Dynamic Spectrum Access for Multi-group Cognitive Radio Networks

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A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Philosophy
in
Information Engineering

July, 2008

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submitted by

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for the degree of Master of Philosophy

at the Chinese University of Hong Kong

Abstract

In cognitive radio networks, the protection of licensed users' access priority and the coordination of multiple unlicensed user groups pose great challenges to system designers. This thesis introduces the Power Regulation Protocol for the spectrum access of unlicensed users. We can prove that under this protocol, both licensed and unlicensed users can achieve satisfied communication qualities by properly setting the parameters of the protocol. Even with the presence of user mobility and fading effect in wireless channels, this result also holds. The Power Regulation Protocol is based on channel sensing with power detectors and does not require inter-group information exchange. Therefore, it is quite applicable to cognitive radio networks where different user groups can hardly have communication in between due to their heterogenous transmission parameters. Simulation result shows that the Power Regulation Protocol can achieve similar network throughput compared with the widely used RTS/CTS mechanism in the 802.11 protocols where information exchange is required.

摘要

在认知无线电网络中，如何保护授权用户的接入优先权，和如何协调多个非授权用户组之间的通信，对于系统设计者来说，是一个很大的挑战。这篇论文介绍了为非授权用户接入频谱而设计的功率管制协议。我们证明，使用这个协议并适当调整协议的参数，授权用户和非授权用户都能获得满意的通信质量。即使考虑了用户的移动性，以及无线信道的衰落，这个结论也成立。 功率管制协议是基于功率检测器的，它不需要不同组之间的信息交换。而对于不同组采用不同传输参数因而很难实现通信的认知无线电网络而言，这个协议尤其适用。仿真结果显示，功率管制协议可以取得与 802.11 协议相似的网路吞吐量。而 802.11 协议是需要信息交换的。

Acknowledgment

I would like to firstly express my appreciation to my supervisor, Prof. WONG Wing Shing, for his patient teaching, prudent advice, and guidance in these two years. His insight in academic fields helps me quickly figure out the problems in my research. He is always willing to talk to students like a friend. Through the discussion with him, I not only gained deep understanding of the knowledge but also learnt the rigorous attitude in conducting research. I would like to express my thanks to Prof. ZHANG Yingjun and Prof. LIN Chinlon. Prof. Zhang inspired me a lot in our study group every week; Prof. Lin showed me the industry world in his course and reminded me of paying extra attention to details. Also, I would like to thank the professors who has taught me or given me advices in the past two years: Prof. CHEN Lian-Kuan, Prof. YEUNG Wai-Ho, Prof. Li Shuo-Yen, and Prof. LAU Wing-Cheong.

I also enjoy my research life in Information and Systems Laboratory. I must thank Dr. CHEN Chung Shue very much. He gives me a lot of suggestions on my papers. I am happy to work with all of my labmates: Dr. CHENG Hui, Mr. CHAU Wai Shing, Mr. CHEUNG Kwok Sum, Ms. JING Nie, Mr. LEE King Ho, Mr. NGAI Chi Kin, Mr. XU Ceng, Mr. YANG Shenghao, Mr ZHANG Yijin, Ms. CHEN Yi and Ms. SHEN Yuxiu in our study group.

Last but not the least, I want to thank my parents. They respect my choice and never give me pressure. I always get support from them no matter success or failure. Their deep love is the most precious thing that I cherish in my life.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

In recent years, we witnessed the deployment of various wireless communication systems which redefined the way of information occupation and greatly changed our daily lives. From mobile phone to wireless LAN, from Bluetooth system to WiMAX, communication with anyone at any time and any where is much easier than ever before. For all these wireless systems, if they want to work simultaneously without interfering each other, each system in general needs to access to different frequency band for transmission. Concerning this, fixed spectrum assignment policy is used to divide the whole spectrum into multiple bands and each band is assigned to certain services or networks. One wireless system should firstly obtain the license of its interested frequency band before it can access. In this way, collision between various wireless systems is avoided. It works well until recently. The dramatic increase of subscription to wireless services and the demand of large volume multi-media information exchange require that the wireless networks occupy larger bandwidth for transmission. As a result, the limited radio spectrum becomes more and more congested and little bandwidth can be assigned to carry those additional data flows.

However, contrary to the belief that spectrum resources is almost exhausted, real measurement reveals that most of the allocated spectrum is largely under-utilized at any specific location and time [3]. To deal with the discrepancy between inefficient spectrum usage of existing licensed users and the limited spectrum resources for new bandwidth-consuming wireless services, cognitive radio networks is proposed. As an emerging technology, it is designed to users to dynamically access the spectrum thus better utilize the precious frequency resources [13]. To be specific, cognitive radios are allowed, under certain business contract or government regulation, to access to the spectrum that has already been assigned to other systems. However, as unlicensed users (secondary users), they only transmit when the licensed users (Primary users) are not using the spectrum. Then the existing licensed users' communication will not be influenced by the enrollment of cognitive radios, meanwhile spectrum can be utilized in an efficient way.

Although with promising future, the design and deployment of cognitive radio networks face various kinds of challenges that are unique to traditional wireless systems. And among all the issues, how to guarantee the coexistence between different user groups is probability the first and the most important questions that needs to be answered. Specifically, the communication of licensed users should not be noticeably influenced by unlicensed users' access. On the other hand, when licensed users are idle, multiple unlicensed user groups should be well coordinated to share the spectrum in an efficient way. In this sense, the access policy of cognitive radios is quite vital. A well designed protocol should increase the efficiency of spectrum utilization at the same time minimize the negative impact to licensed users.

In the past few years, a large number of access schemes with excellent performances have been proposed in both centralized and ad-hoc network environments. However, they can hardly be applied to cognitive radio networks. This is because these schemes are in general designed for a single user group with the assumption that the nodes inside the network can have package exchange among them. Nevertheless, in cognitive radio networks, to modify the already existing licensed users for the communication with unlicensed users is not reasonable because it means big investment and no additional benefit. On the other hand, as the unused spectrum resources is open to all unlicensed users, multiple unlicensed user groups adapting different transmitting parameters may access simultaneously. Unless they have a common radio interface and a dedicated control channel, inter-network communication is hard to realize. All of these lead to difficulties in addressing the coexistence problem.

This thesis introduces a new access theme called Power Regulation Protocol. Under this protocol, licensed users' communication quality is guaranteed. Meanwhile, multiple unlicensed user groups can share the spectrum in a fair and efficient way. What's more, this protocol is based on power detection. No information exchange is needed between different networks. Then the requirements for common radio interfaces and dedicated control channels are relaxed. The operating process and hardware structure can be simplified making cognitive radio networks much more applicable in the real deployment. The rest of this thesis is organized as follows. In Chapter 2, we review the current research results on physical and MAC Layer design of cognitive radio networks. The Power Regulation Protocol is introduced and its performance analyzed in Chapter 3. Chapter 4 extends the discussion to fading wireless channels. Simulation is conducted with its results stated in Chapter 5. Final conclusions and future research directions of cognitive radio networks are addressed in Chapter 6.

Chapter 2

Technology overview

2.1 Associate background

The development of cognitive radio networks is originated from software defined radio technique which refers to the ability of radio to dynamically change the transmitting parameters for multi-band multi-mode wireless communications. As it is firstly proposed by J. Mitola in 1999, cognitive radio is an enhanced version of software defined radio through the use of Radio Knowledge Representation Language (RKRL) [20]. With RKRL, radio is empowered to negotiate among peers on the spectrum usage, then automatically manipulate its transmission to better satisfy the user's need. At this stage, cognitive radio as a new prototype provided an idea of access according to radio environment instead of artificial spectrum regulation. However, how to implement the RKRL in the real settings is not clearly defined and actually quite hard to achieve.

Noticing the inefficient spectrum usage of licensed users, FCC would like to initiate the dynamic spectrum access using cognitive radio techniques. The term cognitive radio is formally defined by FCC as a radio that can change its transmitter parameter based on interaction with the environment in which it operates [9]. In this sense, a cognitive radio should possess two basic functions. The first one is cognitive capability which refers to the ability of the radio technology to capture or sense the information from its radio environment. The second one is reconfigurability which enables the radio to be dynamically programmed according to the radio environment [1].

Nowadays, most of the bands are already allocated to licensed users for exclusive use. Therefore, cognitive radio will not use a dedicated band but access the licensed user's band as an unlicensed user. With the promise that licensed users' communication quality is not degraded, it opportunistically accesses and dynamically changes its transmitting parameters to take advantage of those spatial/temporal unused frequency resources for its own transmission. It should be noted that access without licenses can also be found in license-exempt bands. An example is ISM band on which 802.11 networks, Bluetooth systems and other wireless systems operate simultaneously. However, as no license is granted to any one, radios in this band do not need to avoid interfering any licensed users. The approaches they share the spectrum and eliminate mutual interference are through transmitting power limitation and interference tolerant techniques.

Currently, the band exclusively assigned to TV station broadcasting is viewed to be quite suitable for the deployment of cognitive radio networks. For those rural regions uncovered by TV signal, this band is wasted. Even in the covered regions, not all the 6MHz channels are occupied for 24-hour transmission. The Federal Communication Commission is aware of this and has already released a Notice of Proposed Rule Making to initiate the opening up of spatially/temporally "unused" TV band to unlicensed users [10]. Meanwhile, IEEE has formed a new working group on wireless regional area networks (IEEE 802.22) whose goal is to develop a standard for unlicensed access to TV spectrum on a non-interfering basis [27].

2.2 Physical layer

Cognitive radios, after several years of research, is still at its beginning stage. Many problems existing in the physical layer and MAC layer block the way of its deployment. Most of the current studies as well as this thesis try to solve the challenging problems on these two layers. In the following sections, we will give a brief review on the related opening questions and possible solutions. This section begins with physical layer issues first.

2.2.1 Signal specification

The signals unlicensed users make use of to access can be divided into two categories: narrow band signal and broad band spreading signal. As one can

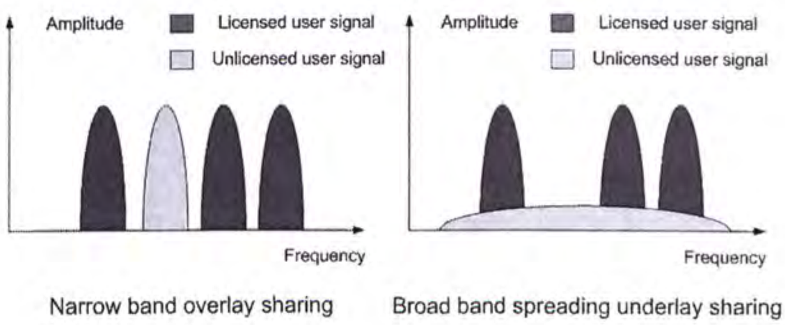

Figure 2.1: Signal specification of unlicensed users.

see from Figure 2.1 that the narrow band signals only focus on a small portion of band while broad band signals spread their power over the whole band. To protect the licensed user, narrow band overlay spectrum sharing tries to avoid any interference by only accessing vacant spectrum resources, while broad band underlay spectrum sharing tries to minimize the interference by lowering its power spectrum density. The performances of these two approaches are compared, based on their influence to the licensed users, in [19]. It turns out that the interference avoidance based overlay scheme is much better than spreading-based underlay scheme. Currently, most of the discussions on cognitive radio is based on narrow band overlay spectrum sharing [2, 5, 17, 24, 28, 29, 30]. In this thesis, we also adapt this access scheme for our discussions.

2.2.2 Spectrum sensing

As mentioned above, one of the basic functions of cognitive radio is to capture the information from radio environment. Through spectrum sensing of the licensed user signal, cognitive radios get to know whether the licensed transmitter is active or not, then access accordingly. Any errors in sensing will lead to interference to licensed receiver or inefficient spectrum utility. Based on how much information of the licensed user signal is known to unlicensed user, three approaches are used for sensing, namely power detection, matched filter detection and cyclostationary feature detection.

If no information of the licensed users' signal waveform is known, it can be proved that power detector is the optimal detector [23]. As shown in Figure 2.2, the output signal of bandpass filter with bandwidth W is squared and integrated over the observation interval T. This result is compared with a threshold P_s to decide whether a licensed user is present or not. The hypothesis

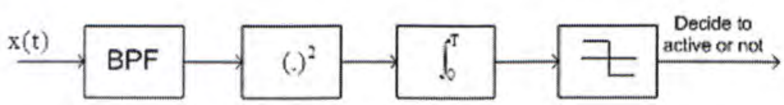

Figure 2.2: Power detector.

model of detection can be expressed as follows

$$x(t) = \begin{cases} n(t) & H_0, \\ hs(t) + n(t) & H_1, \end{cases} \tag{2.1}$$

where s(t) is the signal of the licensed user, h the channel gain and n(t) the Additive White Gaussian Noise (AWGN). H_0 represents that no licensed user is present then cognitive radio can access. And H_1 represents that licensed user is transmitting then cognitive radio should back off. If the channel gain h is fixed, the output of integrator follows chi-square distribution with $2TW$ degrees [26] (the double side noise spectral density N_{02} is normalized to 1):

$$Y = \begin{cases} \chi^2_{2TW}(0) & H_0, \\ \chi^2_{2TW}(2\gamma) & H_1. \end{cases} \tag{2.2}$$

The γ is the signal to noise ratio

$$\gamma = h^2 \int_0^T \frac{s^2(t)}{2N_{02}} dt = \frac{h^2 T P_t}{2}. \tag{2.3}$$

Making decision with the threshold P_s, the probability of detection p_d and false alarm p_f are given as follows [7]:

$$p_d = P\{Y > P_s | H_1\} = Q_m(\sqrt{2\gamma}, \sqrt{P_s}), \tag{2.4}$$

$$p_f = P\{Y > P_s | H_o\} = \frac{\Gamma(m, P_s/2)}{\Gamma(m)}, \tag{2.5}$$

where $m = TW$ is the time bandwidth product, $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are complete and incomplete gamma functions and $Q_m()$ is the generalized Marcum Q-function. For a fixed signal to noise ratio γ, there always exists a trade off in choosing P_s. If P_s is set low, p_d and p_f will be high which means less interference to licensed user as well as low spectrum utilization, on the other hand, verse visa. In wireless channels, channel gain fluctuates with time due to fading and shadowing. For a time varying SNR, the average probability of detection can be derived by averaging (2.4) over fading statistics,

$$p_d = \int_x Q_m(\sqrt{2\gamma}, \sqrt{P_s}) f_\gamma(x) dx \tag{2.6}$$

where $f_\gamma(x)$ is the probability distribution function (pdf) of SNR under fading [11].

Power detector does not require licensed users' signal information. Its simple hardware structure is quite applicable in the real settings. However, its detection ability is largely limited when the signal power approaches the noise power. On the other hand, Power detector measures signal energy in the band. If other unlicensed users are also transmitting, the detection result will be the total signal power from both licensed users and unlicensed users. Therefore, licensed users can not be distinguished. An approach to complement this is to use a pilot tone signal at the licensed users [23]. Through coherent detection, high detection accuracy can be provided even in the low signal to noise ratio environment. Meanwhile, licensed users' signal can be distinguished from other unwanted signals, therefore the SNR of licensed user signal can be measured locally at unlicensed users. Using this SNR as a proxy for distance, it can be proved that a cognitive radio can vary its transmitting power while maintaining a guarantee of service to licensed users [14]. However, the transmission of a pilot tone needs modification to the licensed users which seems unlikely for the practical reasons.

When information of licensed users' signal is known to cognitive radio, the optimal detector in Gaussian noise is matched filter detector. The high processing gain it achieves makes the detection more effective in a relatively short time. With matched filter, those unwanted signals can also be filtered out so that only licensed users are measured. Sometimes, the prior knowledge of licensed users' signal such as modulation scheme, pulse shape may not be easily available. However the preambles or synchronization word which present in most wireless systems can be used for coherent detection.

Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hoping sequences, or cyclic prefixes which result in built-in periodicity. These cyclostationary information of licensed users' signal, if available to cognitive radio, can be exploited for detection [4]. The cyclostationary feature detector works by analyzing a spectral correlation function. The advantage of this function is that it differentiates the noise energy from modulated signal energy, which is a result of the fact that noise is a wide-sense stationary signal with no correlation, while modulated signals are cyclostationary with spectral correlation due to the embedded redundancy of signal periodicity [1]. With partial information about the licensed users' signal, the performance of cyclostationary detector is better than power detector.

2.2.3 Cooperative sensing

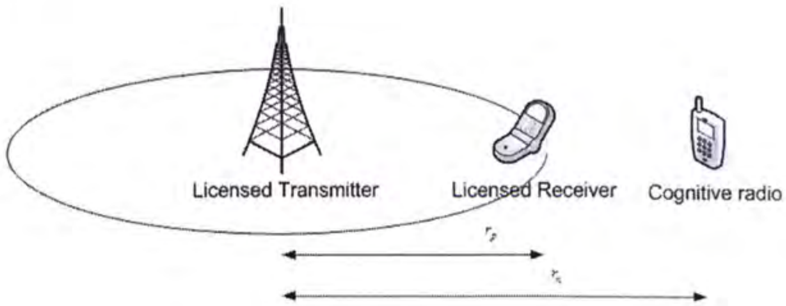

Figure 2.3: High agility requirement.

In the previous part, we introduced three detection methods. The basic assumption is that every cognitive radio is equipped with a detector and based on its own detection it decides whether licensed users are present or not, then access accordingly. However, if this policy is applied, the agility requirement for the detector may be too high to be able to achieve. Specifically, the purpose of detection is actually to avoid the interference to licensed receivers. However, usually a passive device, its position can hardly be traced. With only signals from transmitter available, cognitive radios should be as far as possible so as to keep away from licensed receivers. As illustrated in Figure 2.3, in the coverage area of licensed transmitter with radius r_p, the receiver may located right at the border. Cognitive radio should be at least r_n distance away from licensed transmitter so that a safe distance of $r_n - r_p$ can be guaranteed to licensed receiver. The signal power at r_p is already at the edge for decoding. Then the signal detected at cognitive radio is even smaller due to the additional distance attenuation. What is worse, wireless channel suffers from fading and shadowing. If a high detection probability is required, the detection threshold should be set even lower for the detection of severe attenuation condition. Taking all this into consideration, the detector have to be so sensitive to small signal that even the most advanced technology can't meet this requirement.

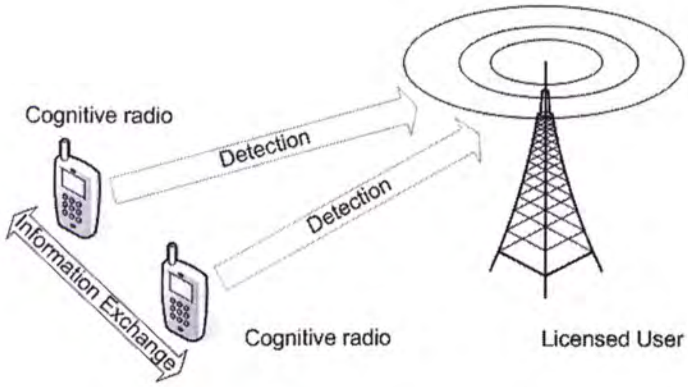

Figure 2.4: Cooperative detection.

To due with this, cooperative sensing is proposed to alleviate the detection task. In cooperative sensing, we rely on the variability of signal strength at various locations. We expect that a large network of cognitive radios with sensing information exchanged between neighbors would have a better chance of detecting the licensed user compared to individual sensing [4]. As illustrated in Figure 2.4, two or multiple cognitive radios individually detect the licensed users' signal, then they share their detection results with each other. The decision each radio makes is based on all the information it collects. In theory, the multi-path fading and shadowing effect can be mitigated. Simulation suggests that collaboration of several nodes located close to each other can improve sensing performance significantly [12]. However, more sophisticated cooperation schemes have to be designed for the optimal tradeoff between detection probability and network load. One concern is that should the final decision result(0 or 1) or the raw detection data be exchanged among cognitive radios? The former one saves bandwidth while the later one can potentially achieve better detection results. For the former one, if censoring method is used, the amount of information exchange can be further decreased at the expense of a little sensing performance loss [25]. For the later one, it can be achieved by applying a relay mechanism in between cognitive radios [11].

Current discussions on cooperative sensing assume that signals received at cognitive radios are statistically independent and all the detection results are the measurement of the same spectral environment. However, this may not be true when spacial distribution of the nodes is taken into account. While multipath fading is in general uncorrelated, shadowing can display high correlation if several radios are blocked by the same object. Therefore, If radios are densely packed together in a small region, the shadowing correlation would degrade performance of collaborative sensing. On the other hand, if radios locate far away from each other, the detection results will represent different spectral environment at different places. Then, it does not make sense for cooperative sensing. Joint decision with information from other radios, in this case, may have negative impact to the detection accuracy. So actually, what we can gain from cooperation is not as much as those simulated. One radio should properly choose its partners of cooperation so that their detection results are really helpful.

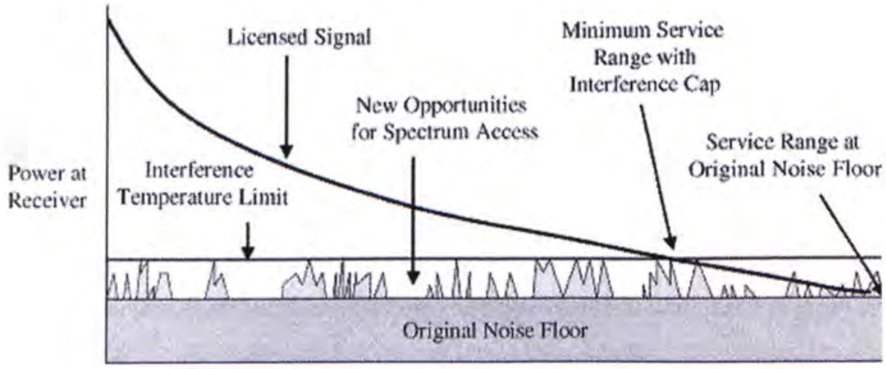

Figure 2.5: Interference temperature [9].

2.2.4 Interference temperature

As mentioned before, the protection of licensed user is actually to prevent too much interference to licensed receivers. Therefore recently, a new model for measuring interference, referred to as interference temperature shown in Figure 2.5 has been introduced by FCC [9]. When unlicensed users enroll, the noise at the licensed receiver includes the original AWGN noise plus the interference introduced by unlicensed transmitters. Interference temperature limit refers to the maximum total noise levels at the licensed receiver. As one can see in the Figure 2.5, the peaks represent the additional interference at various places. As long as the total noise level at licensed receiver does not exceed interference limit, cognitive radio can use this band. This method guarantees a minimum SNR at licensed receiver thus protects its communication quality. However, the service range of licensed user shrinks accordingly.

However, in practice, the difficulties in the measurement of interference temperature limit its application. Unless cognitive radio has the exact location information of its nearby licensed receivers, it can not choose a proper transmitting power to limit its interference under the temperature limit. Even this information is available, when multiple unlicensed users are present, the interference is the combination from all these unlicensed transmitters. One individual cognitive radio can hardly estimate the interference temperature at licensed receivers.

2.3 MAC layer

The previous section focuses on the sensing of available spectrum resources. When detection result shows that licensed user is not present, a media access policy is needed for cognitive radios to share the spectrum. In this section, the challenges and possible solutions on cognitive radio MAC protocols are discussed. Recent works are reviewed with their pros and cons analyzed.

2.3.1 Cooperative spectrum sharing

In a cognitive radio network, all the unlicensed users observe the same protocol of access. They exchange information with others to coordinate their access behaviors so that the global interest of the whole network is maximized. This is referred to as cooperative spectrum sharing. Cooperation can improve the total throughput as well as the fairness. On the other hand, as detection results can be exchanged, higher detection accuracy could be achieved using cooperative sensing. A control channel is needed for information exchange among radios, which poses a challenge in the relevant system design.

In [2], a centralized protocol named DSAP is proposed for managing and coordinating spectrum access to unlicensed bands across diverse technologies. Cognitive radio as a DSAP client contact DSAP server for access request. The DSAP server possesses a "radio map" which is a record database of the spectrum environment of the network. Based on this, optimal spectrum assignment is made and leases containing access specification are granted to DSAP clients. As information is collected to a central point, optimization can be achieved globally with higher spectrum utilization. This protocol uses a dedicated channel for control information exchange, which will consume certain amount of bandwidth resources. Meanwhile, infrastructure like DSAP servers should be built which could be a big investment. The DSAP system is actually a dynamic license granting system. Cognitive radio in order to access needs the permission of another agency instead of its own detection.

Distributed spectrum sharing can be applied when construction of an infrastructure is not preferable. An additional advantage of it over centralized approach is that, in stead of using a dedicated control channel, the local unused licensed band can be utilized for local control information exchange [28]. In [5], a group bargaining approach is proposed where unlicensed users affected by the mobility event self-organize into bargaining groups and adapt their spectrum assignment to maximize the fairness based utilities. Specifically, a user who want to improve its spectrum assignment broadcasts a bargaining request to its neighbors to form the group. It then becomes the group coordinator and preforms bargaining computation to adjust the unfair or low efficient spectrum assignment of the group into a better one. Similar distributed approaches can also be found in [15]. An Asynchronous Distributed Pricing (ADP) scheme is proposed, in which users exchange "price" signals, that indicate the negative effect of interference at local receivers. Given the set of prices corresponding to a set of channels, each transmitter chooses a channel and power level to maximize its net benefit (utility minus cost). This algorithm can mitigate the mutual interference of users staying in the same channel, however the enrollment of one user may lead to channel reselection of all the other users. Therefore it is not quite applicable to the network in which users switch on and off frequently.

2.3.2 Non-cooperative spectrum sharing

Non-cooperative spectrum sharing refers to the scenarios in which unlicensed users only use its own knowledge and detection to exploit vacant spectrum resources. While non-cooperative solutions may result in reduced spectrum utilization, the minimal communication requirements among other nodes introduce a tradeoff for practical solutions.

A device-centric spectrum management scheme with low communication costs is proposed in [30] in which users observe local interference patterns and act independently according to preset spectrum rules. Five rules that tradeoff performance with implementation complexity and communication costs are offered. The cognitive radio is assumed to able to detect the channels available for transmission, its neighboring unlicensed users and their channel occupation conditions. Besides this, no additional information is needed. In this algorithm, although no cooperation in the sense of information exchange is made, utility and fairness among unlicensed users can be achieved by all nodes observing the same rules. If a cognitive radio only has the knowledge of whether one channel (among many channels) is busy or not, which is always the case in practice, opportunistic spectrum access based on the theory of Partially Observable Markov Decision Process (POMDP) can be applied [29]. It can be obtained from this POMDP the optimal decentralized strategies for the unlicensed user to decide which channel to sense and access for the maximization of overall network throughput.

2.3.3 Inter-network spectrum sharing

The access schemes discussed above are mainly formulated for the spectrum sharing of a single network (single unlicensed user group). However, as the motivation of dynamic spectrum access is that unused spectrum can be accessed without license, multiple unlicensed systems providing different services to different user groups may initiate their transmission simultaneously at the same place. An example is illustrated in Figure 2.6. When licensed transmitter is

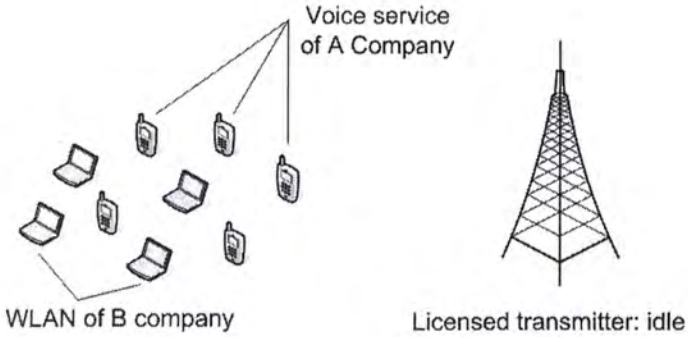

Figure 2.6: Inter-network spectrum sharing.

idle, mobile voice service of company A tries to occupy the band as unlicensed user while WLAN of company B may do the same thing. Without coordination in between the two systems, mutual interference introduced will degrade the communication quality of both of them. Actually, this problem is quite unique to cognitive radio networks. In conventional wireless system, different type of networks are regulated by spectrum assignment policy to stay in different frequency bands or in different location when using the same band. Therefore, they will not interfere with each other. The design of MAC protocol only considers the coordination among homogenous radio devices which belong to the same system. However, in cognitive radio networks, different systems deploying heterogenous devices vary their transmission power, modulation scheme and access protocol. Inter-network information exchange may not be possible. It is even harder to share the spectrum fairly and efficiently among multiple networks. In the following, we will introduce several possible solutions presented in recent publications.

A centralized approach of inter-network spectrum sharing can be found in

[16]. A central spectrum policy server (SPS) is in charge of band assignment to multiple systems. Operators of each system bids for the spectrum with the price it can pay at the server. Then SPS allocates the spectrum by maximizing its profit from these bids. The operators also determine an offer for the users and users select which operator to use for a given type of traffic. This dynamic pricing mechanism can automatically adjust the inefficient spectrum occupation of certain systems. Through competition among operators, higher overall throughput can be achieved. However, infrastructure should be constructed and the realization of SPS needs further scrutiny. In [18], a distributed priority based dynamic channel reservation scheme is proposed. It assumes that each system has a base station (BS) to coordinate the transmission inside. BS competes with its local interferer BSs in a dedicated competition resolution channel to reserve a time frame (Q-frame) for transmission. Then the access is granted to the BS with highest priority which can be its QoS requirement, traffic load or residual lifetime. This approach, as based on local bargaining, relaxes the requirement of any additional central control devices. However, the control information exchange needs a dedicated channel whose availability, as mentioned above, can be a problem in practice. In addtion, an 802.11 WLAN based ad-hoc protocol using the cognitive radio has been proposed in [21]. It separates the channel into data channels and common control channel. Neighbor nodes exchange available channel information to solve the hidden licensed transmitter problem. A MAC protocol named C-MAC, designed for distributed multi-channel cognitive radio networks, can be found in [6]. It divides each channel in to frames. Nodes negotiate during the beacon period of each frame to coordinate their access. These two schemes also require information exchange among different groups.

2.3.4 Interference mitigation

In the previous discussion on MAC protocols of unlicensed users, we firstly focus on how nodes of a single network access the spectrum fairly and efficiently, then how multiple networks coordinate to share the spectrum. All of this is based on the assumption that licensed user is detected to be not transmitting at the moment. This is in fact a simplification of the real scenarios. What the detector actually do is to compare the detection result with a threshold then make a decision. The more sophisticated model is that unlicensed user can only tell how far away it is from the active transmitter. As illustrated in

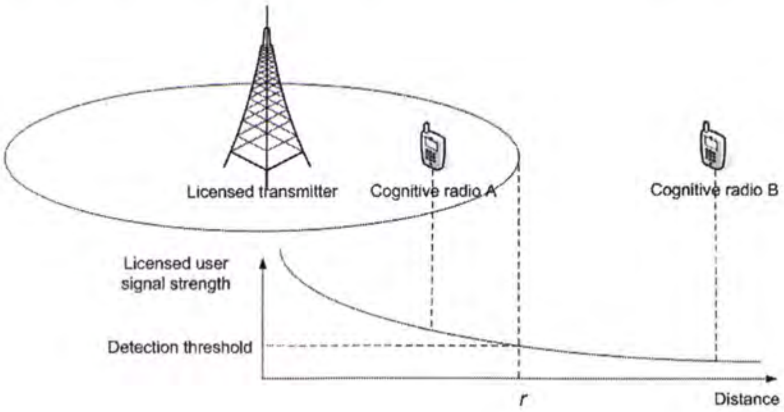

Figure 2.7: Detection of distance.

Figure 2.7, the signal strength of licensed transmitter attenuated with the distance. The weakest signal unlicensed user detector can detect from the noise is the threshold P_s. Cognitive radio A, located in the vicinity of the transmitter, is able to detect the licensed user signals due to the strong signal power. However, as cognitive radio B is far away from the transmitter, the signal power is too weak to be detected. Then B understands that no licensed transmitter exists thus launches its communication. Then its own transmission will introduce interference to licensed receiver. Therefore, what the detector can guarantee is that unlicensed users with distance smaller than r keep idle. A detection result indicating no licensed users present is actually means that the nearest active licensed transmitters is at least r distance away. In this sense, the media access problem is further sophisticated to the one that multiple unlicensed user networks share the spectrum simultaneously with licensed user networks located certain distance away. An additional issue called interference mitigation will be involved in the design of MAC protocol.

Interference mitigation refers to that unlicensed transmitters should mitigate the interference to the licensed receivers. It is very easy for a single unlicensed transmitter to limit its transmitting power so that its interference at licensed receiver, in the worst case, will not exceed a cap value. However, in theory there can be infinite unlicensed transmitters. Then the total interference accumulated can be big enough to degrade the licensed users communication quality. Unlicensed users as a whole should properly choose their transmission power and avoid, through MAC protocol, too much transmitters active at the same time to limit the total interference. This is in fact not easy to achieve. Recent works on this topic can be found in [14]. It assumes that each cognitive radio transmitting with power P will take an area of A. Hence the secondary user power density is obtained $D = P/A$. Based on this density, the author proved that the total interference can be limited even with infinite unlicensed transmitters. However, the constant density assumption may not be reasonable in practice and the communication quality of unlicensed users is not addressed. In this thesis, we will provide a possible solution to address this interference mitigation issue.

Chapter 3

Power Regulation Protocol

3.1 Introduction

In this chapter, we will introduce the Power Regulation Protocol (PRP) for the detection and media access of cognitive radio networks. The network model we adapt for our discussion can be illustrated in Figure 3.1. Assume that there is a narrow band frequency channel which is already assigned to a licensed transmitter T_l and receiver R_l. Multiple unlicensed user groups, each formed by a single transmitter-receiver pair T_i and R_i $(i = 1, 2, 3...)$, would like to use the channel to communicate[1]. They sense the spectrum environment to see if T_l is transmitting or not then access accordingly.

To calculate the mutual interference among radios, a well defined signal attenuation model is needed. In this chapter, the propagation path loss model adapted only takes into account the distance-based path loss and signal emanates in an omnidirectional way. As mentioned in chapter 2, 3 approaches can be applied for the detection of cognitive radios. here we adapt the power detector at the unlicensed transmitters for the channel sensing. The advantage of power detector is that it does not require any licensed user signal information,

[1]Actually, one group is usually composed of several (more than two) users. Each can be a transmitter or a receiver. However, in a snapshot, the group can be decomposed into several transmitter-receiver pairs. In fact, the results of this paper can be easily generalized to multi-user group case. And for the simplification of discussion, here we assume that both licensed group and multiple unlicensed groups are just transmitter-receiver pairs.

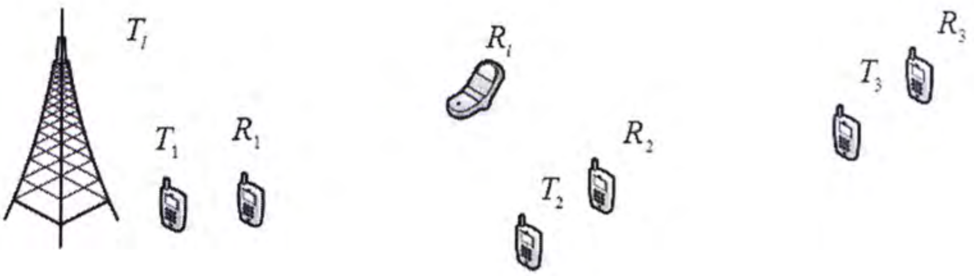

Figure 3.1: Network model.

thus more applicable in the real settings. In this chapter, it is assumed that the power detectors are ideal which can accurately measure interference power in the channel without the influence of noise uncertainty. One observation is that the interference power is typically much greater than the thermal noise. Hence in this thesis, we neglect the noise power and use SIR as the metric to measure link status and channel capacity. Finally, to simplify the analysis, we further assume that the detection time is zero and transmitters will initiate transmission sequentially one after the other in some random order.

As mentioned in the previous chapters, it is in general impossible to give any modification to the existing licensed users for the communication with licensed users. Meanwhile, Unlicensed users in different groups vary their transmission parameters thus can hardly have any information exchange. However, it is possible for unlicensed transmitters to observe some common rules when they initiate their communication. The Power Regulation Protocol is actually a set of common rules used to govern the access behaviors of unlicensed users. Based on the listen-before-talk mechanism, it can be stated in the following 3 steps.

1. Before transmitting, unlicensed transmitter T_i uses its power detector to sense the channel interference power. Only if this power is below a threshold P_s, can it be active.

2. Once active, T_i radiates with a fixed power P_t.

3. The transmission time does not exceeds t_{max}, after which T_i goes to another round of channel sensing.

Here, P_s, P_t and t_{max} are specified by the protocol and identical to all unlicensed transmitters. For those T_i which can be active after sensing, we call them active transmitters. For those T_i which can not transmit after the sensing, we call them idle transmitters. The idle transmitters will back off with a random period then detect the channel again. In the rest of the thesis, if not specified, we all use the term "transmitters" to refer to active transmitters for the ease of discussion.

Under the above mentioned path loss assumption, the signal power, received r distance away from T_i is

$$P_r = P_{t0} \cdot r^{\alpha}, \tag{3.1}$$

where P_{t0} is the signal power at the reference distance. With the transmission power P_t fixed, P_{t0} is also fixed for all unlicensed transmitters. α is the attenuation index which varies according to the propagation environment. Through out this thesis, we use the conventional value -4 so that

$$P_r = P_{t0} \cdot r^{-4}. \tag{3.2}$$

Define S_l and S_u the minimum SIR requirement for decoding of licensed users and unlicensed users. It is assumed that all the unlicensed user groups have the same S_u requirement.

Inspired by [14] which uses the concept of protect zone and no talk zone for the discussion of licensed users. We inherit this terminology for the discussion of unlicensed users in this thesis. Here, the protect zone and no talk zone of a transmitter T_i are concentric circular regions centered at the transmitter and with radius r_p and r_n respectively. The r_p is the coverage distance of T_i while r_n satisfies the following equations

$$P_s = P_{t0} \cdot r_n^{-4}. \tag{3.3}$$

In general, $r_p < r_n$. An illustration is shown in Figure 3.2.

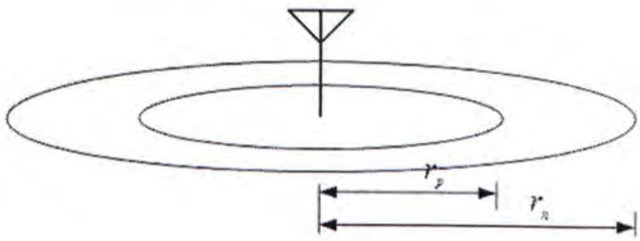

Figure 3.2: Protect zone and no talk zone.

3.2 Unlicensed user coexistence

In this section, we consider the communication of unlicensed users when they are far away from the active licensed users or the licensed users are idle. In this case, the licensed users can be ignored and the narrow band frequency channel is available for access to multiple unlicensed user groups. We will prove that by applying Power Regulation Protocol, the SIR received at unlicensed receivers can be guaranteed to stay above S_u.

We first consider the two-group scenario with T_1, R_1 as group 1 and T_2, R_2 as group 2. Suppose T_1 has already begun to transmit. According to the access rule mentioned, if T_2 wishes to access, the channel interference power it detects should be smaller than the threshold P_s. Therefore according to (3.3), if active, T_2 has to locate exactly outside the no talk zone of T_1. Consider the worst case when receiver R_1 is at the edge of T_1's protect zone and T_2 stays on the edge of the no talk zone to cause greatest interference to R_1 (T_1, R_1 and

T_2 lay in a straight line, see Figure 3.3). We calculate the SIR at R_1 in (3.4).

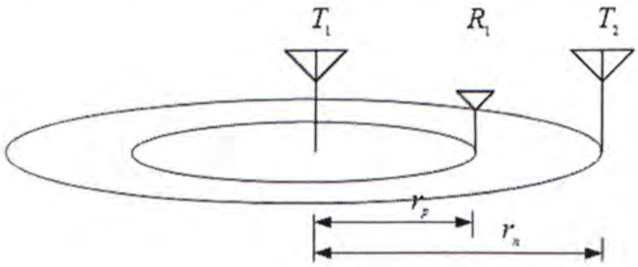

Figure 3.3: Worst case for R_1.

$$S = \frac{P_r}{P_i} = \frac{P_{t0} r_p^{-4}}{P_{t0}(r_n - r_p)^{-4}} = (\frac{r_p}{r_n - r_p})^{-4} \tag{3.4}$$

$$\lim_{r_n \to +\infty} S = +\infty \tag{3.5}$$

From (3.5), one can see that with fixed r_p to guarantee the coverage area of T_1, by properly setting r_n (equivalently with setting P_s), an arbitrary big SIR can be achieved at R_1.

Consider the SIR at receiver R_2. Figure 3.4 shows the worst scenario where R_2 is at the edge of protect zone of T_2. R_2 has the same SIR as R_1. Thus in this two-group case, by setting the worst case SIR above S_u, communication in both groups are guaranteed and coexistence is ensured.

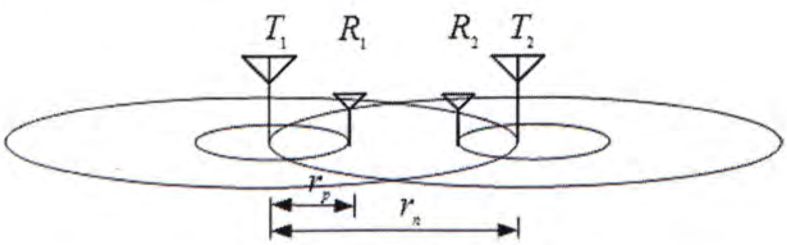

Figure 3.4: Worst case for R_2.

In the following, we will analyze the multi-group scenario which has infinite transmitter-receiver pairs. Due to the identical power model for all the groups, we can consider an arbitrary transmitter, T_0, located in the center of an x-y coordinate.

With the assumption that transmitters are active one after another, we use the subscript to indicate the sequence of their activation time. For those T_i with $i < j$, they have already begun to transmit before T_j and those with $i > j$, they will be active after T_j. We label the position of T_i by $\vec{l_i}$ (see Figure 3.5). Also in the worst scenario when receiver R_0 is located on the edge of the protect zone. According to Figure 3.5, its SIR is given by (3.6).

$$S_0 = \frac{P_{t0} \cdot r_p^{-4}}{\sum_{i \neq 0} P_{t0} \cdot |\vec{r_i}|^{-4}} \tag{3.6}$$

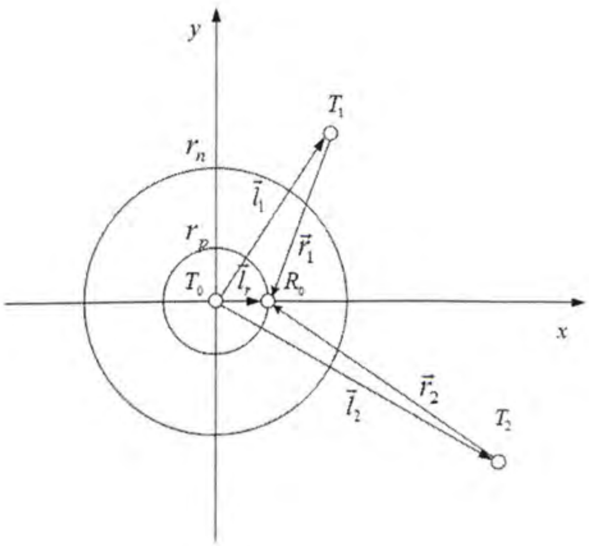

Figure 3.5: Multi-group scenario.

In the next, we will calculate an upper bound of the total interference at R_0 so that the worst case SIR is obtained.

Lemma 1. *In the multi-group case, for any pair of active transmitter T_i and T_j, the distance between them is no smaller than r_n.*

The proof is straight forward due to equation (3.3).

Theorem 1. *The total power of interference at R_0 caused by all the transmitters from other groups has an upper bound and this upper bound can be made arbitrarily small by properly setting the protocol parameters [31].*

Proof. Divide the x-y coordinate space with grids (see Figure 3.6). Each cell divided by the grids is a square with side length $a = r_n/\sqrt{2}$. Obviously, the greatest distance in one cell is the diagonal r_n and according to Lemma 1. only 0 or 1 active transmitter locates inside one cell.

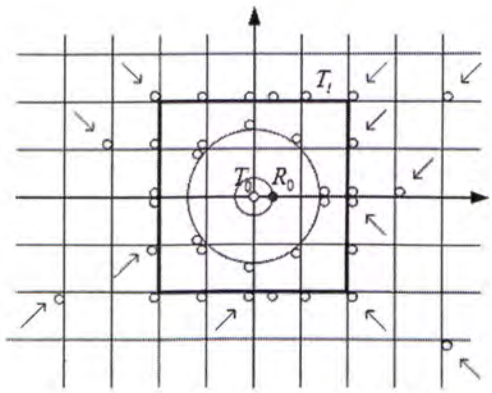

Figure 3.6: Worst case in multi-group scenario.

Consider the worst scenario when each cell has one active transmitter and it locates at the worst place (as close to the R_0 as possible) as shown in Figure 3.6. Define the set of all this active transmitters as C, the set of those inside the black frame in Figure 3.6 as C_1 and those outside the black frame as C_2. Then the total interference at R_0 can be no greater than that caused by the active transmitters in the set C:

$$\begin{aligned}
&\sum_{i\neq 0} P_{t0}|\vec{r_i}|^{-4} \leq \sum_{T_i\in C} P_{t0}|\vec{r_i}|^{-4} \\
=&\sum_{T_i\in C_1} P_{t0}|\vec{r_i}|^{-4} + \sum_{T_i\in C_2} P_{t0}|\vec{r_i}|^{-4}. \qquad (3.7)
\end{aligned}$$

The interference introduced by transmitters inside the black frame is bounded by:

$$\sum_{T_i\in C_1} P_{t0}|\vec{r_i}|^{-4} < 12\cdot P_{t0}(r_n - r_p)^{-4}. \qquad (3.8)$$

For those outside the frame:

$$\begin{aligned}
&\sum_{T_i\in C_2} P_{t0}|\vec{r_i}|^{-4} \\
<\ & 4\sum_{n=1}^{+\infty}\sum_{m=2}^{+\infty} P_{t0}[(a\cdot m - r_p)^2 + (a\cdot n)^2]^{-2} \\
&+12\sum_{m=2}^{+\infty} P_{t0}(a\cdot m - r_p)^{-4}. \qquad (3.9)
\end{aligned}$$

For the first item in (3.9), when $r_p < a$:

$$\begin{aligned}
&4\sum_{n=1}^{+\infty}\sum_{m=2}^{+\infty} P_{t0}[(a\cdot m - r_p)^2 + (a\cdot n)^2]^{-2} \\
<\ & 4a^{-4}P_{t0}\int_0^{+\infty} dy \int_1^{+\infty} [(x - r_p/a)^2 + y^2]^{-2} dx \\
=\ & \frac{\pi}{2} a^{-4}(1 - r_p/a)^{-2} P_{t0}. \qquad (3.10)
\end{aligned}$$

For the second item in (3.9), when $r_p < a$:

$$\begin{aligned}
&12\sum_{m=2}^{+\infty} P_{t0}(a\cdot m - r_p)^{-4} \\
<\ & 12a^{-4}P_{t0}\int_1^{+\infty} (x - r_p/a)^{-4} dx \\
=\ & 4a^{-4}(1 - r_p/a)^{-3} P_{t0}. \qquad (3.11)
\end{aligned}$$

Finally, according to (3.7)-(3.11), we get:

$$\begin{aligned}
& \sum_{i\neq 0} P_{t0}|\vec{r_i}|^{-4} \\
< \; & 12 \cdot P_{t0}(r_n - r_p)^{-4} + \frac{\pi}{2}a^{-4}(1 - r_p/a)^{-2}P_{t0} \\
& +4a^{-4}(1 - r_p/a)^{-3}P_{t0} \\
\doteq \; & I_{max}, \qquad (3.12)
\end{aligned}$$

where $a = r_n/\sqrt{2}$, $r_p < a$ and the interference upper bound obtained is denoted as I_{max}. The above expression (3.12) indicates that even with infinite transmitters from other groups, the interference at R_0 is finitely bounded. Further, with P_{t0} and r_p fixed, I_{max} is a function of r_n. it can be obtained in (3.12) that the $I_{max}(r_n)$ can be made arbitrarily small by setting a large enough r_n. According to (3.3), a large enough r_n can be achieved by setting a small enough P_s. Therefore

$$\lim_{P_s \to 0} I_{max}(P_s) = 0. \qquad (3.13)$$

Then Theorem 1 is proved. □

Now, consider the SIR received at R_0:

$$S = \frac{P_r}{P_i} > \frac{P_{t0} \cdot r_p^{-4}}{I_{max}}. \qquad (3.14)$$

According to Theorem 1, with fixed r_p and P_{t0}, it can be proved that there exists a $\tilde{P}_s$ so that for any $P_s < \tilde{P}_s$,

$$S(P_s) > \frac{P_{t0} r_p^{-4}}{I_{max}(P_s)} > S_u. \qquad (3.15)$$

One can see from (3.15) that by properly choosing a small enough detecting threshold P_s in the Power Regulation Protocol, SIR received at unlicensed receivers $S(P_s)$ can be guaranteed to stay above the S_u. Hence, the communication quality of unlicensed users is guaranteed.

3.3 Protection of licensed user

The coexistence problems in cognitive radio networks are two folds. Firstly, multiple unlicensed users should be able to share the spectrum without great mutual interference. This is already addressed in the previous section. Secondly, the communication quality of licensed users should be protected. We will discuss this issue here.

Consider the case that before time t_0, licensed transmitter T_l is idle and multiple unlicensed transmitters T_i $(i = 1, 2, 3...)$ are active exploiting the vacant spectrum resources. Then at time t_0, T_l begins to transmit with power P_l. We will prove in the following that at time $t_0 + t_{max}$, the SIR received at licensed receiver R_l can be guaranteed to stay above S_l by properly setting the parameters of the protocol.

Similar to the discussion of unlicensed users, T_l's signal strength, received r distance away from T_l, is

$$P_r = P_{l0} \cdot r^{-4} \tag{3.16}$$

where P_{l0}, obtained from P_l, is the signal power at the reference distance. The coverage area of T_l is a circle with radius r'_p. Therefore, the distance between T_l and R_l is no larger than r'_p. Define the no talk zone radius r'_n of T_l as follows

$$P_s = P_{l0} \cdot {r'_n}^{-4}. \tag{3.17}$$

Lemma 2. *At time t_0+t_{max}, The distance between T_l and any active unlicensed transmitter T_i is larger than r'_n.*

Proof. T_i, access according to PRP, has a maximum transmission time of t_{max}

at one time. At the moment $t_0 + t_{max}$, all the T_is in the network have their latest sensing done after t_0. Then the signal power from T_l is added into the measurement of their latest sensing. According to (3.17), if the distance between T_l and T_i is smaller than r'_n, the power detected will be above the threshold so that the T_i can not transmit. Therefore, lemma 2 holds. □

Our discussion on the licensed user is based on the assumption that the its transmission power and range is much larger than unlicensed users ($r'_p > r_p$, $P_{l0} > P_{t0}$). This is the case of TV band as the TV station usually covers several kilometers while the cognitive radios are proposed to works in a very small region. Meanwhile, it is also applicable to GSM band. According to (3.3) and (3.17), one can obtain that

$$r'_n - r_n = \frac{\sqrt[4]{P_{l0}} - \sqrt[4]{P_{t0}}}{\sqrt[4]{P_s}} > 0. \tag{3.18}$$

Further, there exists a small enough detection threshold P_s so that

$$r'_n - r_n > r'_p - r_p \tag{3.19}$$

where $r'_p - r_p$ is a fixed value. Then, consider the interference at R_l as illustrated in Figure 3.7. For the ease of comparison, R_l is located with the same coordinate $(r_p, 0)$ as R_0 in Figure 3.6. T_l and R_l have the biggest separation r'_p among them. Also divide the space into multiple cells with side length $a = r_n/\sqrt{2}$. According to Lemma 2, inside the big circle with radius r'_n, there is no active unlicensed transmitters. Consider the interference at R_0 as discussed in Figure 3.6. Only the small circle with radius r_n is guaranteed to have no active unlicensed transmitters. In addition, from equation (3.19),

$$r'_n - r'_p > r_n - r_p, \tag{3.20}$$

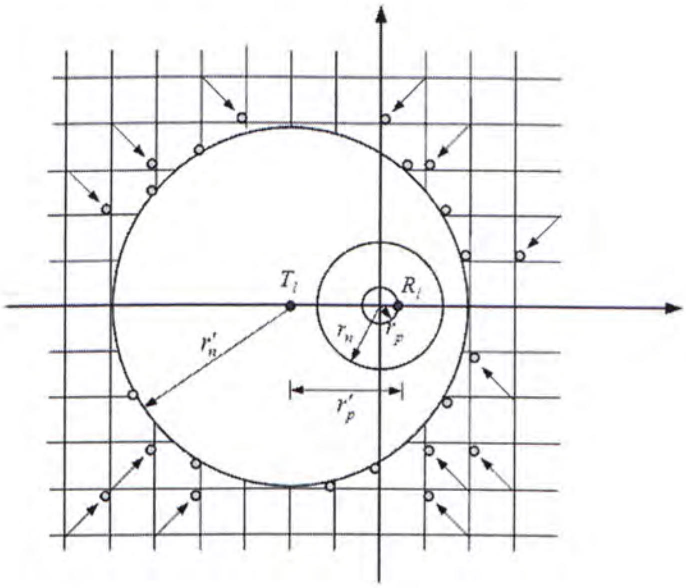

Figure 3.7: Interference at licensed receiver.

therefore the small circle is totally inside the big circle. Hence, the maximum interference I'_{max} at R_l in Figure 3.7 is smaller than I_{max} at R_0 in Figure 3.6:

$$I'_{max} < I_{max}. \tag{3.21}$$

Now, consider the SIR received at R_l:

$$S' = \frac{P_r}{P_i} > \frac{P_{l0} {r'_p}^{-4}}{I_{max}}. \tag{3.22}$$

with the discussion above, it can be proved that there exists a $\tilde{P}'_s$ so that for any $P_s < \tilde{P}'_s$,

$$S'(P_s) > \frac{P_{l0} {r'_p}^{-4}}{I_{max}(P_S)} > S_l. \tag{3.23}$$

One can see from (3.23) that by properly choosing a small enough detecting threshold P_s in the Power Regulation Protocol, SIR received at licensed receivers $S'(P_s)$ can be guaranteed to stay above the S_l. Hence, the communication quality of licensed users is guaranteed. Combined with equation (3.15), it can be proved that for any $P_s < \min(\tilde{P}_s, \tilde{P}'_s)$:

$$\begin{aligned} S(P_s) &> S_u \\ S'(P_s) &> S_l. \end{aligned} \tag{3.24}$$

Then the QoS requirements of both licensed users and unlicensed users are satisfied.

3.4 Mobility issues

In the above discussion of Power Regulation Protocol, we proved that if the unlicensed transmitters access according to it, communication quality of both licensed users and unlicensed users are guaranteed in the sense that the SIR at the receivers are above the required level. However, this analysis is based on the assumption that the distances between any two nodes in the networks are fixed all the time. That is to say, no nodes change their position during their access. Currently, most of the wireless systems have dynamic network topologies changing from time to time due to the mobility of the nodes. Hence, the access protocols designed for the system should be able to adapt to this change to provide the satisfied performances. In this section, the mobility of users is considered in the analysis of the system. It can be proved that the Power Regulation Protocol can still guarantee the SIR level by choosing a even smaller detection threshold.

Consider the performance of the protocol when nodes are moving all the time. Assume that the maximum speed of the node in the network is $v_{max}/2$, then the maximum relative speed of two nodes is v_{max}. Consider the access procedure of one unlicensed transmitter T_1. Suppose at time t_1, the sensing result indicate that it can launch its transmission. Then, at this very moment t_1 when T_1 begins to transmit, Lemma 1 holds. The interference at R_1, according to Theorem 1, will not exceeds the upper bound obtained in (3.12):

$$I(t_1) < I_{max}(P_s). \tag{3.25}$$

However, during T_1's transmission, T_1, R_1 and transmitters from other groups T_i ($i \neq 1$) moves randomly towards any directions. As the power detector will not monitor the channel all the time, then the Lemma 1 will not hold after t_1. One possibility is that R_1 and T_i ($i \neq 1$) moves closer to each other so that the interference becomes larger. Then the required SIR at R_1 may not be guaranteed to stay above S_u due to this mobility.

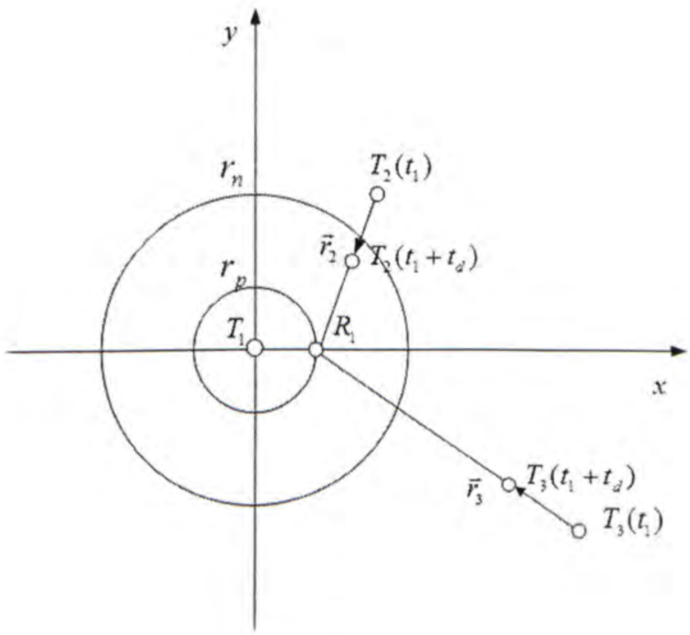

Figure 3.8: Worst case shown in the x-y coordinate.

Now, we will prove that the mobility problem can be overcome by adding margin to the detection threshold P_s. Suppose that begin from t_1, T_1 has already transmitted t_d seconds ($t_d \leq t_{max}$). In the worst case, R_1 moved to the border of T_1's protect zone. Other secondary transmitters T_i ($i \neq 1$) move towards R_1 with the highest relative speed v_{max}(shown in Figure 3.8). Then, the interference received at R_1 at time $t_1 + t_d$ is

$$I(t_1 + t_d) = \sum_{i \neq 1} P_{t0} \cdot r_i(t_1 + t_d)^{-4}. \tag{3.26}$$

It can be proved that when $r_n - r_p > v_{max} t_{max}$,

$$\begin{aligned} & \sum_{i \neq 1} P_{t0} \cdot r_i(t_1 + t_d)^{-4} \\ = & \sum_{i \neq 1} P_{t0} \cdot r_i(t_1)^{-4} \cdot \Big(\frac{r_i(t_1) - v_{max} t_d}{r_i(t_1)}\Big)^{-4} \\ < & \sum_{i \neq 1} P_{t0} \cdot r_i(t_1)^{-4} \cdot \Big(\frac{r_n - r_p - v_{max} t_{max}}{r_n - r_p}\Big)^{-4} \\ = & \; I(t_1) \cdot \Big(\frac{r_n - r_p - v_{max} t_{max}}{r_n - r_p}\Big)^{-4}. \end{aligned} \tag{3.27}$$

Then, according to (3.25), (3.26) and (3.27), it can be obtained that:

$$I(t_1 + t_d) < I_{max}(P_s) \cdot \Big(\frac{r_n - r_p - v_{max} t_{max}}{r_n - r_p}\Big)^{-4}. \tag{3.28}$$

Combined with (3.12) and (3.3), we get:

$$\lim_{P_s \to 0} I(t_1 + t_d, P_s) = 0. \tag{3.29}$$

Finally, it can be proved that their exists a $\bar{P}_s$ so that for any $P_s < \bar{P}_s$, the SIR received at R_i at time $t_1 + t_d$:

$$S(t_1 + t_d, P_s) > \frac{p_{t0} r_p^{-4}}{I(t_1 + t_d, P_s)} > S_u. \tag{3.30}$$

Through the comparison of (3.12) and (3.28), one can see that when mobility is taken into consideration, the worst case interference will increase. However, by setting the detection threshold P_s to a even smaller value, this can be overcome so that the communication quality of unlicensed users is still guaranteed. For licensed users, it can also be proved in a similar way that decreasing P_s will mitigate the negative effect of mobility. Then, we can conclude that the Power Regulation Protocol is also applicable to the network with dynamic topologies.

3.5 Conclusion

In this chapter, we have introduced the Power Regulation Protocol. Compared with other MAC protocols mentioned in Chapter 2, it is a distributed inter-network access scheme working in a non-cooperative manner. At physical layer, unlicensed users sense the channel individually with power detector and transmit opportunistically using narrow band signal. We proved that the coexistence among users can be achieved under this protocol in the sense that licensed users' transmission is protected while unlicensed users can share the spectrum without great mutual interference. In this part, some comments and conclusions are drawn concerning the efficiency and fairness issues of this protocol. Advantages and possible problems in the deployment of the protocol are also discussed here.

In general, access protocols supporting large network throughput at the same time guaranteeing fairness among the users are desirable. Consider the total throughput of multiple unlicensed users in a region where licensed users are not present. With only one narrow band frequency channel available, unlicensed users in the network can either transmit simultaneously or access in a TDMA manner. Without any coordination among users, all the groups will choose to transmit at the same time. This will degrade the total throughput when they are densely packed in a small region. If TDMA is applied to mitigate the mutual interference, in general information exchange is needed among groups. This is not easy to realize for multiple unlicensed groups. The Power Regulation Protocol, only based on channel sensing, can achieve a high total throughput in an indirect TDMA manner. Specifically, when transmitters are close to each other, those initiating transmission later will be able to detect great interference from its surrounding transmitters, thus keep idle. Then, at one time, only part of the users can be active. This will keep a low interference power level so that high network throughput can be achieved. It can be found in chapter 5 that the simulation results comply with this analysis.

Fairness is also a nontrivial consideration in cognitive radio networks. As all the unlicensed users can make use of the vacant frequency resources free of charge, in principle, they should have equal chance of access. Unfairness among unlicensed users is largely due to the heterogeneity of various systems. For example, small power devices are obviously more vulnerable to the influence of large power devices. Different sensing thresholds also lead to different chances of gaining access. With this in mind, we design our protocol to mitigate the asymmetry between different groups. By fixing transmission power and sensing threshold, all transmitters have the same status in the network. The opportunistic access based on sensing also guarantees that, statistically, spectrum resources is equally exploited by each group. Finally, the maximum access duration t_{max} ensures that a channel will not be occupied by any single user for too long but shared equally among all the users.

Compared with other access schemes, the Power Regulation Protocol possesses many advantages which can be stated in the following 3 aspects. Firstly, information exchange among users is not required in the protocol. Therefore, no dedicated control channel and common radio interface is needed. Secondly, transmitters do not have to sense the channel all the time especially when it is transmitting. Although many access schemes assume that transceivers can transmit and sense the same channel at the same time, in practice, it is very hard to realize. Meanwhile, without constant monitoring the channel, this protocol can also help save power at the radios. Finally, since it is required in the protocol a fixed transmission power, the transceiver can be simplified with a fix-gain amplifier at the RF end. All of these lead to cost reduction and easy implementation. Hence, the Power Regulation Protocol is quite applicable in the real deployment.

However, one disadvantage of this protocol is the lost of flexibility in power control. Even when transmitter and receiver are close to each other, transmission power cannot be adjusted to a lower level, leading to a waste of energy and short battery life. This problem can be solved by jointly using multiple channels. Although our discussion of Power Regulation Protocol is only on one channel, in reality, a wide range of spectrum containing multiple channels is available for access to unlicensed users. By applying different protocol parameters such as transmission power, coverage area and detection threshold at different channels. Cognitive radios can choose according to its own specification which channel to access so that the QoS requirement is met at the lowest power consumption.

In the above analysis, we actually assume that the detection time is zero. However, this is not the case in practice. Two or more unlicensed user groups may detect the channel and initiate their transmission at the same time. This will lead to collisions similar to those in CSMA networks. To deal with this, CSMA/CA technology can be added in the Power Regulation Protocol for collision resolution.

In our discussion, we set the attenuation index to a constant value -4 for our calculation. However in practice, this index varies according to the environment. Actually, it can be further proved that for any attenuation index which is smaller than -2, the above analysis also holds. On the other hand, if unlicensed transmitters access with power ranging from P_{min} to P_{max} instead of a constant value, an interference upper bound as a function of detection threshold can also be found. Nevertheless, unlicensed user groups will have different minimum guaranteed SIR values due to their different transmission powers.

Finally, we would like to mention that there is actually a tradeoff in choosing the detection threshold. In the previous discussion, it is proved that when P_s becomes smaller, the SIR at the receiver is guaranteed to stay above a larger value. However, at the same time, it may lead to low spectrum efficiency. Specifically, when P_s decreases, the r_n will increase. According to Lemma 1, more transmitters in the vicinity of an active one will have to keep silent. In fact, the high SIR of one group is at the cost of non-access of many other groups. This will lead to the decrease of total network throughput. Therefore, the system designers should carefully balance between efficiency and QoS level when choosing the detection threshold. Further, a small P_s also means that the power detector needs to have high detection agility. Especially, when P_s approaches noise power level, power detector will not be able to function properly.

Chapter 4

Wireless fading channels

In the discussion above, the path loss model adapted only takes into account the distance-based path loss. However, in practice, wireless channels suffer from fading. Even when the distance between transmitter and receiver is fixed, the channel gain varies a lot with time and location. Meanwhile, it is assumed in previous chapter that the power detector can accurately measure the interference signal power in the channel. Nevertheless, with the presence of noise uncertainty, the detection error is inevitably introduced. In this chapter, we will take the fading and detection error into consideration. The performance analysis of Power Regulation Protocol is based on a more complex probability model. We will prove that the QoS requirement in the sense of outage probability is guaranteed an upper bound and this upper bound can be arbitrarily small by properly setting the detection threshold.

4.1 Model and assumption

Fading in wireless channels is used to describe the rapid fluctuations of the amplitudes and phases of a radio signal over a short period of time or travel distance. It is caused by interference between two or more versions of the transmitted signal which arrive at the receiver at slightly different times [22].

Concerning this, the wireless channel gain h is not a constant value but fluctuates following certain distribution $f(h)$ around the average value $\bar{h}$. Various models such as Rayleigh fading and Ricean fading are proposed to describe its statistical time varying nature and each model has its own application scenario. When there is a dominant stationary (non-fading) signal component present, such as a line-of-sight propagation path, the fading channel gain is modeled with Ricean. When there is no dominant signal and all the components are of similar signal strength, the channel gain is modeled with Rayleigh. Different models of probability distribution will have different performance at the power detector. Define p_a the probability of being active after the detection of the transmitter. Then, if the effect of noise uncertainty is considered, p_a can be expressed, according to (2.6), as

$$p_a = 1 - p_d = 1 - \int_x Q_m(\sqrt{2\gamma}, \sqrt{P_s}) f_\gamma(x) dx \tag{4.1}$$

where $f_\gamma(x)$ can be obtained from $f(h)$.

In this thesis, however, we do not adapt any specific models but base our discussion on a reasonable assumption. As one can see from equation (2.2)-(2.4) that when p_t and P_s are fixed and h is time constant, p_d is a monotone increasing function of h. Here we assume that, if h is time varying, then $p_a = 1 - p_d$ is a monotone decreasing function of $\bar{h}$. This can be intuitively explained as follows. When the average channel gain bigger, the signal power received at the detector is larger, then the probability of the detected signal power below the threshold is smaller. Further, it is believed in wireless channel that the average channel gain is distance related:

$$\bar{h}(r) = kr^{-\alpha} \tag{4.2}$$

where k is a constant and $\alpha > 0$. Therefore, p_a is an increasing function of the distance r. To illustrate this, consider the following example. Suppose there exists only one active transmitter T_1 in the network. T_2, originally idle, begins to sense the channel to access (see Figure 4.1). When T_2 gets far away from T_1, T_1's signal detected at T_2 attenuates to a lower level. Even with the presence of detection error and fading effects, statistically, the probability of detected power under the threshold becomes larger. Therefore, T_2 will have more chance to initiate communication. Define $p_a(r)$ the probability of being

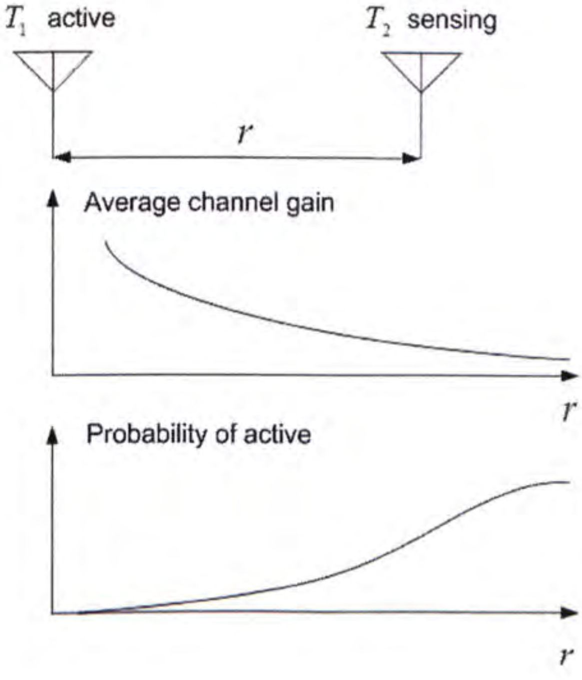

Figure 4.1: Probability of active as a function of distance.

active when the detector is r distance away from the transmitter, then Lemma 3 can be obtained.

Lemma 3. *When there is only one active transmitter, the probability for another one to be active is smaller than $p_a(r)$ if the distance between them is smaller than r.*

Now we consider the scenario of multiple unlicensed user groups with more than one active transmitters. If an idle transmitter wish to launch communication, the signal received at its detector is the superposition of the signals from its nearest active transmitter and those from other active transmitters together with noise. Then, the output value of the integrator at the detector is bigger than that with signals only from its nearest active transmitter and noise. Thus, the active probability is smaller than that with the nearest active transmitter as the only one active transmitter. Therefore, lemma 4 is derived.

Lemma 4. *When multiple active transmitters are present, the probability for a new transmitter to be active is smaller than* $p_a(r)$, *if the distance to its nearest active transmitter is smaller than* r.

In this chapter, the fading effect and detection error are taken into consideration, therefore it is impossible to guarantee that the interference at the receiver is always under certain level. However, the QoS requirement can be expressed in the sense that the outage probabilities do not exceed certain values (smaller than 1). Define p_l and p_u the maximum outage probability so that when $p(SIR < S_l) < p_l$ at the licensed receiver and $p(SIR < S_u) < p_u$ at the unlicensed receivers are guaranteed, both of them can get satisfied communication qualities. We will prove that these outage probability upper bounds can be achieved under Power Regulation Protocol by properly setting the detection threshold.

4.2 Outage probability upper bound

Similar to the discussion in chapter 3, we firstly consider the communication of unlicensed users when they are far away from the active licensed users or the licensed users are idle. In this case, the licensed users can be ignored and the narrow band frequency channel is available for access to multiple unlicensed groups. Assume that each group has the same effective transmission range r_p which is the maximum distance between the transmitter and receiver. Then, consider an arbitrary active transmitter, T_0, located in the center of an $x-y$ coordinate. The coordinate is divided by grids into many cells with side length a where $a > r_p$. As illustrated in Figure 4.2, receiver R_0 stays inside the circle

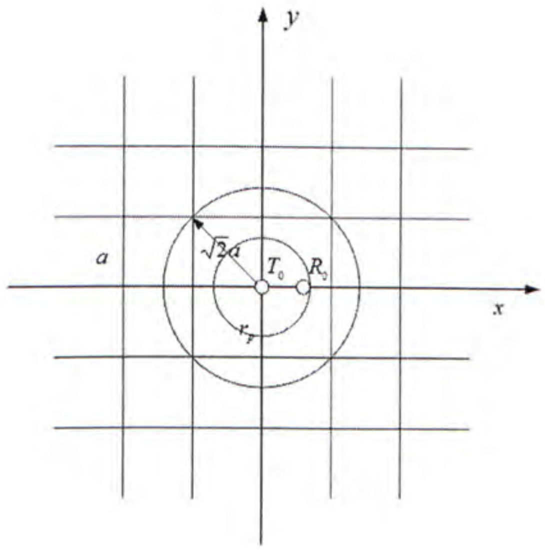

Figure 4.2: Space divided by grids.

with radius r_p which is the coverage area of T_0. We first calculate the average interference $E(I_{out})$ at R_0 from transmitters outside the circle with radius $\sqrt{2}a$ (the big circle). It is straight forward that

$$E(I_{out}) = \sum_i E_i(I) \tag{4.3}$$

Where $E_i(I)$ is the average interference from cell i. Then

$$E_i(I) = E(n) * I_i \tag{4.4}$$

where $E(n)$ is the average number of transmitters in each cell while I_i is the average interference at R_0 caused by one transmitter in cell i. Therefore,

$$E(I_{out}) = E(n)\sum_i I_i. \tag{4.5}$$

Assuming the average interference is only distance related with attenuation index of -4, It is proved in (3.12) that

$$\begin{aligned}\sum_i I_i &< I_{max} \\ &= 12P_{t0}(\sqrt{2}a - r_p)^{-4} + \frac{\pi}{2}P_{t0}a^{-4}(1 - \frac{r_p}{a})^{-2} \\ &\quad +4P_{t0}a^{-4}(1 - \frac{r_p}{a})^{-3}. \end{aligned} \tag{4.6}$$

For $E(n)$, if the density of the unlicensed user groups is ρ, then in average, $s_1 = \rho a^2$ potential transmitters located in one cell. Obviously,

$$E(n) \leq \rho a^2. \tag{4.7}$$

Then, according to (4.5), (4.6) and (4.7)

$$\begin{aligned}E(I_{out}) &< I_{max}\rho a^2 \\ &= P_t\rho a^{-2}[12(\sqrt{2} - \frac{r_p}{a})^{-4} + 4(1 - \frac{r_p}{a})^{-3} \\ &\quad +\frac{\pi}{2}(1 - \frac{r_p}{a})^{-2}]. \end{aligned} \tag{4.8}$$

One observation is that this upper bound of $E(I_{out})$ is a monotone decreasing function of a and

$$\lim_{a\to\infty} E(I_{out}) = 0. \tag{4.9}$$

Due to Markov inequality, the probability that the interference exceeds a level

I_0 has an upper bound:

$$p(I_{out} > I_0) \leq \frac{E(I_{out})}{I_0}. \tag{4.10}$$

Inside the big circle of Figure 4.2, there are on average $s_0 = 2\pi a^2 \rho$ potential transmitters. According to Lemma 4, when T_0 begins to transmit, the probability that all of them are kept being idle (no interference at R_0) follows from equation (4.11):

$$\begin{aligned} p(I_{in} = 0) &> \Sigma prob(i)(1 - p_a(\sqrt{2}a))^i \\ &= E[(1 - p_a(\sqrt{2}a))^i]. \end{aligned} \tag{4.11}$$

Because $(1 - p_a(\sqrt{2}a))^x$ is a convex function of x, then according to Jensen's inequality,

$$\begin{aligned} E[(1 - p_a(\sqrt{2}a))^x] &\geq (1 - p_a(\sqrt{2}a))^{E(x)} \\ &= (1 - p_a(\sqrt{2}a))^{s_0}. \end{aligned} \tag{4.12}$$

Therefore,

$$p(I_{in} = 0) > (1 - p_a(\sqrt{2}a))^{s_0}. \tag{4.13}$$

Combined with (4.10), One can derive an upper bound of the probability that the total interference at R_0 exceeds I_0:

$$\begin{aligned} p(I_{total} > I_0) &\leq 1 - p(I_{in} = 0)p(I_{out} < I_0) \\ &< 1 - \big(1 - p_a(\sqrt{2}a)\big)^{s_0}\big(1 - \frac{E(I_{out})}{I_0}\big). \end{aligned} \tag{4.14}$$

Now, let us reconsider the probability of active p_a. Previously, we mentioned that it is an increasing function of the distance between transmitter and receiver. However, this is under the premise that the transmission power and detection threshold is fixed. From equation (4.1), one can see that p_a is not only related to distance, but also an increasing function of the detection threshold P_s. Further,

$$\lim_{P_s \to 0} p_a = 0. \tag{4.15}$$

This can be intuitively explained as follows. If P_s raises, the value after the integrator of power detector will have more chance to stay below this threshold. Then transmitters will have more chance to be active. However if this threshold approaches 0, transmitters will almost have no chance to be active. Now express p_a as $p_a(r, P_s)$, we prove the following theorem.

Theorem 2. *By properly setting the detection threshold P_s, the probability that the interference at R_0 exceeds certain level I_0 can be arbitrarily small.*

Proof. For a small enough value ε, the proof is to find the detection threshold P_d so that $p(I_{total} > I_0) < \varepsilon$. According to (4.9), one can find a value of a so that

$$1 - \frac{E(I_{out})}{I_0} > 1 - 0.5\varepsilon. \tag{4.16}$$

According to (4.15), there exists a P_s so that

$$(1 - p_a(P_s, \sqrt{2}a))^{s_0} > \frac{1-\varepsilon}{1-0.5\varepsilon} \tag{4.17}$$

where $s_0 = 2\pi a^2 \rho$ and a is derived from (4.16). Substitute (4.16) and (4.17) into (4.14), one can obtain

$$p(I_{total} > I_0) < 1 - \big(1 - p_a(\sqrt{2}a)\big)^{s_0}\big(1 - \frac{E(I_{out})}{I_0}\big) < \varepsilon \tag{4.18}$$

Thus, theorem 2 is proved. □

Finally, consider the SIR at R_0. We will prove that the upper bound of outage probability p_u can be achieved by properly setting P_s. According to the definition, the outage refers to the scenario that the SIR at the receiver is smaller than the QoS requirement for decoding: S_u. The outage probability can be expressed as follows

$$p(SIR < S_u) = p(\frac{S}{I} < S_u) < 1 - p(I < I_0)p(S > I_0 S_u). \tag{4.19}$$

where I_0 can be any arbitrary value. Consider the signal power S received at R_0. As $S > 0$, there exists a small enough $\bar{I_0}$ that for any $I_0 < \bar{I_0}$,

$$p(S > I_0 S_u) > (1 - p_u)(1 + \frac{p_u}{2}). \tag{4.20}$$

where p_u is the outage probability upper bound (smaller than 1). According to theorem 2, there also exists a P_s so that:

$$p(I < I_0) > \frac{1}{1 + \frac{p_u}{2}} \tag{4.21}$$

where the I_0 is obtained in (4.20). Therefore according to equation (4.19)-(4.21), we get:

$$p(SIR < S_u) < p_u. \tag{4.22}$$

Thus, we proved that for any required upper bound of outage probability p_u at the unlicensed receiver, it can be achieved through Power Regulation Protocol with a proper detection threshold.

The outage probability of licensed user can also be analyzed in a similar way. As shown in Figure 4.3, also divide the space into cells with side length a. The difference from Figure 3.7 is that, due to the fading and detection error, the active unlicensed transmitters can also stay inside the big circle (with radius r_n'). The interference at R_l from transmitters outside the small circle (with radius r_n) has the same upper bound as analyzed in equation (4.6). For those unlicensed transmitters inside the small circle, strong signal powers from T_l will be present in their sensing measurement. A small enough detection threshold

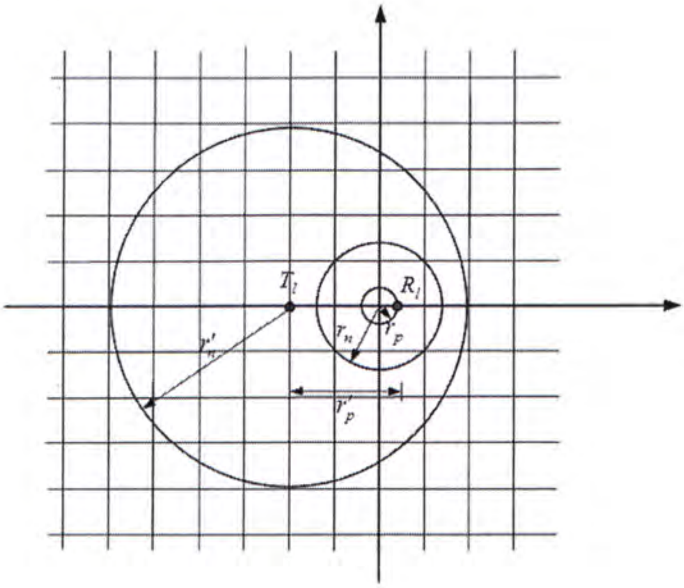

Figure 4.3: Outage probability of licensed user.

can achieve the same results as in equation (4.17). It can be proved similarly that any required upper bound of outage probability at licensed receiver can be achieved with a proper detection threshold at unlicensed transmitter.

4.3 Conclusion

In this chapter, we have considered the fading in wireless channel and detection error of power detector. Due to multi-path effect, the strength of signal power received or detected is not a constant but varies following certain distribution. Detection error caused by noise uncertainty makes it even harder to obtain accurate sensing results. With the assumption that the average channel gain is only distance related, our discussion on the performance of Power Regulation Protocol is based on a probability model. The QoS requirement in the sense of outage probability upper bound is proved to be achieved by properly setting the detection threshold.

We can obtain from mathematical analysis in this chapter that a smaller P_s can have better QoS performances. However, as mentioned in Chapter 3, this will trade off the spectrum efficiency and may be impossible due to the limited agility of detection device. Also, in the previous discussion, we did not take the noise power into account in the calculation of SIR. Normally, the interference power is much bigger than noise. However, when it approaches zero, noise power will dominate. Thus in practice, the SIR can't be set to infinite large, even with an arbitrary small detection threshold.

Chapter 5

Simulation and numerical results

In the above discussion, we have mathematically proved that by applying Power Regulation Protocol, QoS requirement of both licensed and unlicensed users can be satisfied by properly setting the detection threshold. In this chapter, simulations are conducted to test the performances of this protocol. We firstly introduce an easy-to-implement algorithm to estimate the achievable interference upper bound. With this algorithm, further analysis is made to illustrate the inherent tradeoff of this protocol. Then the efficiency and fairness of networks adapting this protocol are compared with those using other access schemes. Corresponding to the analysis in Chapter 3, the path loss model applied in the simulation only takes into account the distance-based path loss and the power detector is assumed ideal.

5.1 Greedy algorithm

It is proved in Theorem 1 the existence of interference upper bound at the unlicensed receivers. However, one can see from the proof that the upper bound obtained in 3.12 is not tight. To calculate the exact achievable upper bound, one should solve, according to Figure 3.5, the following constrained optimization problem whose solution is quite hard to obtain:

$$\begin{aligned} \max \quad & \sum_{k\neq 0} P_{t0}|\vec{l_k} - \vec{l_r}|^{-4} \\ s.t. \quad & \sum_{i=-\infty}^{j-1} P_{t0}|\vec{l_i} - \vec{l_j}|^{-4} \leq P_s \quad \text{for all j.} \end{aligned} \tag{5.1}$$

In order to find this achievable upper bound to facilitate the system design, an easy-to-implement greedy algorithm (GA) is utilized to estimate it. Instead of acquiring the global maximum as in (5.1), GA maximizes the interference in each step. Specifically, we add the active unlicensed transmitters T_i ($i > 1$) as close as possible to receiver R_1 according to Power Regulation Protocol. The interference accumulated at R_1 is used to estimate the interference upper bound. In the following, one example is served to illustrate the detailed

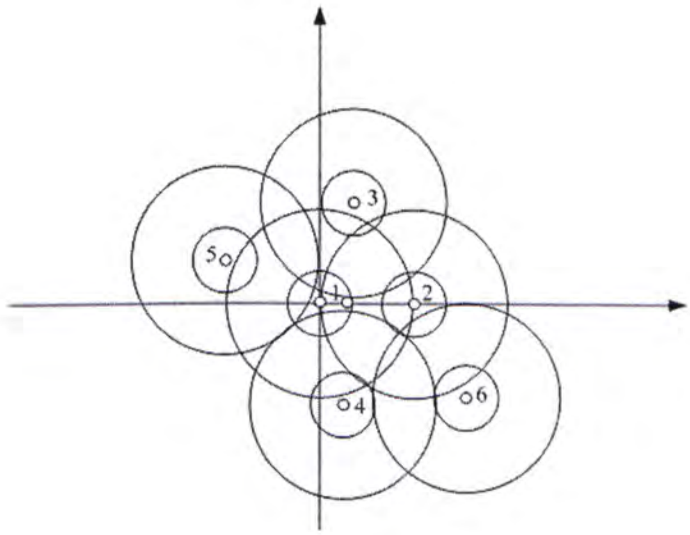

Figure 5.1: Node distribution with greedy algorithm.

procedures. Suppose that $P_{t0} = 1$, $r_p = 1$ and $r_n = 3$, then:

$$P_s = P_{t0} r_n^{-4} = 0.0123. \tag{5.2}$$

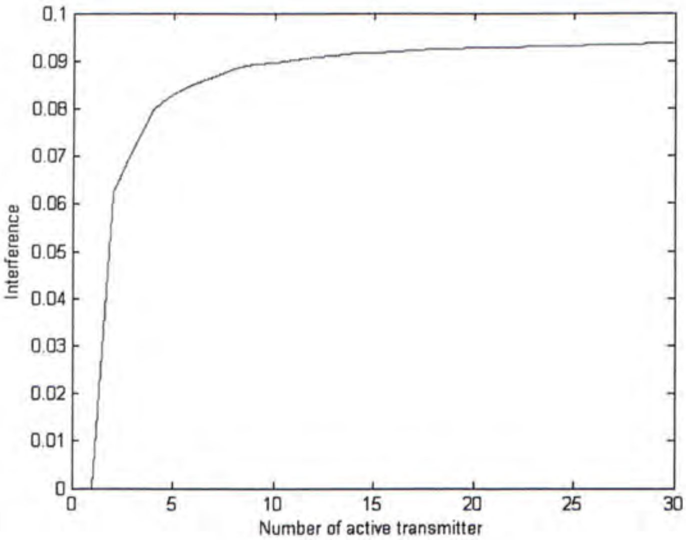

Figure 5.2: The increase of interference with active transmitters.

Unlicensed transmitter T_1 stay in the center of the x-y coordinate and R_1 locates on the border of protect zone: (1,0) as shown in Figure 5.1. By utilizing a greedy algorithm and beginning with the activation of T_1, in each step a new transmitter T_i is generated so that its detected interference power is smaller than P_s while its location is as close to R_1 as possible to cause the maximum interference. The location of the first 6 transmitters are shown with their protect zone and no talk zone in Figure 5.1. The number represents the sequence of activation time. Figure 5.2 illustrates the growth of interference at R_1 with the number of active transmitters. One can see that the interference increases rapidly at the beginning. Then, when more transmitters become active, the interference rises with a slower rate and finally approaches 0.095 when the number of simulated transmitters exceeds 15. This is reasonable because in the process, later active users will be located further away from R_0 compared to earlier transmitters. This is also consistent with the analysis in Chapter 3 concerning the upper bound of the interference.

To check whether the upper bound attained through the GA can provide a heuristic upper bound estimate, a random simulation is conducted with the following procedure. In a 200*200 region, transmitters were randomly generated and admitted according to the access protocol until region was saturated with admissible users (see Figure 5.3). Interferences at the receivers (1 distance away from transmitters) are calculated. Results show that among the total 94480 sampled receiver locations of 1524 transmitters, the maximum interference (its location illustrated as a circle in Figure 5.3) reaches 0.0656, only about two thirds of the result 0.095 we derived from the greedy algorithm, justifying the GA as a relatively reliable method in finding the upper-bound.

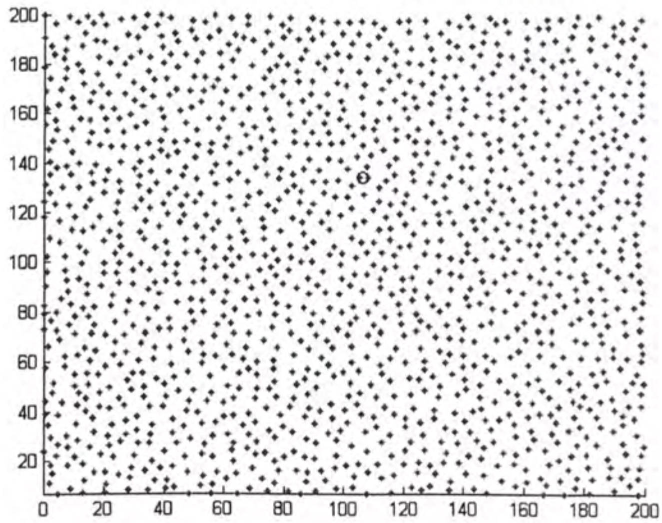

Figure 5.3: Random simulation.

5.2 Detection threshold tradeoff

In this section, we will discuss the tradeoff in choosing the protocol parameter. In unlicensed user networks adapting Power Regulation Protocol, when P_{t0} and r_p are normalized to 1, the only parameter that needs to be fixed is r_n (equivalent to fix P_s). Let us consider the following three network performance indices: spectrum reuse, sensing threshold P_s and guaranteed minimum SIR. Here, in order to quantify the spectrum reuse, we define the spectrum reuse index u as the ratio of protect area to the no talk area:

$$u = \frac{\pi r_p^2}{\pi r_n^2}. \tag{5.3}$$

It should be noted that in order for protect zone not overlapping with each other, $u < 0.25$.

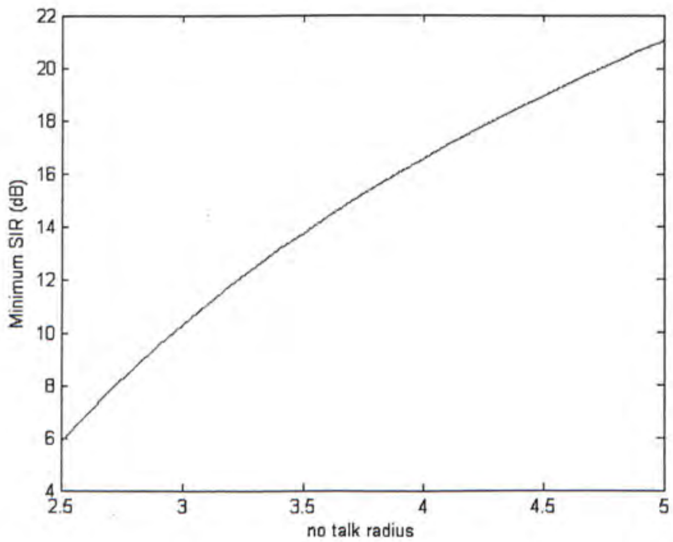

Figure 5.4: No talk radius VS minimum SIR.

Figure 5.4 shows the relationship between r_n and minimum guaranteed SIR.

It is obtained using GA algorithm. One can see that in order to maximize the minimum guaranteed SIR, r_n should be as large as possible. However, according to (3.3), P_s decrease sharply with the rise of r_n. Then, energy detector should be able to detect the very weak signals that even the most advanced technologies nowadays can't detect. Especially when P_s drops under the power level of noise, it would be impossible for energy detector to make measurement. In addition, the spectrum reuse index u also decreases when r_n increases, indicating inefficient spectrum utilization. So, in summary, a balance between minimum guaranteed SIR, sensing power threshold and spectrum reuse is required when choosing the parameter r_n.

5.3 System performance analysis

In this section, the performance of unlicensed user networks deploying Power Regulation Protocol is analyzed. Under Matlab simulation environment, the efficiency and fairness of the protocol are evaluated. The results are compared with those under other access schemes to demonstrate the advantages of Power Regulation Protocol.

Licensed users and unlicensed users coexist in the cognitive radio networks. As licensed users can't gain any additional benefit from the enrollment of unlicensed users, the efficiency and the fairness issue we talk about here only refers to those among multiple unlicensed user groups. When a channel is available, how can these groups coordinate to share it? The Power Regulation Protocol actually achieves cooperation among groups through channel sensing. Two other approaches can be either totally no cooperation or coordination with information exchange. In the following, we will compare them with the Power Regulation Protocol separately of their performances.

Unlicensed users access without any form of coordination is similar to the scenarios in licensed-exempt networks in which any users can launch communication as they wish without owning licenses. One example is ISM band in which Bluetooth systems, 802.11 wireless LAN and other systems operate simultaneously. No communication and detection is made among different systems. The following simulation will compare the detect-then-access power regulation scheme with this simultaneous access scheme.

Suppose in a 8*8 region, there are in total 10 unlicensed user groups. Randomly generate the position of transmitters and their corresponding receivers 1 distance away from them as shown in Figure 5.5. Consider the case when

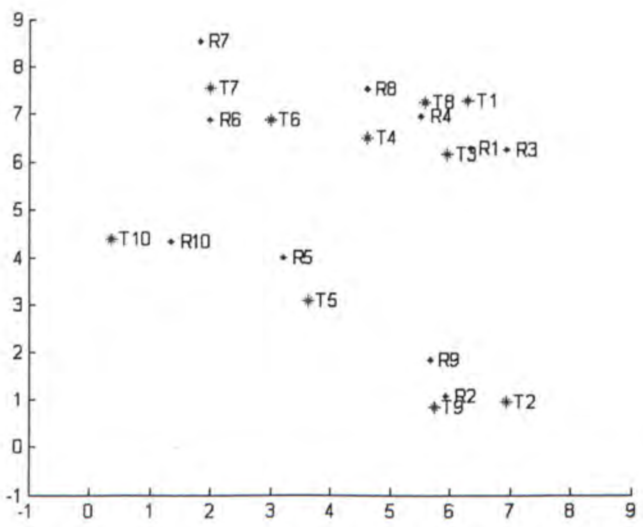

Figure 5.5: User distribution.

Power Regulation Protocol is applied. P_s and r_p are normalized to 1, $r_n = 3$. The ten user groups initiate transmission sequentially with some random order shown in Table 5.1. Under this access sequence, each group detect the channel before access. Only group 4, 9 and 10 launch their transmission. The interference at their receivers are 0.0017, 0.0028 and 0.0053 respectively. Calculate

User group No.	1	2	3	4	5	6	7	8	9	10
order	6	2	4	3	5	10	8	9	1	7

Table 5.1: The order of initiation.

the whole network throughput using equation (5.4), the total network capacity is 25.3 bit.

$$C = \sum_{i=4,9,10} \log_2(1 + SIR_i) \tag{5.4}$$

Now consider the case when all the groups access simultaneously without any cooperation in between. Suppose they transmit with the same power P_s. Under the same geographic distribution as above, the interference at the receivers can be calculated shown in Table 5.2. Similarly, the total network

User group No.	1	2	3	4	5
Interference	40.72	125.6	0.6066	125.9	0.0665
User group N0.	6	7	8	9	10
Interference	5.005	0.0777	1.2387	0.2221	0.0521

Table 5.2: Interference at receiver for simultaneous access.

capacity can be obtained using equation (5.5) to be 17.2 bit.

$$C = \sum_{i=1}^{10} \log_2(1 + SIR_i) \tag{5.5}$$

In the above case study, we adapt two different access schemes to the same network structure. Using Power Regulation Protocol, although only 3 out of 10 user groups launch their communication, the total network capacity exceeds the case when all of them transmit simultaneously. In our later discussion, a large number of similar simulation processes will be conducted to obtain the statistical results.

Consider the efficiency of the network with different number of user groups n in the region. Also adapt the above parameters: $P_s = 1$, $r_p = 1$ and $r_n = 3$.

For each n, randomly generate 100 network distributions and for each distribution randomly generate 100 initiate orders. The average network capacity for each n is illustrated in Figure 5.6. From this figure, one can see that,

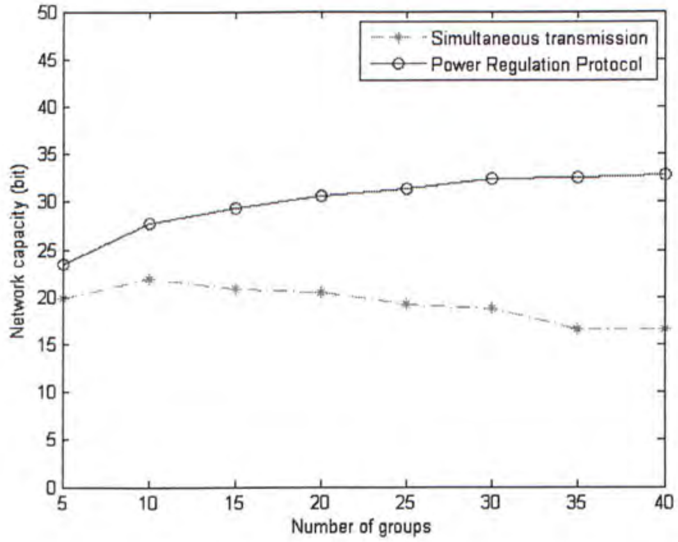

Figure 5.6: Network capacity with different number of user groups.

statistically, Power Regulation Protocol outperforms the simultaneous transmission scheme in total network capacities. Thus, the cooperation through power detection is demonstrated to be able to provide system performance improvement. It should be noted that, when there is fewer user groups (5 groups as shown in Figure5.6), the two schemes offer similar network capacities. This is because fewer groups can have better inter-group separation, thus mutual interference is not obvious. However, when more and more users get into the region, Power Regulation Protocol begins to show its ability in mitigating the mutual interference by only allowing part of the users to access. While for the simultaneous access scheme, the raise of the interference level would finally degrade the total network capacity.

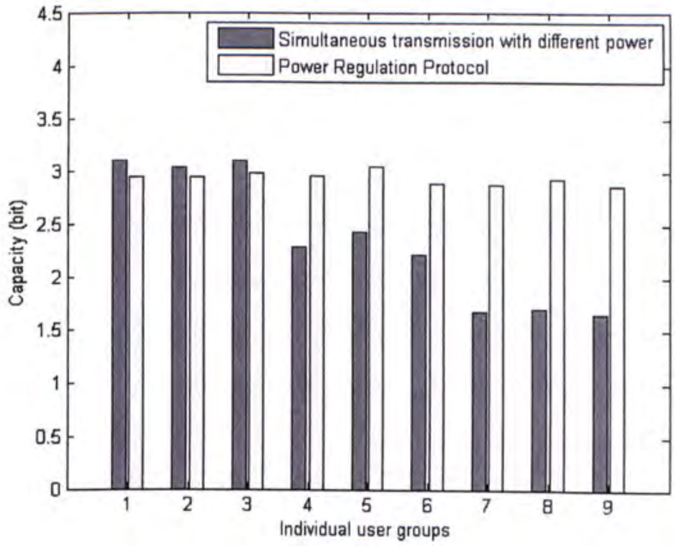

Figure 5.7: Capacity of individual group.

Besides efficiency, fairness is equally important to the users. For Power Regulation Protocol, each users have the same status, thus with random geographic distributions, statistically, the spectrum is equally utilized among all groups. For the simultaneous access scheme, the above discussion assume that transmitters emit with the identical power. However, in practice like ISM band, Bluetooth and wireless LAN apply different power levels. Consider the fairness in this case. Suppose in the regions, groups 1, 2, 3 transmit with power $P_{t0} = 2$, groups 4, 5, 6 with $P_{t0} = 1$ and groups 7, 8, 9 with $P_{t0} = 0.5$. Following the similar simulation process, the average network capacities available to each individual group is shown in Figure 5.7. One can see that the power heterogeneity of different groups can lead to unfair network capacity sharing among them. This is also the reason why Power Regulation Protocol insists that each transmitter, once active, emit with the same power level: to guarantee fairness.

Then, consider the case when multiple groups coordinate their access with information exchange. Currently, IEEE 802.11 is the most commonly used standard for wireless LAN communications. The RTS/CTS mechanism is included in the 802.11 wireless networking protocol to reduce the collisions. Specifically, A node wishing to send data initiates the process by sending a Request to Send frame (RTS). The destination node replies with a Clear To Send frame (CTS). Any other node receiving the RTS or CTS frame should refrain from sending data for a given time [8]. In the following, the simulation is conducted in the network adapting RTS/CTS mechanism. Its performance is compared with those of Power Regulation Protocol.

From the definition, one can see that RTS/CTS actually guarantees that the distance from transmitter or receiver of one active group to those of another active group is no smaller than the communication range d. In power regulation protocol, it also ensure that the distance between two active transmitter is larger than r_n and those between receiver and its interfering transmitter is larger than $r_n - r_p$. The simulation of Power Regulation Protocol adapts the following parameters: $r_n = 3$, $r_p = 1$ and $P_{t0} = 1$. For the equivalence of comparison, we set $d = (r_n + r_n - r_p)/2 = 2.5$ and $P_{t0} = 1$ in the simulation of RTS/CTS scheme. Suppose in a 50*50 region, n groups of transmitter receiver pair randomly locate inside it. They initiate their transmission sequentially with some random order. The above two schemes are used separately for access. Under more than 10000 times of simulation with different network topologies and access orders, the average total network capacity with these two schemes versus the number of groups in the region is illustrated in Figure 5.8. It can be found in the figure that the performances of these two schemes are approximately the same. That is to say, solely based on detection, the network can achieve similar network throughput as those with information exchange. This result is quite useful for cognitive radio networks. As we mentioned before, the homogeneity of users in traditional network makes it easy

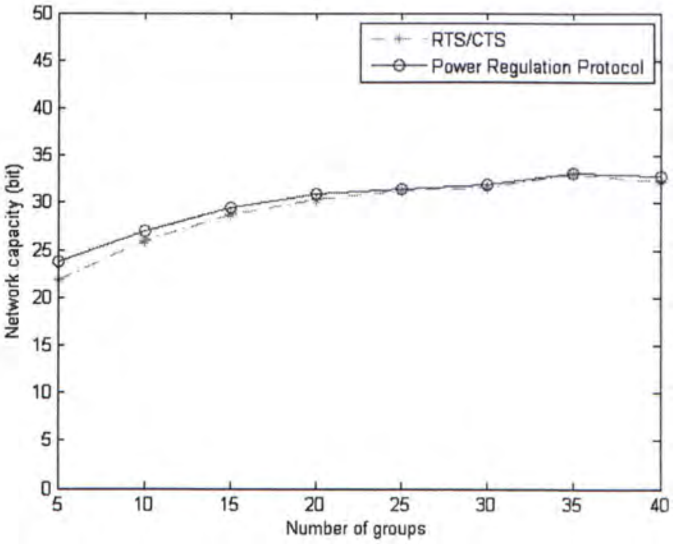

Figure 5.8: Network capacity comparison.

to have package exchange among them. Thus no matter centralized or distributed, their access schemes can take advantage of this knowledge sharing to improve the network capacity. However, for cognitive radio networks, multiple unlicensed user groups adapt different transmission parameters such as power, modulation scheme and package structure. Unless there is a dedicated control channel and each user possesses an identical radio interface, information exchange among them is quite hard to achieve. The contribution of Power Regulation Protocol is that, without additional system for information sharing, without prior knowledge of other groups, unlicensed users can also share the spectrum in an efficient way. This is quite useful in the real deployment of cognitive radio networks.

Chapter 6

Conclusion and future work

6.1 Conclusion

When the fast booming wireless industry confronts the out-dated frequency band assignment policy. The voice calls for dynamic spectrum access is even larger than ever before. When the spectrum resources itself is not the limitation but our artificial regulations, cognitive radios are proposed to eliminate this restriction. Although currently, the research and deployment of cognitive radio networks are still at its beginning stage, we have already achieved some useful results. The hot pursuit from government, industry and academic field makes it one of the fastest developing communication technologies. The previous software defined radio techniques have already paved the way for multi-mode access. The channel sensing techniques are also mature to be able to achieve the environment awareness functions at cognitive radios. In the policy making level, TV band is suggested by government to be opened for dynamic spectrum access. And at industry, companies such as Siemens have already set up their R&D departments on cognitive radios. Without the need to pay for the licenses, cognitive radio networks can be an attractive option in the wireless market.

On the other hand, we still have a long way to go before the large scale deployment of cognitive radio networks. Some concerns come from the licensed users. Technically, can unlicensed users effectively mitigate their total interference at the licensed receivers so that the interference temperature there is nuder the limit? Economically, what is the incentive for licensed users to agree the access of unlicensed users? For multiple unlicensed user groups, there are still few feasible solutions on their coexistence. The detailed sensing and access procedures are largely under discussion.

This thesis introduces a Power Regulation Protocol for the spectrum access of cognitive radios. Power detector is used for channel sensing and each unlicensed transmitter, once active, is required to emanate with the same power. We prove that under this protocol, the QoS requirements of both licensed users and unlicensed users can be satisfied by properly setting the detection threshold. Even when fading effect, detection error and mobility are taken into consideration, this result also holds. Simulation results show that the network capacity under this protocol outperforms those with totally no coordination and is approximately the same to those with information exchange. Fairness among users is also guaranteed due to the identical transmission power requirement in this protocol. Therefore for multiple unlicensed user groups which can hardly have information exchange among them, this protocol achieves efficiency and fairness solely based on detection, thus is quite applicable in the real deployment.

6.2 Future work

After several years of development, cognitive radio networks is still in great need of research efforts to solve many outstanding problems. At the hardware level, RF end of the radio which can be programmed to work in a large range of radio frequencies is required. However, current technologies may not be able to provide the satisfied components. These include adaptive filters, wide range synthesizers and antennas that adapt to wide range carrier frequencies.

Meanwhile, how can the radio be designed to be software reconfigurable is also a great challenge for the future RF circuit designers.

Another concern that needs further scrutiny is the channel spacing. When vacant spectrum is detected, should the available band be accessed as a single channel or it is divided into multiple small channels to accommodate more users simultaneously? Power Regulation Protocol is designed for a single channel. It can also be applied to multiple channels with different protocol parameters at different channels. However, how to assign these parameters to achieve better performances needs further study. Meanwhile, when multiple channels are available, cognitive radios also need additional access policies for channel selection.

Although most of current works focus on physical and MAC layers of cognitive radio networks. The upper layer issues such as routing also deserve research efforts. Due to the temporal and spacial variation of vacant spectrum resources, routing algorithms should be able to adjust the routing path frequently to adapt to this change. Reactive routing would be preferable to proactive routing due to the dynamic network topologies. Joint optimization with cross layer design may potentially achieve better performances.

Finally, we would like to mention that besides technical issues, the successful deployment of cognitive radio networks also lies in good business models which can provide the incentive to both licensed users and unlicensed users. The licensed users purchase the licenses for the exclusive use of the band. They would reluctant, if not reject, to open the band for free access to other users at the risk of their own services' degradation. Unlicensed users may be charged by licensed users for their access. However, if this price is too high, they may consider buying licenses in another band where they can get better service qualities. Thus a deal between them that can balance their interests is critical. On the other hand, the governments also need intelligence on their rule makings in order to promote the deployment of cognitive radio networks.

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