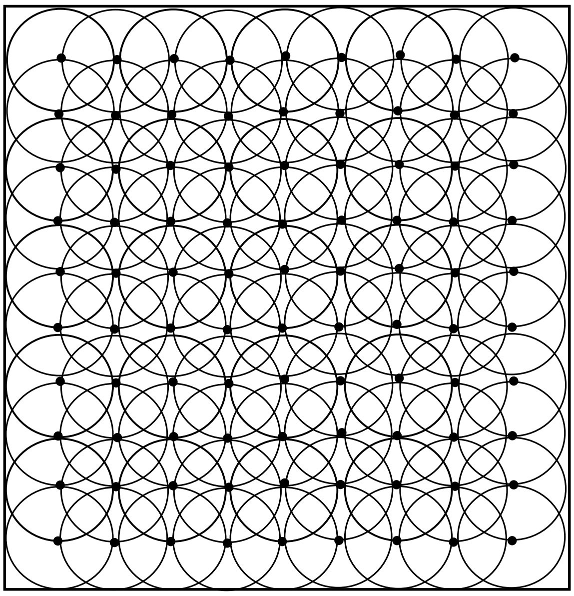


Figure 4.2 Clusters formation in extremely dense CRN. Black dots are cluster heads, cluster members are not drawn.

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

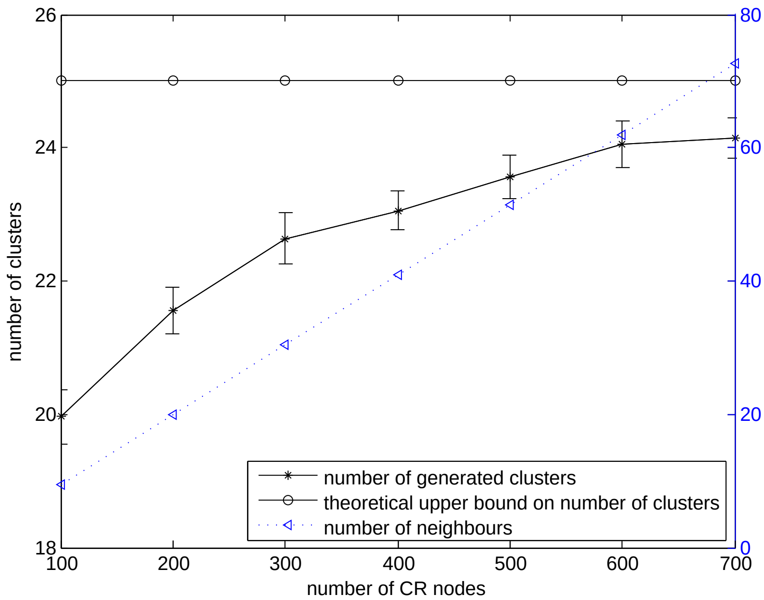


Figure 4.3 Number of clusters formed

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 large, there is substantial burden on cluster heads to manage the cluster members, which is a challenge for resource limited cluster heads. 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: CCC 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.

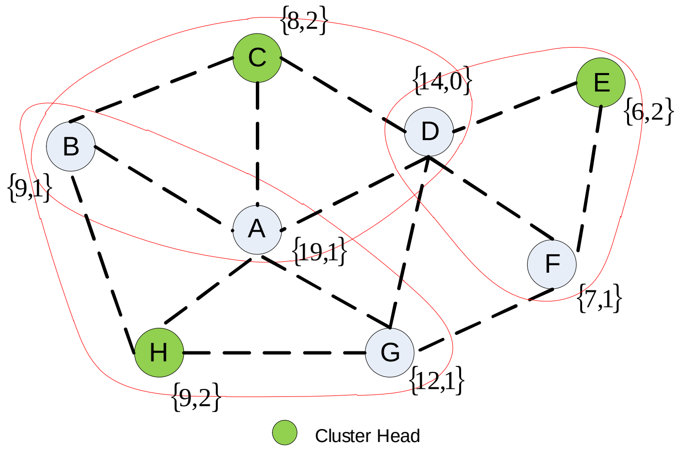


Figure 4.4 Clusters formation after the first phase of ROSS. Some nodes remain debatable nodes after the first phase.

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.

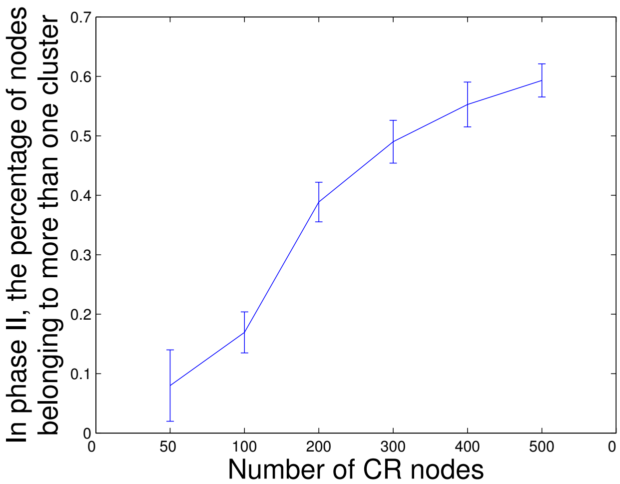


Figure 4.5 Clusters formation after the first phase of ROSS. Some nodes remain debatable nodes after the first phase.

Distributed Greedy Algorithm

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 CCCs 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 $\lambda = \mathrm{Min}_{C \in S_i}(|K_{C \setminus i}| - |K_C|)$;
define set $\mathcal{C}_1$;
for *each* $C \in S_i$ **do**
  if $|K_{C \setminus i}| - |K_C| == \lambda$ **then**
    $\mathcal{C}_1 \leftarrow C$
  end
  `/* metric is the increase of CCCs due to` i' `departing */`
end
if $|\mathcal{C}_1| == 1$ **then**
  choose cluster C;
  break;
else
  calculate $\mu = \mathrm{Max}_{C \in \mathcal{C}_1}(V_{H_C} \cap V_i)$;
  define set $\mathcal{C}_2$;
  for *each* $C \in \mathcal{C}_1$ **do**
    if $V_{H_C} \cap V_i == \mu$ **then**
      $\mathcal{C}_2 \leftarrow C$
    end
    `/* metric is the number of common channels between` i `and cluster head of demanding cluster */`
  end
  if $|\mathcal{C}_2| == 1$ **then**
    choose cluster C;
    break;
  else
    calculate $\nu = \min_{C \in \mathcal{C}_2} |C|$;
    define set $\mathcal{C}_3$;
    for *each* $C \in \mathcal{C}_2$ **do**
      if $|C| == \nu$ **then**
        $\mathcal{C}_3 \leftarrow C$
      end
      `/* metric is cluster size */`
    end
    if $|\mathcal{C}_3| == 1$ **then**
      choose cluster C;
      break;
    else
      choose the $C \in \mathcal{C}_3$, 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.

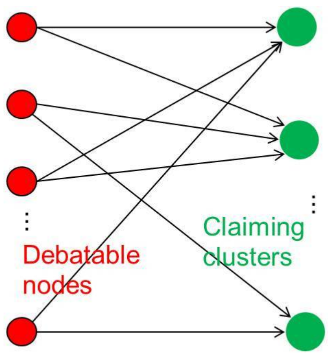


Figure 4.6 debatable nodes and claiming clusters

- $\mathcal{R} = \cup S_i, i \in \mathcal{P}$, 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 CCCs in cluster C caused by debatable node i' joining in it. As to cluster $C \in S_i$, the decrement of CCCs 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 CCCs $\sum_{i:C\in S_i} \Delta|K_C^i|$, 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.

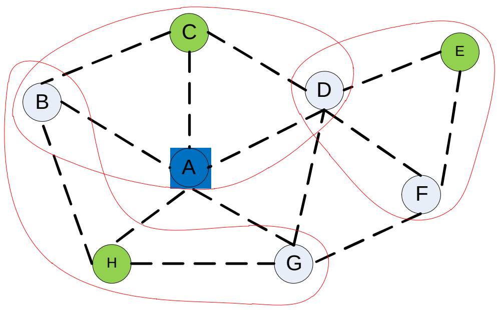
As to singleton congestion game, there exists pure equilibria which can be reached with greedy update [13].

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

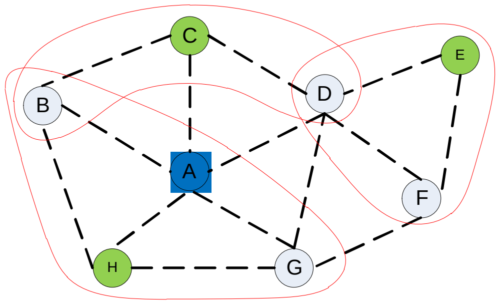
Distributed Fast Algorithm (DFA)

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 CCC 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

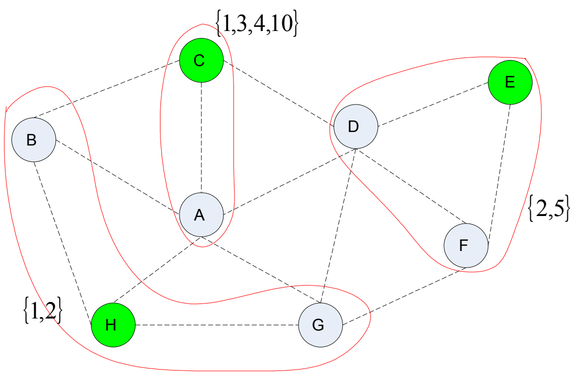


Figure 4.8 Final formation of clusters, common channels for each cluster is shown.

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 $k \geqslant 3$. [51]

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, $\omega : \mathcal{S} \rightarrow \mathbb{Z}^+$.

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.

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

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

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 $\texttt{cost}\,(\delta)$ 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.

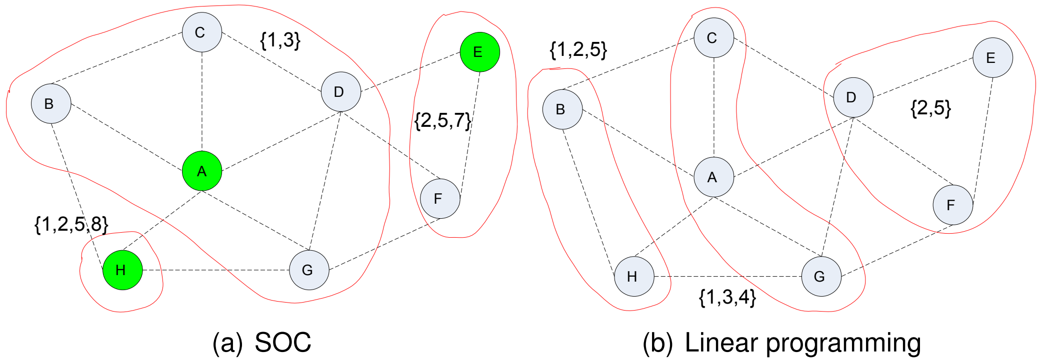


Figure 4.10 Final clustering of the example CRN

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 [75] is the only work emphasizing on the robustness of clustering structure from all previous work on clustering in CRN. The authors of [75] 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 [27], or for CRN but just considering basic connection among CR nodes [136]. 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 [64]. 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 CRs and PUs are deployed within a squire whose edge is 100 m. We adopt the round disk model to simulate transmission. Transmission ranges of CR and PU 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 PU'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 PU 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 [81] 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.

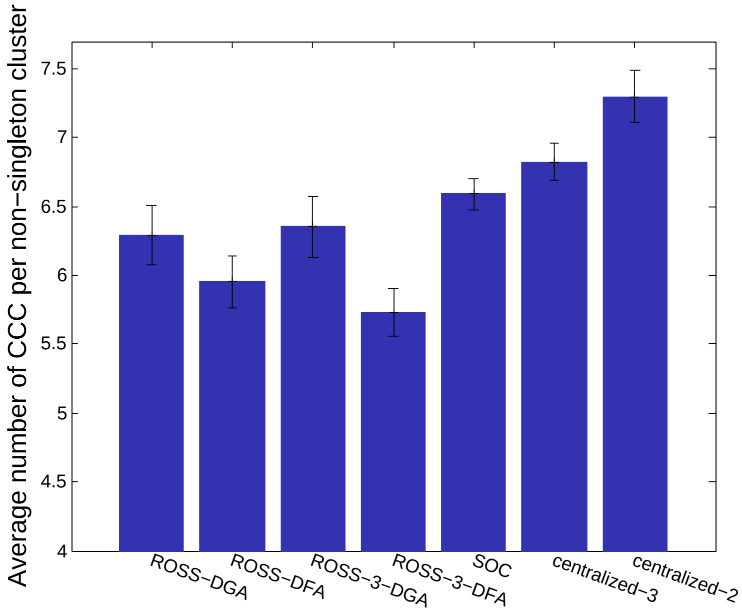


Figure 4.11 Number of common channels for non-singleton clusters, the numbers in the names of schemes annotate the desired cluster size.

Survival Rate of Clusters with Increasing Primary 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 PU 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.

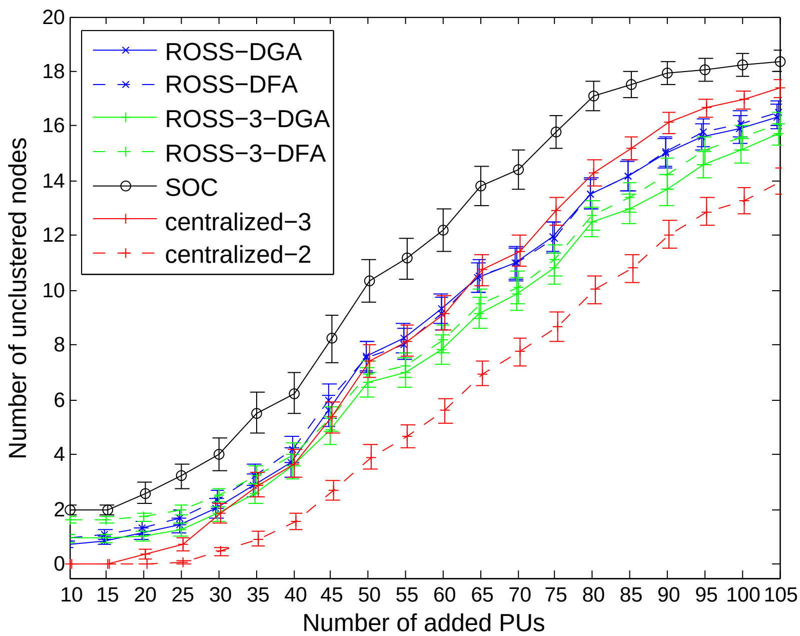


Figure 4.12 Number of CRs which are not included in any clusters

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

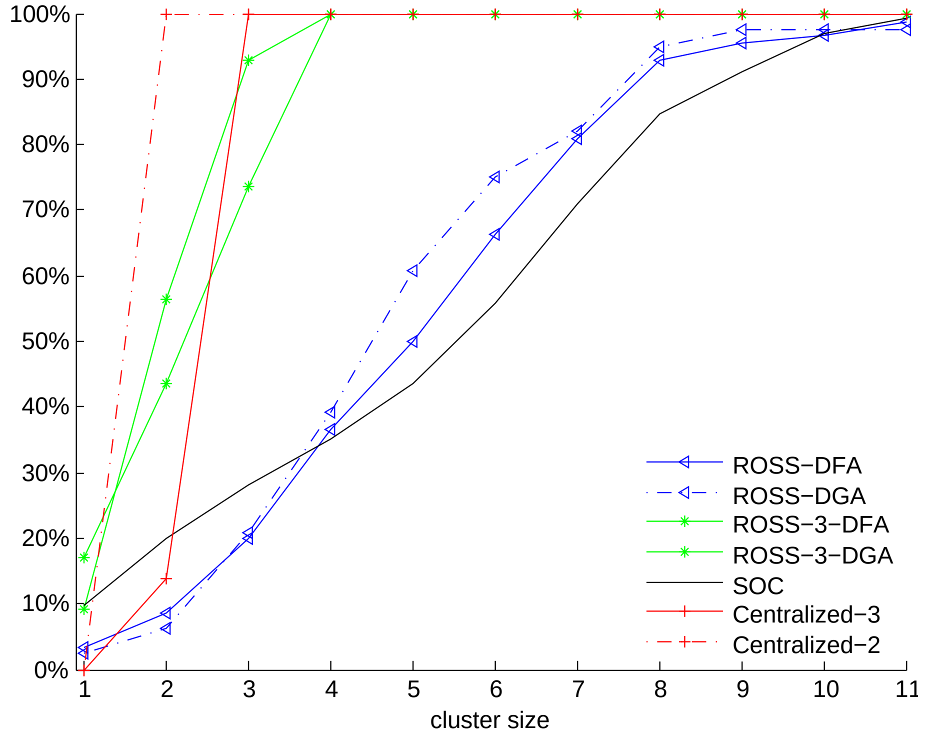


Figure 4.13 Distribution of CRs residing in clusters with different sizes, as to ROSS with size control feature, the desired cluster size is 3. The average number of neighbours is 4.838.

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

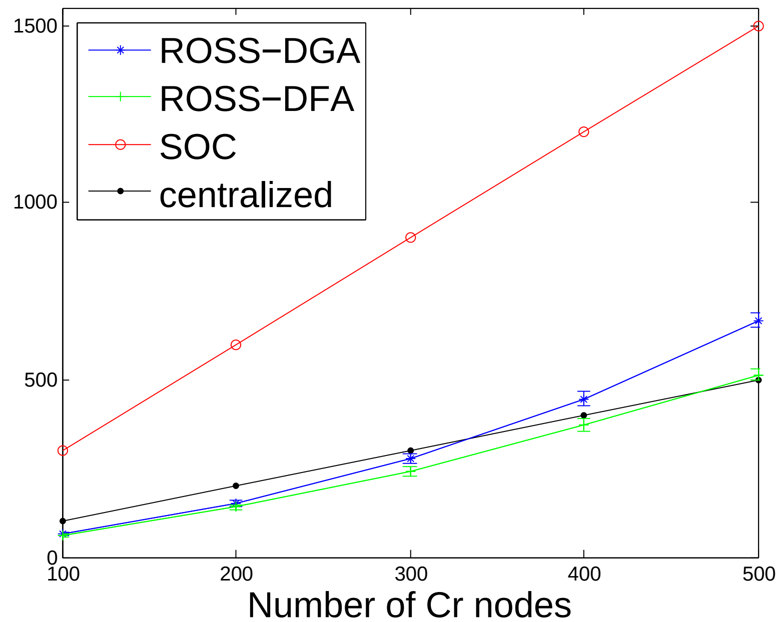


Figure 4.14 Number of control messages

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 PU 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

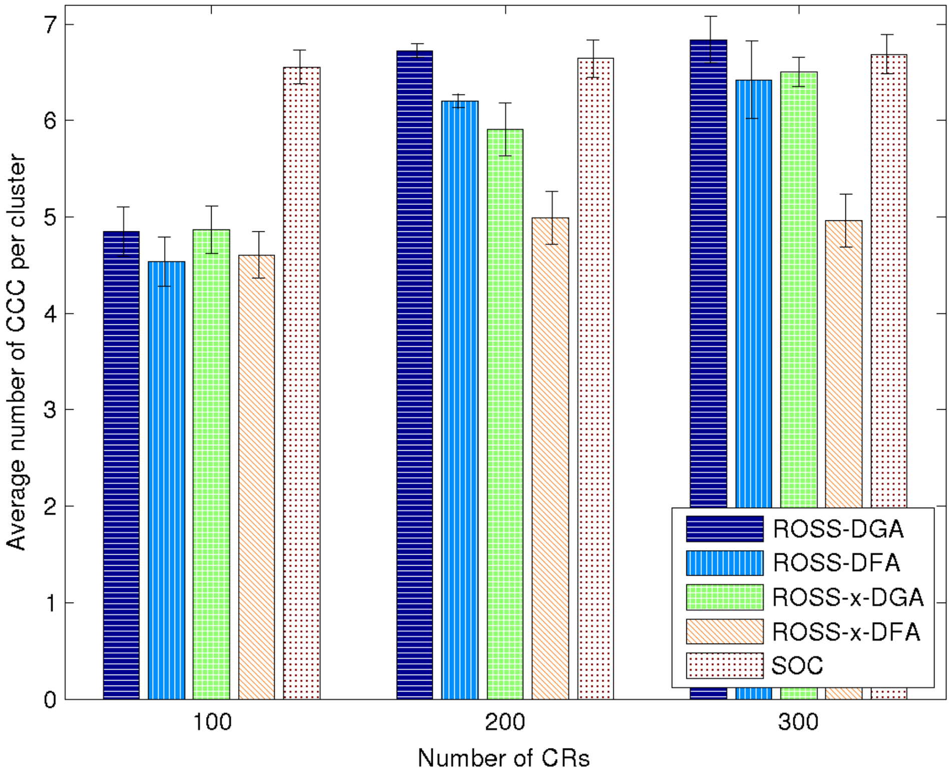


Figure 4.15 Number of common channels for non-singleton clusters. As to ROSS with size control feature, we adopt $x = 6$ when $N = 100$, $x = 12$ when $N = 200$, $x = 21$ when $N = 300$, which is around $2/3$ of the number of average neighbours

Figure 4.15 illustrates the average number of CCCs of the non-singleton clusters. It shows when $N = 100$, variants of ROSS have 30% less CCCs than SOC, but this gap is decreased significantly when N is 200 and 300, i.e., when $N = 300$, number of CCCs achieved by ROSS variants (except for ROSS-x-DFA) is almost the same with that resulted from SOC.

This means SOC performs better on average number of CCCs per non-singleton clusters when network density is small [5], when the network becomes denser, ROSS-DGA achieves even more CCCs than SOC, and ROSS-DFA and ROSS-x-DGA visibly increase their performances on the number of CCCs.

Survival Rate of Clusters with Increasing Primary Users

With the increase of PRs in the network, some clusters will lose certain CCCs as these CCCs are no longer available on certain cluster members. When there is no CCCs avail-

[5]this is also observed in the evaluation in Section 4.6.1 where $N = 20$

able in a cluster, the cluster is said to be broken. In this part of simulation, we investigate the robustness of clusters by increasing the PRs working on certain channels.

Figure 4.16 shows the increasing tread of singleton clusters, or to say, unclustered nodes, with the increase of PRs. SOC generates around 10 more singleton clusters than the variants of ROSS, which accounts for 10% of the total CR nodes. 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 that ROSS-3-DFA results in more singleton clusters when PRs are few. The reason is that ROSS-3-DFA conducts cluster membership clarification for only once, which causes large number of singleton clusters, while, in ROSS-3-DGA increase the size of smaller clusters through debatable nodes' repeated updates thus drastically decreases the number of singleton clusters.

From the Figure 4.16 and 4.17, we can conclude that the greedy versions of ROSS are more robust than their counterpart variants of ROSS. When the network is more dense, the improvement on cluster sizes and robustness by the greedy search in the membership clarification phase is more obvious.

Cluster Size Control

The number of formed clusters is shown in Fig. 4.18. When the network scales up, the number of formed clusters by ROSS increases by smaller margin. This result coincides with the analysis in Section 45, that with ROSS, the number of formed clusters saturates when the network scales. When the network becomes denser, more clusters are generated by SOC compared with ROSS variants. To better understand the distribution of the sizes of formed clusters, we depict the cluster sizes with cumulative distribution. In this group of evaluation, the number of PRs is 30.

We see in Figure 4.19, when variants of ROSS are applied, most CRs are included into clusters with size between 2 and 5, in particular, ROSS-2-DGA achieves homogeneous distribution of cluster sizes, 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 because in membership clarification phase, greedy search not only increases the number of CCCs of relevant clusters, but is liable to leave debatable nodes to stay in smaller clusters, as stated in Algorithm 4. SOC doesn't have size control feature, thus the cluster sizes diverge strongly, i.e., the sizes span from 1 to 35.

In a denser network with 300 CRs as shown in Figure 4.21, 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.

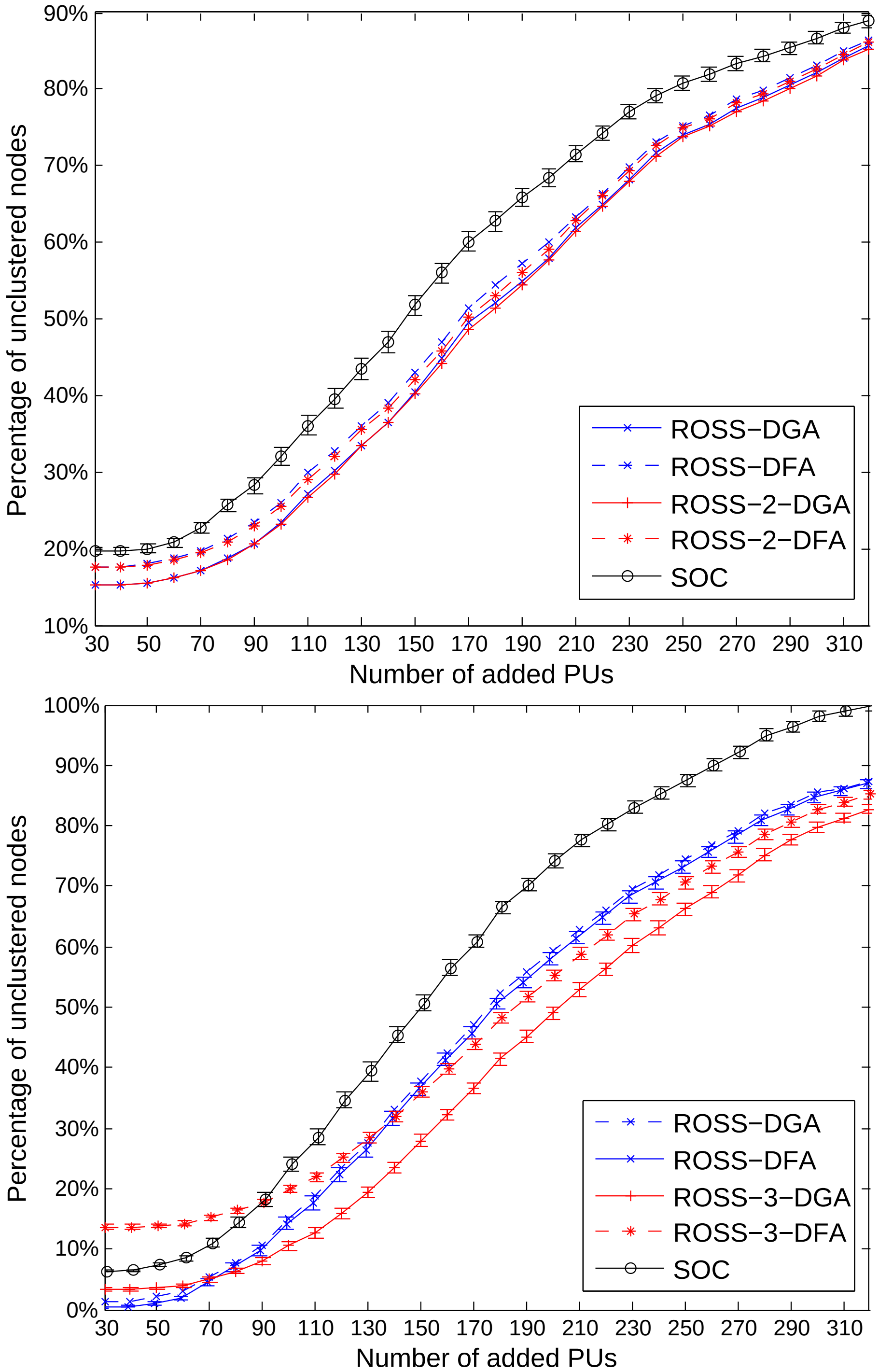


Figure 4.17 Number of CRs which are not included in any clusters, $N = 300$

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

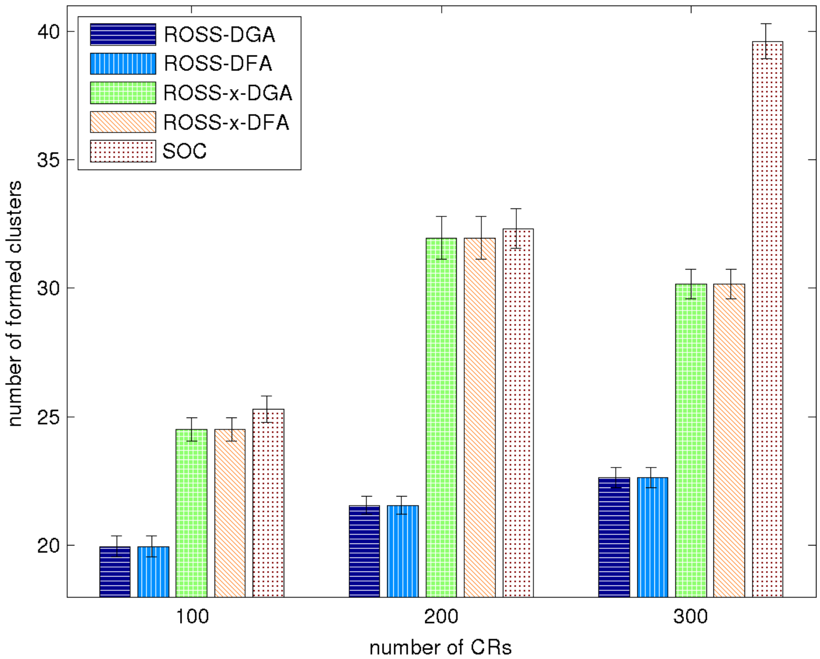


Figure 4.18 Number of formed clusters

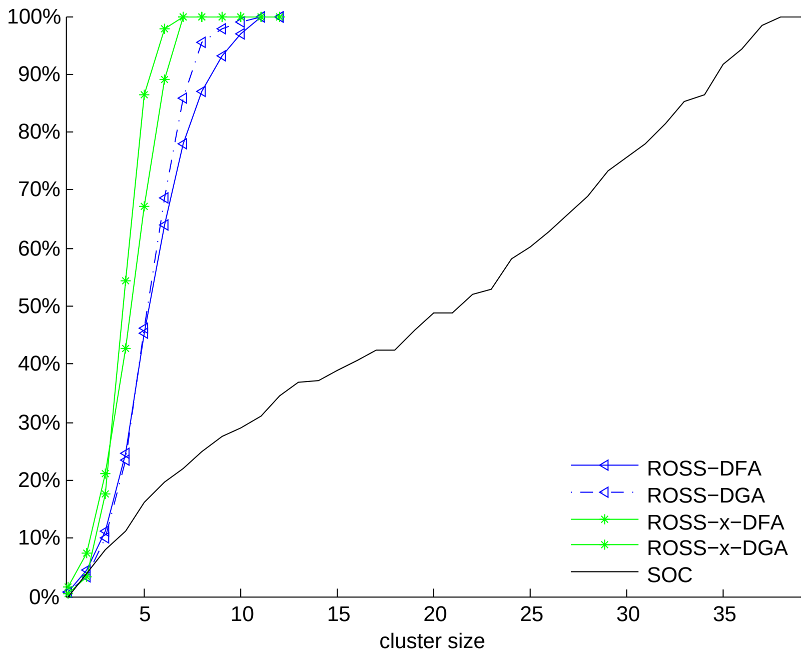


Figure 4.19 100 CRs, 30 PRs, the average number of neighbours is 9.5.

scheme under primary users' influence. An light weighted cluster size control mechanism 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

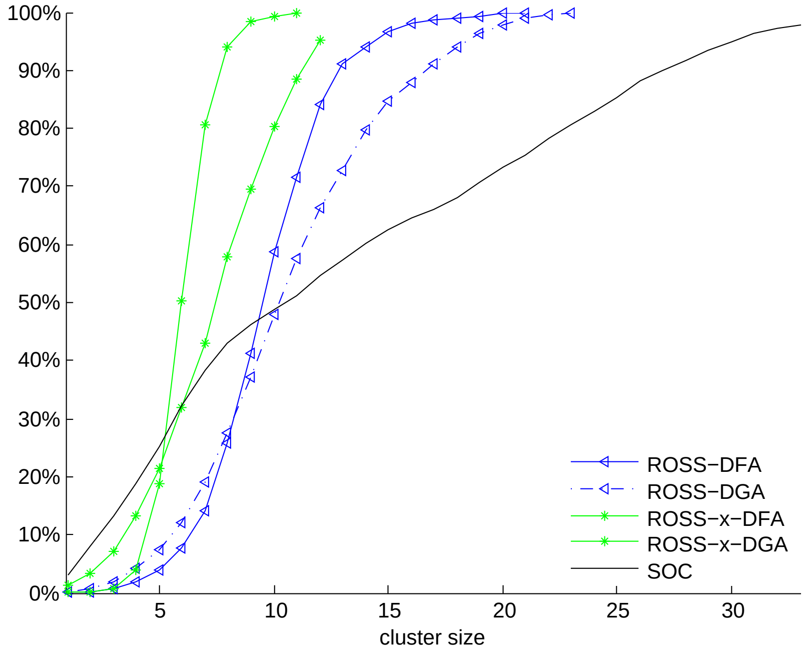


Figure 4.20 200 CRs, 30 PRs, the average number of neighbours is 20

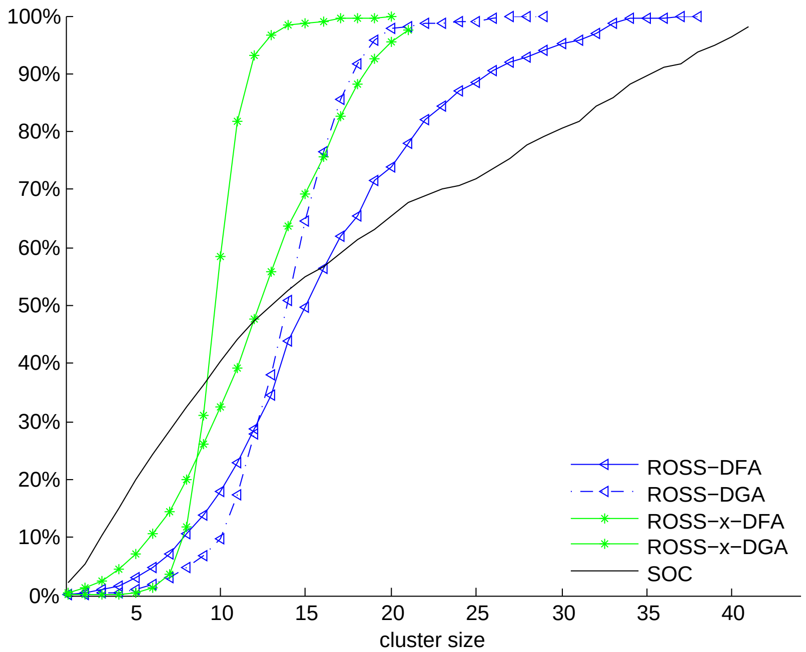


Figure 4.21 300 CRs, 30 PRs, the average number of neighbours is 30

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

Primary users' activity demonstrates different patterns [69], consequently 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 [89]. 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 [96, 121] 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 [96] 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 [12]. 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 [20] 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 [95]. 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 [10], besides, one centralized controller is needed to calculate the routing path on the basis of collected information from the network [95, 97].

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. [109] 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 [83], or the prediction on channel availability in the forthcoming time slot [82], 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 [113]. 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 [69, 107].

The solution provided by Chowdhury et al. [41] improves geographic routing in multiple channel CRN by introducing circumventing mechanism, i.e., the source node launches geographic routing on each channel, and every routing path bypasses the next hop, which is chosen based on geographic routing metric (e.g., Euclidean distance), if it 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. *SEARCH* adopts routing table and doesn't involve frequent overhead exchanges. 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 source node needs to periodically launch route request to update the routing path which may have been invalid. As a result, 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.

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.

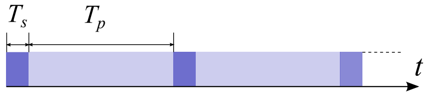


Figure 5.1 Sensing duration T_s and sensing period T_p

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 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 [20, 33]. 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 virtual coordinate assignment protocol (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 [20] in wireless sensor networks. The hop based virtual coordinate is independent on actual physical position, but supports greedy geographic routing successfully [20, 33]. 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.

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

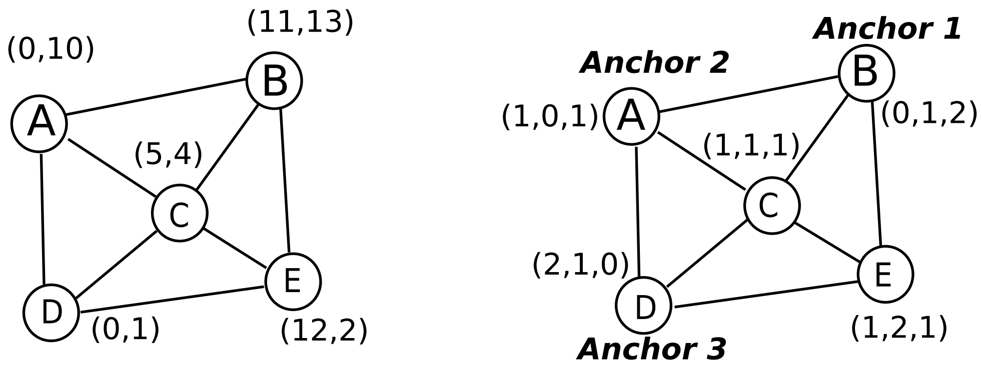


Figure 5.2 Left: nodes with physical locations, Right: nodes with doublet virtual coordinate, each element in the virtual coordinate is the number of hops away from corresponding anchor. Connecting lines denote the communication is possible.

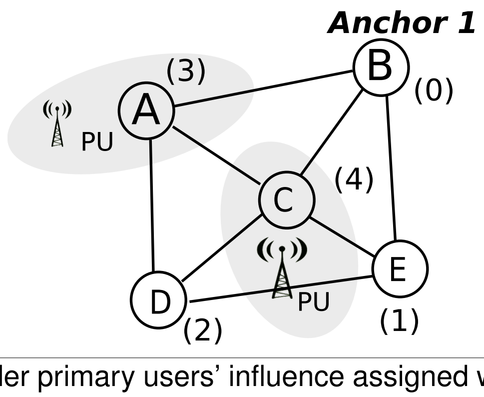


Figure 5.3 A network under primary users' influence assigned with SAViC, only anchor 1 is adopted. Flooding of anchor messages is not shown.

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 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

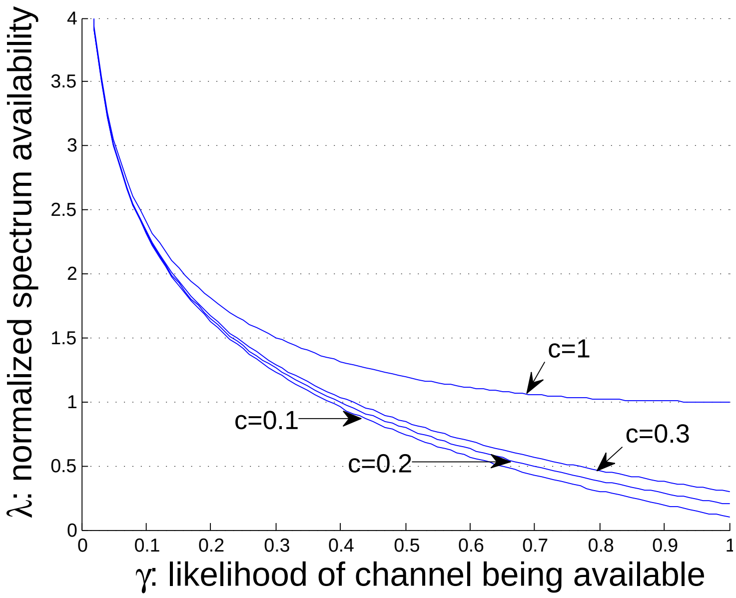


Figure 5.4 Normalized spectrum availability with respect to the likelihood of spectrum being available one a node

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,

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

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,

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

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 [96], 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. [96] 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 [107], mitigating co-channel interferences [77] 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 [53, 88] 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 [118], 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.

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

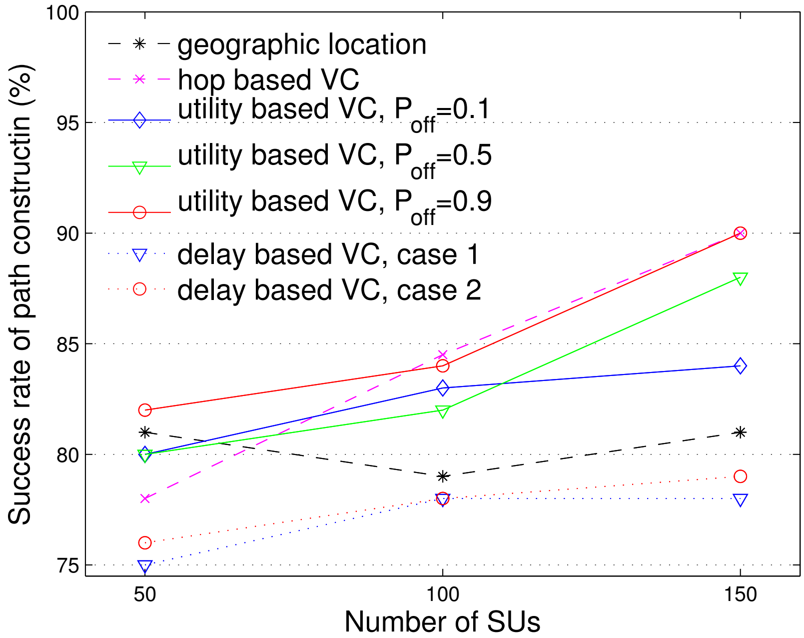


Figure 5.5 Reachability of different virtual coordinates, the average number of neighbors is 6, 12, and 14

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.

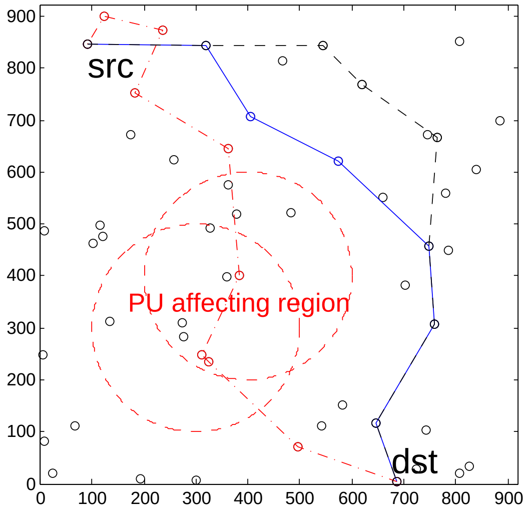
5.6.3 Routing Performance

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* [41] 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.

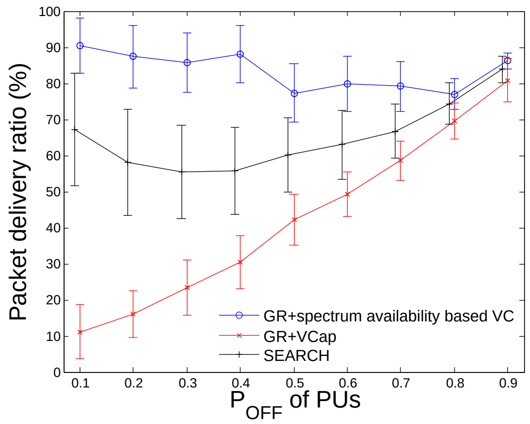
Duty Cycle Based Virtual Coordinate

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

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

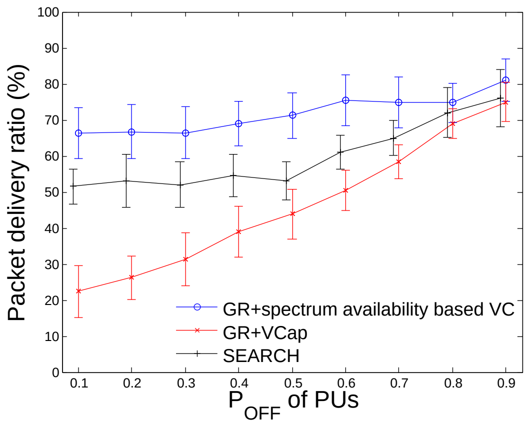


(a) Routing paths

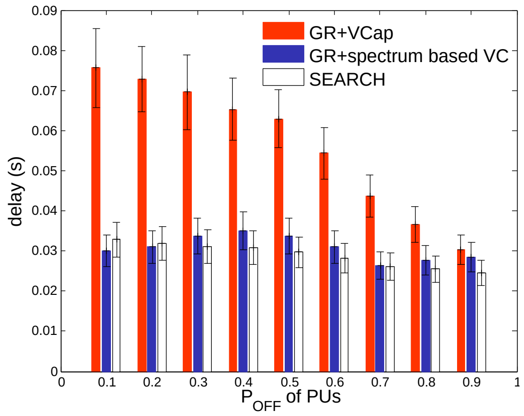


(b) PDR over 50 random CRN network, PU's location is fixed as shown in Figure 5.6(a)

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

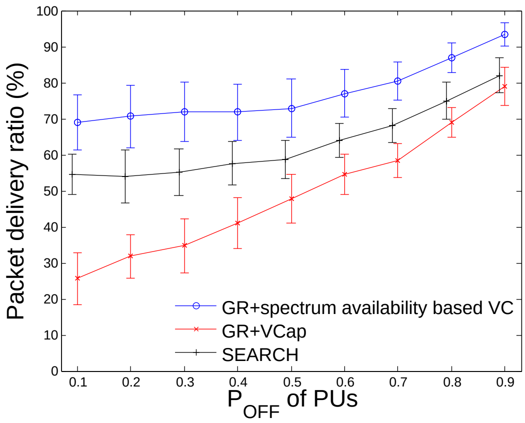
We start with a case study, two primary users locate at the centers of dashed cycles as shown in Figure 5.6(a). VC based on spectrum availability and VCap (hop is its metric) are assigned to secondary users separately. The red dashed path in Figure 5.6(a) is formed by geographic routing with VCap, which 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.

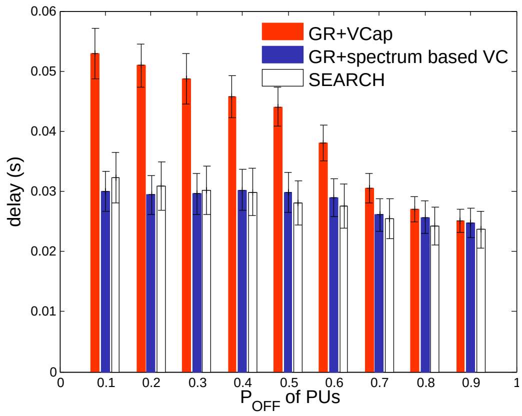
The paradox that more licensed spectrum leads to worse PDR can also be observed on *SEARCH*, whose PDR curve declines first and increases later on. When channel is heavily utilized by primary users, the routing request is more likely to encounter operating primary user, then a node out of the primary 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

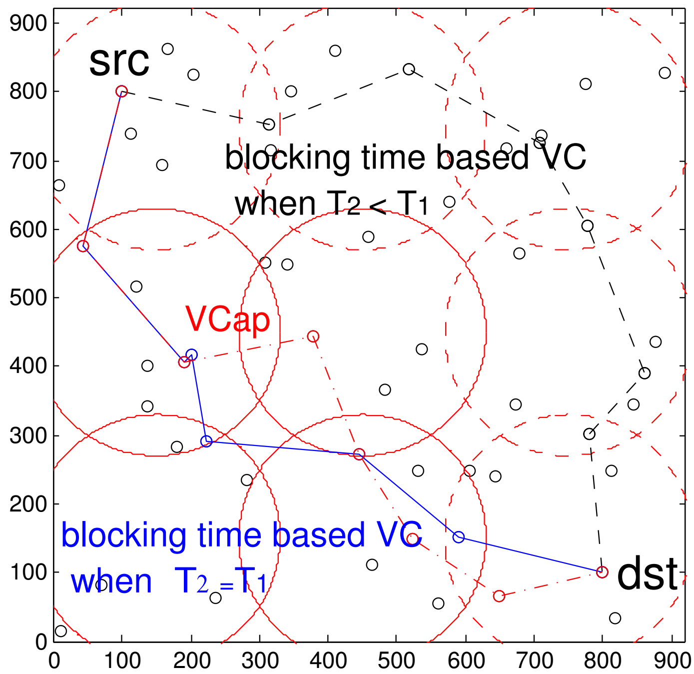


Figure 5.9 Routing paths in one network, $T_1 = 3s$. cycles denote the transmission range of primary uers.

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.

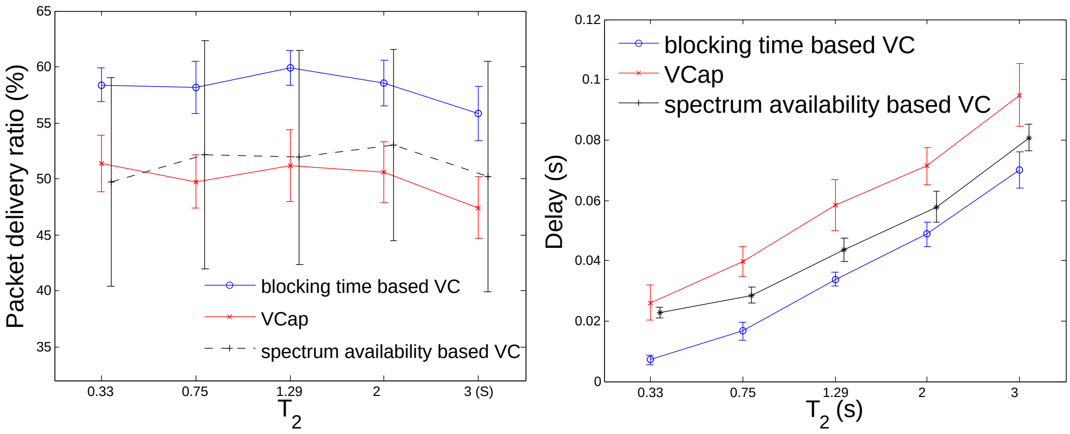


Figure 5.10 Geographic routing in single secondary channel scenario, $P_{\text{OFF}} = 0.9$ for all primary users, $T_1 = 3s$, T_2 varies.

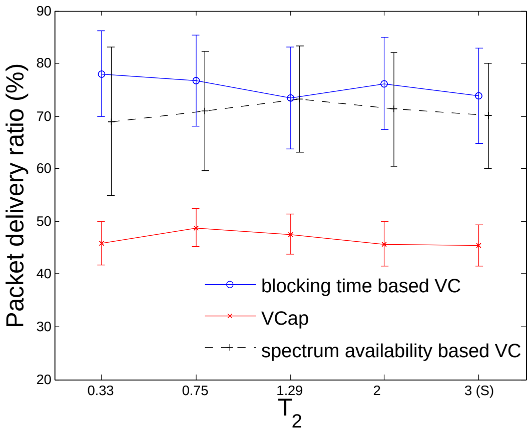
Figure 5.10(b) shows as T_2 increases from 0.33s to 3s, the delay of successfully delivered packets also increases for both blocking time based virtual coordinate and VCap, but a constant gap exists in between. Whereas, the delay of spectrum availability based virtual coordinate is random as respect 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.

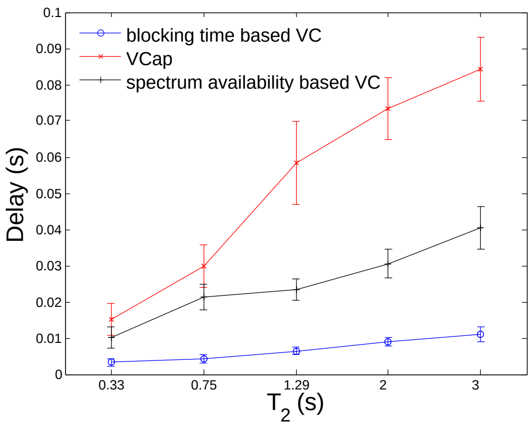
Now we have a look at the CRN with two licensed channels. As to performance of delay, because of the second available channel, blocking time based virtual coordinate achieves very delay, in contrast, spectrum availability based virtual coordinate still demonstrates obvious randomness, as is shown in 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.

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,



(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.

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%.

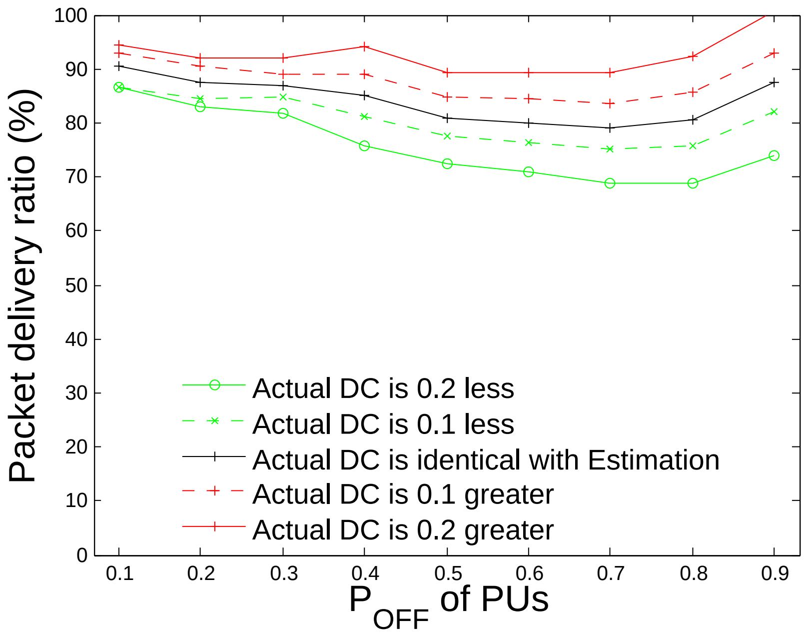


Figure 5.12 In the setting of Figure 5.6(a), perofrmance of DC based virtual coordinate is not affected greatly by the erroneous estimation

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 and Future work

The goal of this thesis is to design paradigms and algorithms that enable individual cognitive radio to act autonomously, and finally converge to a equilibrium state, meanwhile, the performance of cognitive radio users are improved. In this dissertation, we solve a series of problems residing from layer 1 to layer 3 in the OSI model [3] of CRN with distributed solutions, and employ game theory to seek the guarantee on convergence and Nash equilibrium.

6.1 Contribution

We propose a complete strategy of power and spectrum allocation in IEEE 802.22 networks. We make full use of the centralized database which is required by the standard and relevant regulations. The maximal transmission power on channel for each WBS is decided in the database by solving an optimization problem. Then a two stage channel power allocation scheme is proposed in a distributed manner, where the database is involved to assist interaction between secondary users. This work 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 predecided schedule) into a canonical congestion game, then propose distributed algorithm corresponding to the behaviour of player in the game.

As to improving the accuracy of spectrum sensing with clusters, we designed a distributed clustering scheme ROSS. ROSS is lightweight, thus is suitable CRAHN where the network connection varies due to the mobility of spectrum and secondary users. ROSS increases the number of common available channels within one cluster, thus improves the robustness of formed clusters against primary users, so that cooperative sensing can make the best use of clusters. 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.

6.2 Future Work

Building on the top of the our contributions, game theory can help to design distributed solution for further problems in CRN. In this section, we describe the future work, and sketch the solutions briefly.

Structureless Diffusion Based Routing in Game Theoretical Framework in Event-driven Cognitive Radio Sensor Network

One future work is to propose a structure less data fusion paradigm for cognitive radio sensor network. Sensor nodes are deployed to sense physical phenomena of interests (PoIs), and they transmit the PoIs to the sink node. Cognitive radio capability is transplanted onto sensor network [15], so as to alleviate collision and decrease delay. But congestion is still difficult to be totally eliminated by merely providing more spectrum. Congestion occurs in wireless sensor network when incoming traffic load exceeds the capacity. Variant solutions [111] have been proposed to mitigate congestion, e.g., implementing flow control to avoid transmitting to the downstream node where congestion is detected, changing the MAC behaviour to give the congested sensor larger possibility to transmit, adding rely nodes to reroute data around the congested nodes.

When there are multiple upstream nodes[1] transmitting to sink node, and there are several downstream nodes are available to be relies, then which portion of the data on the upstream node should be sent to which downstream node becomes a question. As shown in Figure 6.1, several nodes are downstream nodes for node 2 and 3. We have proposed routing solution for end to end communication in CRN, where geographic routing is conducted with spectrum aware virtual coordinate. As to multiple to one communication, simply using our proposed scheme is problematic, as we need to consider the possible collision caused by multiple transmission, priority of services and possible congestion appearing on the relying nodes.

Problem Statement

The basic idea is from the *server matching* introduced in Section 2.

Delay of the packets is used to represent the congestion. This delay could be the average of delay on all packets, or a function of delay of individual packet. Although it is not clear how to granulate the data based on their priorities, it is clear that the total congestion (delay) is a increasing function of the amount of incoming data. When there are only one group of downstream nodes and one group of upstream nodes involved, and the upstream nodes have finite number of transmission strategy (a certain portion is sent to a certain

[1] Downstream nodes of one node i represent the nodes relying data from node i towards to the sink node, upstream nodes of node i means the nodes sending data to node i.

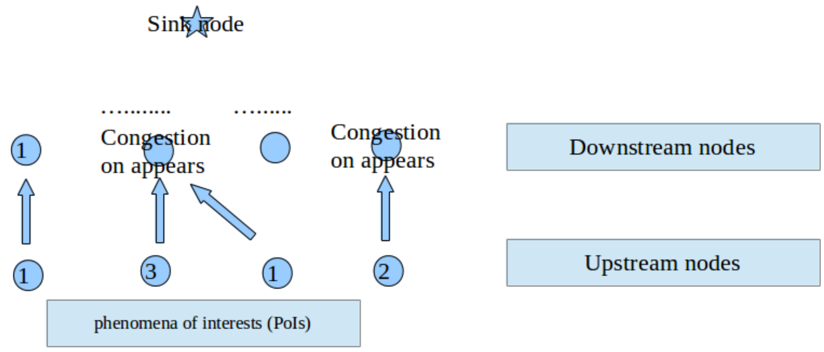


Figure 6.1 Multiple to one communication

downstream node), then the convergence will be brought by best response strategy. But the converge is not guaranteed when consider within a bigger picture, as the downstream nodes can become upstream nodes when they send data to their downstream nodes.

The questions needed to be answered are as follows,

- What is the strategy for each sensor node to assign its data to different downstream nodes.
- As this problem is a cascaded of congestion games, is there equilibrium?

because the structured techniques incur relatively higher overheads to maintain the network structure.

Other Future Research Works

- 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.

Bibliography

[1] http://hraunfoss.fcc.gov. http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-301650A1.pdf.

[2] IEEE 802.22 wireless regional area networks. http://www.ieee802.org/22/Technology/.

[3] Information technology – open systems interconnection – basic reference model – conventions for the definition of osi services. http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=18824.

[4] Order document FCC 03-322: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies. https://apps.fcc.gov/edocs_public/attachmatch/FCC-03-322A1.pdf. Accessed: 2014-12-26.

[5] TV white space amendment to 802.15.4. http://www.ieee802.org/15/pub/TG4m.html.

[6] Wireless coexistence in the TV white space. http://ieee802.org/19/pub/TG1.html.

[7] Report of the spectrum efficiency working group. http://www.fcc.gov/sptf/reports.html, 2002. FCC Spectrum Policy Task Force.

[8] In the matter of unlicensed operation in the TV broadcast bands: second memorandum opinion and order, Federal Communications Commission, FCC 10-174, Jan. 2011. Visited July 2012. http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-11-131A1.pdf.

[9] Technical and operational requirements for the possible operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz, Cardiff. http://www.erodocdb.dk/docs/doc98/official/Pdf/ECCRep159.pdf, Jan. 2011. Visited July 2012. http://www.erodocdb.dk/docs/doc98/official/Pdf/ECCRep159.pdf.

[10] ABBAGNALE, A., AND CUOMO, F. Gymkhana: A connectivity-based routing scheme for cognitive radio ad hoc networks. In *Proc. of IEEE INFOCOM on Computer Communications Workshops, 2010* (march 2010), pp. 1 –5.

[11] ABBASI, A. A., AND YOUNIS, M. A survey on clustering algorithms for wireless sensor networks. *Comput. Commun. 30*, 14-15 (2007), 2826–2841.

[12] ABDRABOU, A., AND ZHUANG, W. Statistical QoS routing for IEEE 802.11 multihop ad hoc networks. *IEEE Transactions on Wireless Communications 8*, 3 (2009), 1542–1552.

[13] ACKERMANN, H., RÖGLIN, H., AND VÖCKING, B. Pure Nash equilibria in player-specific and weighted congestion games. *Theoretical Computer Science Vol. 410*, 17 (2009), 1552 – 1563.

[14] AHMED, N., SHRIVASTAVA, V., MISHRA, A., BANERJEE, S., KESHAV, S., AND PAPAGIANNAKI, K. Interference mitigation in enterprise wlans through speculative scheduling. In *Proc. of ACM MobiCom 2007* (Sep. 2007). `http://doi.acm.org/10.1145/1287853.1287900`.

[15] AKAN, O. B., KARLI, O. B., AND ERGUL, O. Cognitive radio sensor networks. *Netwrk. Mag. of Global Internetwkg. 23*, 4 (July 2009), 34–40. `http://dx.doi.org/10.1109/MNET.2009.5191144`.

[16] AKYILDIZ, I. F., LEE, W.-Y., AND CHOWDHURY, K. R. CRAHNs: Cognitive radio ad hoc networks. *Ad Hoc Netw. Vol. 7*, 5 (2009), 810–836.

[17] AKYILDIZ, I. F., LEE, W.-Y., VURAN, M. C., AND MOHANTY, S. Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer networks journal (ELSEVIER) 50* (2006), 2127–2159.

[18] AKYILDIZ, I. F., LO, B. F., AND BALAKRISHNAN, R. Cooperative spectrum sensing in cognitive radio networks: A survey. *Phys. Commun. 4*, 1 (Mar. 2011), 40–62.

[19] ALI JORIO, SANAA EL FKIHI, B. E., AND ABOUTAJDINE, D. An energy-efficient clustering routing algorithm based on geographic position and residual energy for wireless sensor network. *Journal of Computer Networks and Communications 2015* (April 2015).

[20] ALIZAI, M., VAEGS, T., LANDSIEDEL, O., GÖTZ, S., LINK, J., AND WEHRLE, K. Probabilistic addressing: Stable addresses in unstable wireless networks. In *Proc. of IPSN 2011* (April 2011), pp. 61–72.

[21] ASTERJADHI, A., BALDO, N., AND ZORZI, M. A cluster formation protocol for cognitive radio ad hoc networks. In *Proc. of European Wireless Conference 2010*, pp. 955–961.

[22] AZARFAR, A., FRIGON, J.-F., AND SANSO, B. Improving the reliability of wireless networks using cognitive radios. *Communications Surveys Tutorials, IEEE 14*, 2 (Second 2012), 338–354.

[23] BABADI, B., AND TAROKH, V. Distributed dynamic frequency allocation in wireless networks under time-varying user activities. In *In Proceedings of IEEE Sarnoff Symposium 2008* (April 2008), pp. 1–5.

[24] BADDOUR, K., URETEN, O., AND WILLINK, T. Efficient clustering of cognitive radio networks using affinity propagation. In *Proc. of ICCCN 2009* (2009).

[25] BAHRAMIAN, S., AND KHALAJ, B. Joint dynamic frequency selection and power control for cognitive radio networks. In *Telecommunications, 2008. ICT 2008. International Conference on* (June 2008), pp. 1–6.

[26] BALDO, N., AND ZORZI, M. Cognitive network access using fuzzy decision making. *IEEE Transactions on Wireless Communications 8*, 7 (July 2009), 3523–3535.

[27] BASAGNI, S. Distributed clustering for ad hoc networks. *Proc. of I-SPAN '99* (1999), 310 –315.

[28] BEZABIH, H., ELLINGSAETER, B., NOLL, J., AND MASENG, T. Digital broadcasting: Increasing the available white space spectrum using TV receiver information. *Vehicular Technology Magazine, IEEE 7*, 1 (March 2012), 24–30.

[29] BEZABIH, H., ELLINGSAETER, B., NOLL, J., AND MASENG, T. Digital broadcasting: Increasing the available white space spectrum using TV receiver information. *IEEE Vehicular Technology Magazine 7*, 1 (march 2012), 24 –30.

[30] BIAN, K., AND PARK, J.-M. A coexistence-aware spectrum sharing protocol for 802.22 WRANs. In *Proceedings of 18th Internatonal Conference on Computer Communications and Networks* (Aug 2009), pp. 1–6.

[31] BOCCARDI, F., HEATH, R., LOZANO, A., MARZETTA, T., AND POPOVSKI, P. Five disruptive technology directions for 5G. *Communications Magazine, IEEE 52*, 2 (February 2014), 74–80.

[32] CACCIAPUOTI, A., CALCAGNO, C., CALEFFI, M., AND PAURA, L. CAODV: routing in mobile ad-hoc cognitive radio networks. In *Proc. of IFIP Wireless Days 2010*.

[33] CARUSO, A., CHESSA, S., DE, S., AND URPI, A. GPS free coordinate assignment and routing in wireless sensor networks. In *Proc. IEEE INFOCOM '05*, vol. 1, pp. 150 – 160 vol. 1.

[34] CAVE, M., DOYLE, C., AND WEBB, W. *Essentials of Modern Spectrum Management*. Cambridge University Press, 2007.

[35] CESANA, M., CUOMO, F., AND EKICI, E. Routing in cognitive radio networks: challenges and solutions. *Ad Hoc Networks 9*, 3 (2011), 228 – 248.

[36] CHEE, B. J. S., AND FRANKLIN, JR., C. *Cloud Computing: Technologies and Strategies of the Ubiquitous Data Center*, 1st ed. CRC Press, Inc., Boca Raton, FL, USA, 2010.

[37] CHEN, L., LOW, S., AND DOYLE, J. Contention control: A game-theoretic approach. In *Proc. of 2007 46th IEEE Conference on Decision and Control* (Dec 2007), pp. 3428–3434.

[38] CHEN, T., ZHANG, H., MAGGIO, G., AND CHLAMTAC, I. Cogmesh: A cluster-based cognitive radio network. *Proc. of DySPAN '07* (apr. 2007), 168 –178.

[39] CHEN, X., AND HUANG, J. Game theoretic analysis of distributed spectrum sharing with database. In *Distributed Computing Systems (ICDCS), 2012 IEEE 32nd International Conference on* (June 2012), pp. 255–264.

[40] CHEN, X., AND HUANG, J. Game theoretic analysis of distributed spectrum sharing with database. In *Proc. of 2012 IEEE 32nd International Conference on Distributed Computing Systems (ICDCS)* (June 2012), pp. 255–264.

[41] CHOWDHURY, K., AND DI FELICE, M. SEARCH: a routing protocol for mobile cognitive radio ad-hoc networks. In *Proc. of IEEE Sarnoff Sym. '09*, pp. 1–6.

[42] DI FELICE, M., GHANDHOUR, A., ARTAIL, H., AND BONONI, L. Integrating spectrum database and cooperative sensing for cognitive vehicular networks. In *Proc. of IEEE VTC 2013 Fall* (Sept 2013), pp. 1–7.

[43] ELIAS, J., AND KRUNZ, M. Distributed spectrum management in TV white space cognitive radio networks. In *Proc. of IFIP Networking Conference, 2015* (May 2015), pp. 1–8.

[44] ELLINGSAETER, B., BEZABIH, H., NOLL, J., AND MASENG, T. Using TV receiver information to increase cognitive white space spectrum. In *Processings of 2012 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)* (Oct 2012), pp. 131–141.

[45] FELEGYHAZI, M., CAGALJ, M., BIDOKHTI, S., AND HUBAUX, J.-P. Non-cooperative multi-radio channel allocation in wireless networks. In *Proc. of IEEE INFOCOM 2007* (May 2007).

[46] FENG, X., ZHANG, J., AND ZHANG, Q. Database-assisted multi-AP network on TV white spaces: Architecture, spectrum allocation and ap discovery. In *Proc. of IEEE DySPAN 2011* (may 2011), pp. 265 –276.

[47] FENG, X., ZHANG, Q., AND ZHANG, J. A hybrid pricing framework for tv white space database. *IEEE Transactions on Wireless Communications 13*, 5 (May 2014), 2626–2635.

[48] FLORES, A., GUERRA, R., KNIGHTLY, E., ECCLESINE, P., AND PANDEY, S. IEEE 802.11af: a standard for TV white space spectrum sharing. *Communications Magazine, IEEE 51*, 10 (October 2013), 92–100.

[49] GALINDO-SERRANO, A., AND GIUPPONI, L. Aggregated interference control for cognitive radio networks based on multi-agent learning. In *Proc. of CrownCom 2009* (Jun. 2009).

[50] GARDELLIN, V., DAS, S., AND LENZINI, L. A fully distributed game theoretic approach to guarantee self-coexistence among wrans. In *Proc. of IEEE INFOCOM, Computer Communications Workshops* (march 2010), pp. 1 –6.

[51] GAREY, M. R., AND JOHNSON, D. S. *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W. H. Freeman, 1979.

[52] GE, Y., ZHANG, Y., QIU, Q., AND LU, Y.-H. A game theoretic resource allocation for overall energy minimization in mobile cloud computing system. In *Proceedings of the 2012 ACM/IEEE International Symposium on Low Power Electronics and Design* (New York, NY, USA, 2012), ISLPED '12, ACM, pp. 279–284.

[53] GEIRHOFER, S., TONG, L., AND SADLER, B. A measurement-based model for dynamic spectrum access in WLAN channels. In *Proceedings of IEEE Military Communications Conference 2006* (Oct 2006), pp. 1–7.

[54] GURNEY, D., BUCHWALD, G., ECKLUND, L., KUFFNER, S., AND GROSSPIETSCH, J. Geo-location database techniques for incumbent protection in the TV white space. In *Proc. of IEEE DySPAN 2008* (Oct. 2008).

[55] HAN, Z., AND LIU, K. J. R. *Resource Allocation for Wireless Networks: Basics, Techniques, and Applications*. Cambridge University Press, New York, NY, USA, 2008.

[56] HARRISON, K., MISHRA, S., AND SAHAI, A. How much white-space capacity is there? In *Proc. of DySPAN 2010* (Apr. 2010), pp. 1 –10.

[57] HART, S., AND COLELL, A. A simple adaptive procedure leading to correlated equilibrium. *Econometrica 68*, 5 (2000), 1127–1150. `http://dx.doi.org/10.2307/2999445`.

[58] HMAM, H. Quadratic optimisation with one quadratic equality constraint. Tech. rep., DTIC Document, 2010.

[59] HOANG, A., LIANG, Y., AND ISLAM, M. Power control and channel allocation in cognitive radio networks with primary users' cooperation. *IEEE Transactions on Mobile Computing 9*, 3 (Mar. 2010), 348–360. `http://dx.doi.org/10.1109/TMC.2009.136`.

[60] HOANG, A. T., AND LIANG, Y.-C. Downlink channel assignment and power control for cognitive radio networks. *Wireless Communications, IEEE Transactions on 7*, 8 (August 2008), 3106–3117.

[61] HU, W., GERLA, M., VLANTIS, G., AND POTTIE, G. Efficient, flexible, and scalable inter-network spectrum sharing and communications in cognitive IEEE 802.22 networks. In *In Proceedings of First International Workshop on Cognitive Radio and Advanced Spectrum Management 2008* (Feb 2008), pp. 1–5.

[62] HUANG, J., AND KRISHNAMURTHY, V. Cognitive base stations in LTE/3GPP femtocells: A correlated equilibrium game-theoretic approach. *IEEE Transactions on Communications 59*, 12 (Dec. 2011), 3485–3493.

[63] HUANG, J., ZHU, Q., KRISHNAMURTHY, V., AND BASAR, T. Distributed correlated q-learning for dynamic transmission control of sensor networks. In *Proc. of IEEE ICASSP 2010* (Mar. 2010).

[64] HUAZI ZHANG, ZHAOYANG ZHANG1, H. D. R. Y., AND CHEN, X. Distributed spectrum-aware clustering in cognitive radio sensor networks. In *Proc. of GLOBECOM 2011*.

[65] HURWICZ, L. The design of mechanisms for resource allocation. *American Economic Review 63*, 2 (1973), 1–30.

[66] I, C.-L., ROWELL, C., HAN, S., XU, Z., LI, G., AND PAN, Z. Toward green and soft: a 5G perspective. *Communications Magazine, IEEE 52*, 2 (February 2014), 66–73.

[67] JÄNTTI, R., KERTTULA, J., KOUFOS, K., AND RUTTIK, K. Aggregate interference with fcc and ecc white space usage rules: case study in finland. In *Proc. of IEEE DySPAN 2011* (May 2011).

[68] KAWADIA, V., AND KUMAR, P. R. Power control and clustering in ad hoc networks. In *Proc. of INFOCOM '03* (2003), pp. 459–469.

[69] KHALIFE, H., MALOUCH, N., AND FDIDA, S. Multihop cognitive radio networks: to route or not to route. *Network, IEEE 23*, 4 (july-august 2009), 20 –25.

[70] KIM, H., AND SHIN, K. Efficient discovery of spectrum opportunities with mac-layer sensing in cognitive radio networks. *IEEE Transactions on Mobile Computing 7*, 5 (May 2008), 533–545.

[71] KO, B., MISRA, V., PADHYE, J., AND RUBENSTEIN, D. Distributed channel assignment in multi-radio 802.11 mesh networks. In *Proc. of IEEE WCNC 2007* (Mar. 2007).

[72] KOTHARI, A., SURI, S., TÓTH, C. D., AND ZHOU, Y. Congestion games, load balancing, and price of anarchy. In *Proc. of CAAN'04* (2004), pp. 13–27.

[73] KOUFOS, K., RUTTIK, K., AND JANTTI, R. Controlling the interference from multiple secondary systems at the TV cell border. In *Proc. of IEEE PIMRC 2011* (Sep. 2011).

[74] LANGAR, R., SECCI, S., BOUTABA, R., AND PUJOLLE, G. An operations research game approach for resource and power allocation in cooperative femtocell networks. *IEEE Transactions on Mobile Computing, 14*, 4 (April 2015), 675–687.

[75] LAZOS, L., LIU, S., AND KRUNZ, M. Spectrum opportunity-based control channel assignment in cognitive radio networks. *Proc. of SECON '09* (jun. 2009), 1 –9.

[76] LEE, W.-Y., AND AKYLDIZ, I. A spectrum decision framework for cognitive radio networks. *IEEE Transactions on Mobile Computing 10*, 2 (Feb 2011), 161–174.

[77] LI, D., AND GROSS, J. Distributed TV spectrum allocation for cognitive cellular network under game theoretical framework. In *Proc. of IEEE DySPAN 2012*.

[78] LIN, C. R., AND GERLA, M. Adaptive clustering for mobile wireless networks. *IEEE Journal on Selected Areas in Communications 15* (1997), 1265–1275.

[79] LIN, Y., AND SCHRAGE, L. The global solver in the lindo api. *Optimization Methods Software 24*, 4-5 (Aug. 2009), 657–668. `http://dx.doi.org/10.1080/10556780902753221`.

[80] LIU, M., AND WU, Y. Spectum sharing as congestion games. In *Proc. of Allerton Conference 2008* (Sep. 2008).

[81] LIU, S., LAZOS, L., AND KRUNZ, M. Cluster-based control channel allocation in opportunistic cognitive radio networks. *IEEE Trans. Mob. Comput. 11*, 10 (2012), 1436–1449.

[82] LIU, Y., CAI, L., AND SHEN, X. Spectrum-aware opportunistic routing in multi-hop cognitive radio networks. *IEEE Journal on Selected Areas in Communications 30*, 10 (2012), 1958–1968.

[83] LIU, Y., CAI, L., SHEN, X., AND MARK, J. W. Exploiting heterogeneity wireless channels for opportunistic routing in dynamic spectrum access networks. In *Proc. of IEEE ICC 2011* (2011), pp. 1–5.

[84] LOPEZ-BENITEZ, M., AND CASADEVALL, F. Discrete-time spectrum occupancy model based on markov chain and duty cycle models. In *Proc. of 2011 IEEE DySPAN*.

[85] MACKENZIE, A., AND WICKER, S. Game theory in communications: motivation, explanation, and application to power control. In *Proc. of IEEE GLOBECOM 2001* (2001), vol. 2, pp. 821–826 vol.2.

[86] MITOLA, J., I., AND MAGUIRE, G.Q., J. Cognitive radio: making software radios more personal. *Personal Communications, IEEE 6*, 4 (aug. 1999), 13 –18.

[87] MITOLA, J. *Cognitive Radio — An Integrated Agent Architecture for Software Defined Radio*. DTech thesis, Royal Institute of Technology (KTH), Kista, Sweden, May.

[88] MITZENMACHER, M., AND UPFAL, E. *Probability and Computing: Randomized Algorithms and Probabilistic Analysis*. Cambridge University Press, New York, NY, USA, 2005.

[89] MURTY, R., CHANDRA, R., MOSCIBRODA, T., AND BAHL, V. Senseless: A database-driven white spaces network. In *Proc. of IEEE DySpan 2011* (May 2011).

[90] NEEL, J. O. *Analysis and Design of Cognitive Radio Networks and Distributed Radio Resource Management Algorithms*. PhD thesis, Blacksburg, VA, USA, 2006. AAI3249450.

[91] NIE, N., AND COMANICIU, C. Adaptive channel allocation spectrum etiquette for cognitive radio networks. In *Proc. of IEEE DySpan 2005* (Nov. 2005).

[92] NISAN, N., ROUGHGARDEN, T., TARDOS, E., AND VAZIRANI, V. V. *Algorithmic Game Theory*. Cambridge University Press, 2007.

[93] NOAM, E. M. Taking the next step beyond spectrum auctions: Open spectrum access. *Comm. Mag. 33*, 12 (Dec. 1995), 66–73. `http://dx.doi.org/10.1109/35.476925`.

[94] OMIDVAR, N., AND KHALAJ, B. A game-theoretic approach for joint channel and power allocation in downlink of cellular cognitive radio networks. In *Proc. of IEEE PIMRC 2012* (Sept 2012), pp. 1198–1202.

[95] PAL, R. Efficient routing algorithms for multi-channel dynamic spectrum access networks. In *Proc. of IEEE DySPAN 2007* (April 2007), pp. 288–291.

[96] PALAIOS, A., RIIHIJARVI, J., AND MAHONEN, P. From Paris to London: Comparative analysis of licensed spectrum use in two european metropolises. In *Proc. of IEEE DySPAN 2014* (April 2014), pp. 48–59.

[97] PAN, M., ZHANG, C., LI, P., AND FANG, Y. Joint routing and link scheduling for cognitive radio networks under uncertain spectrum supply. In *Proc. of IEEE INFOCOM 2011*.

[98] PARAMVIR BAHL, RANVEER CHANDRA, T. M. R. M., AND WELSH, M. White space networking with Wi-Fi like connectivity. In *Proc. of ACM SIGCOMM 2009* (Aug. 2009).

[99] PASSIATORE, C., AND CAMARDA, P. A centralized inter-network resource sharing (CIRS) scheme in IEEE 802.22 cognitive networks. In *Proc. of 2011 The 10th IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net),* (June 2011), pp. 17–24.

[100] PASSIATORE, C., AND CAMARDA, P. A centralized inter-network resource sharing (CIRS) scheme in IEEE 802.22 cognitive networks. In *Ad Hoc Networking Workshop (Med-Hoc-Net), 2011 The 10th IFIP Annual Mediterranean* (june 2011), pp. 17 –24.

[101] RAHMAN, M. I., BEHRAVAN, A., KOORAPATY, H., SACHS, J., AND BALACHANDRAN, K. License-exempt LTE systems for secondary spectrum usage: scenarios and first assessment. In *Dyspan 2011, IEEE* (May 2011).

[102] RANIWALA, A., AND CHIUEH, T. Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network. In *Proc. of IEEE INFOCOM 2005* (Mar. 2005).

[103] RAPPAPORT, T. *Wireless Communications: Principles and Practice*, 2nd ed. Prentice Hall PTR, Upper Saddle River, NJ, USA, 2001.

[104] ROSENTHAL, R. A class of games possessing pure-strategy Nash equilibria. *International Journal of Game Theory 2* (1973), 65–67. `http://dx.doi.org/10.1007/BF01737559`.

[105] RUTTIK, K., KOUFOS, K., AND JANTTI, R. Model for computing aggregate interference from secondary cellular network in presence of correlated shadow fading. In *In Proceedings of IEEE PIMRC 2011* (Sept 2011), pp. 433–437.

[106] SAHAI, A., TANDRA, R., MISHRA, S. M., AND HOVEN, N. Fundamental design tradeoffs in cognitive radio systems. In *Proceedings of the First International Workshop on Technology and Policy for Accessing Spectrum* (New York, NY, USA, 2006), TAPAS '06, ACM.

[107] SAIFAN, R., KAMAL, A., AND GUAN, Y. Spectrum decision for efficient routing in cognitive radio network. In *Proc. of IEEE MASS 2012*.

[108] SALAHI, M. Convex optimization approach to a single quadratically constrained quadratic minimization problem. *Central European Journal of Operations Research 18*, 2 (2010), 181–187.

[109] SAMPATH, A., YANG, L., CAO, L., ZHENG, H., AND ZHAO, B. Y. High throughput spectrum-aware routing for cognitive radio networks. In *Proc. of IEEE CrownCom* (2008).

[110] SENGUPTA, S., CHANDRAMOULI, R., BRAHMA, S., AND CHATTERJEE, M. A game theoretic framework for distributed self-coexistence among IEEE 802.22 networks. In *Proc. of IEEE GLOBECOM 2008* (30 2008-dec. 4 2008), pp. 1 –6.

[111] SERGIOU, C., ANTONIOU, P., AND VASSILIOU, V. A comprehensive survey of congestion control protocols in wireless sensor networks. *Communications Surveys Tutorials, IEEE 16*, 4 (Fourthquarter 2014), 1839–1859.

[112] SHAH, G., AND AKAN, O. Spectrum-aware cluster-based routing for cognitive radio sensor networks. In *Proc. of IEEE ICC 2013* (June 2013), pp. 2885–2889.

[113] SHAH, G., ALAGOZ, F., FADEL, E., AND AKAN, O. A spectrum-aware clustering for efficient multimedia routing in cognitive radio sensor networks. *IEEE Transactions on Vehicular Technology PP*, 99 (2014), 1–1.

[114] SHAH, V., MANDAYAM, N., AND GOODMAN, D. Power control for wireless data based on utility and pricing. In *Proc. of IEEE PIMRC 1998* (Sep 1998), vol. 3, pp. 1427–1432 vol.3.

[115] SUCEC, J., AND MARSIC, I. Clustering overhead for hierarchical routing in mobile ad hoc networks. In *Proc. of IEEE INFOCOM 2002* (2002), vol. 3, pp. 1698 – 1706 vol.3.

[116] SUN, C., ZHANG, W., AND LETAIEF, K. B. Cluster-based cooperative spectrum sensing in cognitive radio systems. In *proc. of IEEE ICC* (2007), pp. 2511–2515.

[117] TAO, X., ZHAO, Z., AND ZHANG, H. Location information based interference control for cognitive radio network in TV white spaces. In *Proc. of IEEE WCNC 2013*, pp. 3614–3619.

[118] VARGA, A., AND HORNIG, R. An overview of the omnet++ simulation environment. In *Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops* (ICST, Brussels, Belgium, Belgium, 2008), pp. 1–10.

[119] VÖCKING, B. Congestion games: Optimization in competition. In *Proc. of second ACiD Workshop* (Durham, UK, Sep. 2006).

[120] WANG, B., WU, Y., AND LIU, K. R. Game theory for cognitive radio networks: An overview. *Comput. Netw. 54*, 14 (Oct. 2010), 2537–2561.

[121] WELLENS, M., RIIHIJÄRVI, J., AND MÄHÖNEN, P. Empirical time and frequency domain models of spectrum use. *Physical Communication 2*, 1–2 (2009), 10 – 32.

[122] WILLKOMM, D., BOHGE, M., HOLLÓS, D., GROSS, J., AND WOLISZ, A. Double hopping: A new approach for dynamic frequency hopping in cognitive radio networks. In *Proc. of PIMRC 2008*.

[123] WU, D., CAI, Y., ZHOU, L., AND WANG, J. A cooperative communication scheme based on coalition formation game in clustered wireless sensor networks. *IEEE Transactions on Wireless Communications, 11*, 3 (march 2012), 1190 –1200.

[124] WU, F., ZHONG, S., AND QIAO, C. Globally optimal channel assignment for non-cooperative wireless networks. In *Proc. of IEEE INFOCOM 2008* (Apr. 2008).

[125] WU, H., AND ABOUZEID, A. Cluster-based routing overhead in networks with unreliable nodes. In *Proceedings of IEEE WCNC 2004* (march 2004), vol. 4, pp. 2557 – 2562 Vol.4.

[126] WU, Q., DING, G., WANG, J., LI, X., AND HUANG, Y. Consensus-based decentralized clustering for cooperative spectrum sensing in cognitive radio networks. *Chinese Science Bulletin 57*, 28-29 (2012), 3677–3683.

[127] WU, Y., AND TSANG, D. Distributed power allocation algorithm for spectrum sharing cognitive radio networks with qos guarantee. In *Proc. of IEEE INFOCOM 2009* (Apr. 2009).

[128] XIE, R., YU, F., AND JI, H. Dynamic resource allocation for heterogeneous services in cognitive radio networks with imperfect channel sensing. *IEEE Transactions on Vehicular Technology, 61*, 2 (Feb 2012), 770–780.

[129] XU, L., TÖNJES, R., PAILA, T., HANSMANN, W., FRANK, M., AND ALBRECHT, M. DRiVE-ing to the internet: Dynamic radio for IP services in vehicular environments. 281–289.

[130] YE, B., NEKOVEE, M., PERVEZ, A., AND GHAVAMI, M. TV white space channel allocation with simulated annealing as meta algorithm. In *Proc. of 2012 7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications* (June 2012), pp. 175–179.

[131] YUCEK, T., AND ARSLAN, H. A survey of spectrum sensing algorithms for cognitive radio applications. *Communications Surveys Tutorials, IEEE 11*, 1 (First 2009), 116–130.

[132] YUE, X., WONG, C.-F., AND CHAN, S.-H. CACAO: Distributed client-assisted channel assignment optimization for uncoordinated WLANs. *IEEE Transactions on Parallel and Distributed Systems, 22*, 9 (Sept 2011), 1433–1440.

[133] ZHANG, L., YUAN, L., FENG, Z., AND FENG, Z. Mutual-interference-aware available spectrum resource distribution in TV white space. In *Proc. of IEEE PIMRC 2013* (Sept 2013), pp. 2743–2747.

[134] ZHANG, Y., YU, G., LI, Q., WANG, H., ZHU, X., AND WANG, B. Channel-hopping-based communication rendezvous in cognitive radio networks. *Networking, IEEE/ACM Transactions on 22*, 3 (June 2014), 889–902.

[135] ZHANG, Z., LONG, K., AND WANG, J. Self-organization paradigms and optimization approaches for cognitive radio technologies: a survey. *Wireless Communications, IEEE 20*, 2 (April 2013), 36–42.

[136] ZHAO, J., ZHENG, H., AND YANG, G.-H. Spectrum sharing through distributed coordination in dynamic spectrum access networks. *Wireless Communications and Mobile Computing 7*, 9 (2007), 1061–1075.

[137] ZHAO, Q., AND SADLER, B. A survey of dynamic spectrum access. *Signal Processing Magazine, IEEE 24*, 3 (May 2007), 79–89.

List of Figures

List of Tables

Glossary

2TDMC two-state discrete time Markov chain. 97
5G 5th generation mobile networks. 2

CCC common control channel. 11, 59, 65
CH cluster head. 55
COS Cost of Oscillation. 47
CR cognitive radio. 2, 55
CRAHN Cognitive radio ad hoc network. 7
CRN cognitive radio network. 3
CW contention window. 16

DCF distributed coordination function. 15
DiCAPS Distributed Channel Allocation and Power Selection. 33
DSR Dynamic Source Routing. 88
DTV digital TV. 25

ECC Electronic Communications Committee in Europe. 5, 23

FCC Federal Communications Commission in U.S.. 23

GSM global system for mobile communications. 1

ISM band industrial, scientific, and medical. 1

LP linear programming program. 32

MAN Metropolitan Area Networks. 29

NE Nash equilibrium. 16

PDA personal digital assistant. 2
PO Pareto Optimality. 18
PoA price of anarchy. 18
PU primary user. 2

QoS quality of service. 25

ROSS Robust Spectrum Sharing. 59
ROSS-DFA Robust Spectrum Sharing-distributed fast algorithm. 56
ROSS-DGA Robust Spectrum Sharing-distributed greedy algorithm. 56
RSSI Received Signal Strength Index. 24, 42

SINR signal-to-noise-and-interference ratio. 25, 26

TC Time Complexity. 80
TVBD TV band devices. 9
TVWS TV white space. 8

UHF Ultra high frequency. 24

VCap virtual coordinate assignment protocol. 90

WhiteCat White space Channel allocation. 33
WRAN Wireless Regional Area Network. 29