SPECTRUM COORDINATION PROTOCOLS AND ALGORITHMS FOR COGNITIVE RADIO NETWOKRS

by

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A Dissertation submitted to the

Graduate School-New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

Graduate Program in Electrical and Computer Engineering

Written under the direction of

Professor Dipankar Raychaudhuri

and approved by

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New Brunswick, New Jersey

January, 2008

ABSTRACT OF THE DISSERTATION

Spectrum Coordination Protocols and Algorithms for
Cognitive Radio Networks

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This thesis focuses on the problem of efficiently sharing spectrum resources in wireless networks through the use of appropriate spectrum etiquette protocols and related coordination algorithms. The performance of the proposed class of spectrum etiquette protocols is evaluated in various wireless network scenarios and compared with simpler reactive interference avoidance schemes. After validating its utility for coordination between existing wireless standards (such as IEEE 802.11/WiFi, Bluetooth, and 802.16/WiMax), the spectrum etiquette protocol is extended to serve as the foundation for a more complete adaptive wireless network where radio nodes may cooperate by forming or joining autonomous ad hoc clusters with multi-hop routing. A cognitive radio protocol stack is proposed for this scenario and validated using a combination of *ns-2* simulations and experiments on the ORBIT radio grid testbed.

The spectrum etiquette protocol proposed here is based on the Common Spectrum Coordination Channel (CSCC) approach which allows explicit coordination for spectrum usage among heterogeneous wireless radio nodes by announcement of their operation parameters such as frequency, power, rate, interference, etiquette policies, etc. An experimental proof-of-concept protocol evaluation is conducted to examine interoperability between WiFi and Bluetooth networks, demonstrating significant performance gains with CSCC as compared to the case with

no coordination. Simpler reactive interference avoidance schemes in which radio nodes adjust their transmit parameters such as frequency, power and transmission time based on local observations are also examined in more detail for comparison with CSCC. In particular, we present a detailed comparison between reactive algorithms and proactive CSCC-based etiquette for a co-existence scenario in which both 802.11b and 802.16a operate in the same shared spectrum.

With a higher level of spectrum coordination complexity, we examine the ad hoc collaboration scenario in which radio nodes may cooperate with each other to form so-called adaptive wireless networks with multi-hop routing. The CSCC protocol provides a reasonable foundation for this scenario as well by serving as a bootstrapping and resource coordination protocol for radios involved in ad hoc collaboration. Using the CSCC as a base, we propose a complete cognitive radio protocol stack which includes bootstrapping, network/service discovery, cross-layer routing and name/address translation. Each protocol component is validated using a combination of ORBIT experiments and *ns-2* simulations.

Acknowledgement and/or Dedication

I would like to gratefully thank my advisor Professor Dipankar Raychaudhuri for his enthusiasm, his inspiration, his encouragement, his sound advice and great efforts during my research years at Wireless Information Network Laboratory (WINLAB). I am very thankful to Professor Narayan Mandayam, Professor Wade Trappe, and Dr. Hang Liu for being on my thesis committee and for their advice and suggestions regarding the thesis and beyond. I am grateful to my colleagues at WINLAB and other friends at Rutgers University for their emotional support and help, which makes my study at Rutgers enjoyable and fruitful. I would like to thank the staff at WINLAB and Department of Electrical and Computer Engineering for their assistance and support. Finally, I wish to thank my parents, my sister, and my wife for their understanding, endless encouragement, and love. To them, I dedicate this thesis.

The research presented in this thesis was supported in part by National Science Foundation via grants numbers CCR-0205362, CNS-0435370 and CNS-0626740. I thank these funding agencies for their generous financial support.

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Chapter 1 Introduction

1.1 Background

Recent "Moore's law" advances in programmable integrated circuits have created an opportunity to develop a new class of intelligent or "cognitive" radios [1][2][3][4] which can adapt to a wide variety of radio interference conditions and multiple protocol standards for collaboration between otherwise incompatible systems. Such a cognitive radio would be capable of very dynamic physical layer adaptation via scanning of available spectrum, selection from a wide range of operating frequencies (possibly non-contiguous), rapid adjustment of modulation waveforms and adaptive power control. In addition, a suitably designed cognitive radio with a software-defined physical layer would be capable of collaborating with neighboring radios to ameliorate interference using higher-layer protocols. These higher layer coordination protocols could range from multi-node signal combining and coding methods to etiquette mechanisms all the way to fully collaborative multi-hop forwarding between radio nodes. Thus, suitably designed cognitive radios have the potential for creating a next-generation *adaptive wireless network* [5] in which a single universal radio device is capable of operating in a variety of spectrum allocation and interference conditions by selecting appropriate physical and network layer parameters often in collaboration with other radios operating in the same region. Such a "cognitive network" will lead to increased network capacity and user performance. Perhaps for the first time in the short history of networking, cognitive radios offer the potential for organic formation of infrastructure-less collaborative network clusters with dynamic adaptation at every layer of the protocol stack including physical, link and network layers [6][7].

While the development of cognitive radio hardware and software, especially at the physical layer, has received considerable attention, the question of how one transforms a set of cognitive radios into a cognitive network is much less well understood, and there is a lack of research on protocols for cognitive radio *networks* in the community. As such, *adaptive networks* of cognitive radios represent an important but demanding research challenge for both the wireless and networking communities. The extreme flexibility of cognitive radios has significant implications for the design of network algorithms and protocols at both local/access network and global internetworking levels. In particular, support for cross-layer algorithms which adapt to changes in physical link quality, radio interference, radio node density, network topology or traffic demand may be expected to require an advanced control and management framework with support for cross-layer information and inter-node collaboration. At the wireless local-area network level, an important technical challenge is that of distributing and managing this inter-node and cross-layer information then using this control information to design stable adaptive networking algorithms that are not overly complex. At the global internetworking level, clusters of cognitive radios represent a new category of access network that needs to be interfaced efficiently with the wired network infrastructure both in terms of control and data. End-to-end architecture issues of importance include naming and addressing consistent with the needs of self-organizing network clusters, as well as the definition of sufficiently aggregated control and management interfaces between cognitive radio networks and the global Internet [8].

This thesis studies the spectrum coordination protocols and algorithms for cognitive radio technology as it evolves from autonomous interference avoidance methods to explicit spectrum etiquette protocols and eventually to adaptive wireless networks of collaborating radios. We start with a discussion of the rationale for cognitive radios, leading to an identification of the available design space defined in terms of hardware capabilities and protocol complexity. Different levels of spectrum coordination methods will be introduced, ranging from autonomous *reactive* control [9] of radio parameters (time/frequency/power) to more complex *proactive* coordination schemes [10] based on explicit spectrum etiquette protocols, which define rules or “etiquettes” for how to utilize and share spectrum resources between wireless devices by allowing them to exchange appropriate messages and parameters.

In particular, we propose a specific spectrum etiquette mechanism called the "common spectrum coordination channel" or the "CSCC" [11]. The concept is to enable mutual observability between neighboring radio devices via a simple common protocol by which each wireless device announces its radio parameters. It is noted that mutual observation is the foundation for all forms of "civil society" in which members can coordinate their behavior to meet their individual needs while paying attention to the "common good". Spectrum sharing has much in common with the usage of other public resources (such as parks, public spaces, waterways, etc.), and it is interesting to note that only the radio scenario is currently characterized by a complete lack of mutual awareness of users with potentially competing needs. The problem cannot be solved adequately by the previous generation of spectrum etiquette policies such as listen-before-talk (LBT) due to increasingly complex service requirements (e.g., media streaming with assured quality-of-service, low-delay communications, emergency response, etc.). Also, LBT can result in relatively low overall spectrum efficiency due to interference between signals that overlap partially in frequency or time and the lack of guidance towards selecting a "clear" channel or time-slot. This leads us to conclude that there is a real need for a more advanced type of etiquette protocol that provides a foundation for efficient radio resource sharing without the need for a single PHY/MAC standard in each band. Upon some reflection, it is clear that although improved LBT-type mechanisms could have limited value, a more general solution is going to require a common coordination channel typically implemented as a simple protocol operating at the edge of each unlicensed band. This approach does incur the additional cost of a dual-mode radio, but it can be argued that a modest increment in device cost is well worth the increase in end-user value (reliable services, QoS assurances, graceful degradation under congestion conditions) and societal value (improved utilization of public spectrum).

We first apply the CSCC etiquette protocol to a co-existence scenario of IEEE 802.11bg [12] and Bluetooth at the 2.4GHz band [13] with simple priority-based etiquette policy for proof-of-concept. The CSCC protocol is validated by both a simple indoor experiment using

802.11b/Bluetooth and a dense radio scenario using 802.11g/Bluetooth on the ORBIT radio grid testbed [14]. In particular, the CSCC protocol is implemented using a dual mode radio where a separate 802.11 radio prototype is used for sending and receiving spectrum coordination packets on a fixed control channel. In the ORBIT experiments, we integrate the etiquette protocol with a baseline rate adaptation and a transmission backoff algorithm for Bluetooth radios to avoid interference. System performances in terms of throughput and session delay are evaluated.

To further study the CSCC protocol and various spectrum coordination algorithms and policies, we then investigate the feasibility of spectrum co-existence between IEEE 802.11b (Wi-Fi) and 802.16a (Wi-Max) [15] networks using both reactive interference avoidance methods and the CSCC etiquette protocol. Reactive spectrum coordination methods are based on local channel sensing and distributed adaptation of transmit parameters such as frequency, power, bit-rate and time occupancy, which may sometimes be insufficient such as in scenarios where there are "hidden nodes" [10]. The CSCC protocol coordinates radio nodes in a proactive way, where a common spectrum coordination channel at the edge of available spectrum bands is allocated for announcement of radio parameters such as frequency, power, modulation, duration, interference margin, service type, etc. By executing proactive spectrum coordination algorithms, the hidden-node problem can be effectively solved. The reactive and proactive approaches are compared in the WiFi/WiMax scenario using *ns-2* [16] simulations.

The next step up from spectrum etiquette is the concept of collaborative networks of cognitive radios, an approach which may be expected to provide significant performance gains in dense usage scenarios. In a collaborative adaptive wireless network, radio nodes avoid interference at the PHY and MAC layers by opportunistically forming or joining an ad hoc network which carries data packets (at relatively high speed and low power) over multiple radio hops. A specific protocol architecture ("*CogNet*") [17] based on the concept of a cleanly separated "global control plane (GCP)" [18] is introduced as a candidate architecture for these adaptive wireless networks. The GCP supports spectrum coordination, PHY/MAC adaptation, ad hoc network discovery and cross-layer routing requirements which arise in a general adaptive wireless network scenario. This thesis will also provide design and validation results for a baseline *CogNet* protocol that includes node bootstrapping, discovery, routing and addressing.

1.2 Thesis Outline

The rest of this thesis is organized as follows.

Chapter 2 gives an overview of the spectrum coordination problem for cognitive radio technology with a discussion of the available design space in terms of hardware capabilities and protocol complexity. Different levels of spectrum coordination methods are introduced. We also summarize prior work in the cognitive radio/network field, and discuss the interesting spectrum sharing scenarios and research scope.

Chapter 3 introduces the common spectrum coordination channel (CSCC) protocol as an explicit spectrum etiquette protocol which uses a common edge-of-band control channel for coordination between transceivers using different radio technologies. We introduce the CSCC protocol stack, give its specifications and discuss spectrum coordination algorithms and policies which can be varied using the CSCC protocol framework. We also give details on the implementation and set up proof-of-concept experiments for protocol validation in different co-existence scenarios of IEEE 802.11bg and Bluetooth networks at the 2.4GHz band.

Chapter 4 further studies the CSCC protocol with proactive coordination algorithms, and compares with reactive spectrum coordination methods for co-existence between short-range Wi-Fi and long-range Wi-Max networks sharing the same spectrum. In particular, we study three reactive methods, and two proactive coordination algorithms using the CSCC protocol. Variations of node geographic distribution (clustered vs. uniform) are simulated for Wi-Fi hotspots and Wi-Max subscriber stations using an *ns-2* system model. Clustering regions where CSCC can significantly improve the network throughput by solving the hidden-node problem are identified.

Chapter 5 describes a specific *CogNet* protocol architecture to enable the formation and operation of adaptive wireless networks with cognitive radio nodes. In particular, control protocol components in this architecture including bootstrapping, network discovery, end-to-end path setup and naming/addressing schemes are proposed and validated using a combination of *ns-2* simulation and ORBIT experiments.

Chapter 6 concludes this thesis with remarks for future research directions.

Chapter 2 Spectrum Coordination for Cognitive Radios

2.1 Cognitive Radio Design Space

One of the important goals of designing cognitive radio is to improve the spectrum sharing efficiency. Notable approaches for spectrum sharing have been discussed in the technical and regulatory communities, including property rights regimes [19][20][21][22], spectrum clearinghouse [23], unlicensed bands with simple spectrum etiquette [24][25], open access [26][27][28][29] and cognitive radio [1][2]. The cognitive radio principles currently under consideration by the FCC and the research community span a fairly wide range of possible functionalities both at physical and network layers. Figure 2.1 outlines a number of possible coordination schemes for cognitive radios in terms of their hardware and software complexities.

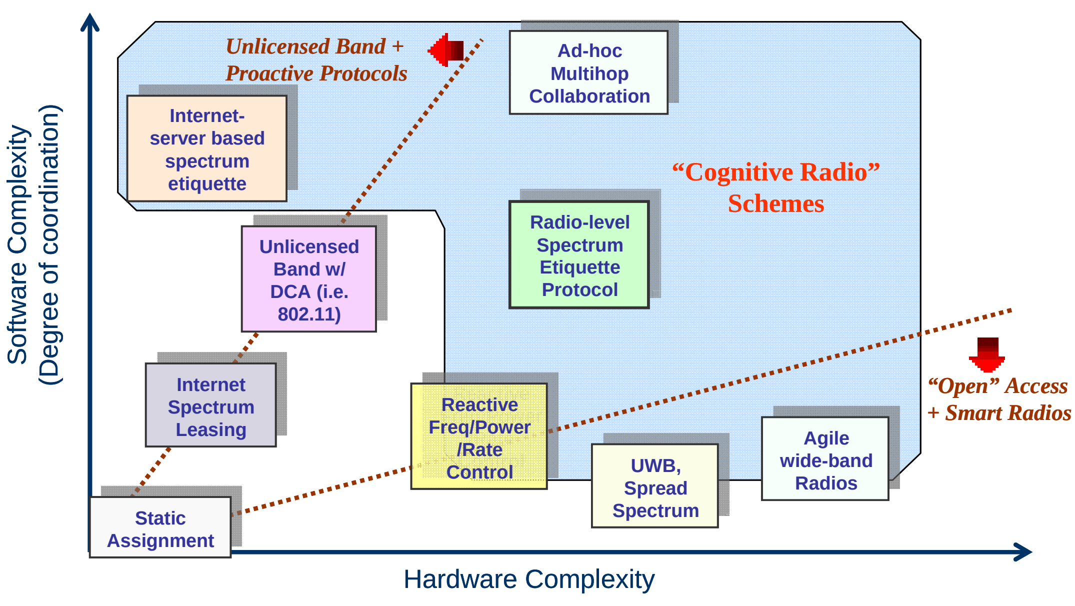


Figure 2.1: Cognitive radio design space.

The "agile wideband radio" scheme shown [30] at the lower right side of Figure 2.1 is the most prevalent concept for cognitive radio in which transmitters scan the channel and autonomously choose their frequency band and modulation waveform to meet interference minimization criteria without any protocol-level coordination with neighboring radio nodes. We observe here that although autonomous adaptation of the radio PHY is the simplest method and requires no coordination standards, it suffers from serious limitations due to "hidden node" problems [10][31] that arise in such scenarios illustrated in Figure 2.2. When transmission pairs AB and CD are sharing the same spectrum band, the receiver B will suffers from transmitter C's interference (similarly D suffers from A's interference) because of the fact that interference is a receiver property while spectrum scanning alone only provides information about transmitters. That is, node A or C cannot detect the existence of silent node D or B only by performing local channel scanning. Figure 2.2 also indicates the fact that this can be overcome by a small amount of explicit protocol level coordination (which will be discussed in details in Chapter 3) in which control information is exchanged between transmitters and receivers (if A is explicitly notified the transmission patterns of CD, it can adjust its own waveform to avoid interfering D).

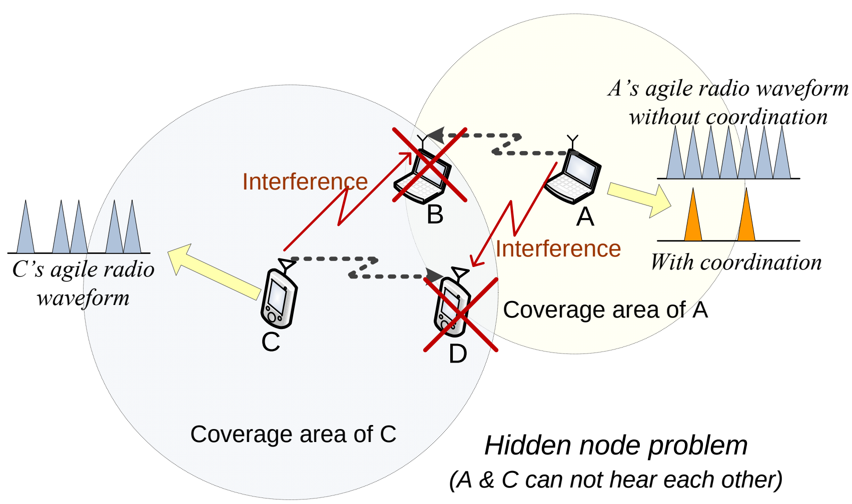


Figure 2.2: Illustration of the hidden node problem with agile radios, with and without a coordination protocol.

Another simple technique is "reactive control" of transmit rate/power [9], in which radio nodes do not have any explicit coordination with neighbors but seek equilibrium resource allocation using reactive algorithms to control rate and power, analogous to the way the TCP protocol reactively adjusts source bit-rate over the Internet. At a slightly higher level of protocol complexity in the design space of Figure 2.1, it is possible to use proactive schemes such as spectrum etiquette protocols [11] to improve coordination between radio nodes, using either Internet-based spectrum services or a common spectrum coordination channel at the edge of the shared frequency band for distributed coordination. Note that the etiquette approach requires some protocol coordination ability including the use of a common physical layer for coordination, but may not require full-fledged agile radio capabilities with programmable waveforms. At the next level of complexity in Figure 2.1 is “ad-hoc multi-hop collaboration” which involves a high degree of adaptation at both physical and network layers. In this scheme, radio nodes in a dense environment recognize the mutual value of collaboration and set up an ad-hoc network via bootstrapping of a control PHY between adjacent nodes along with appropriate collaborative MAC and network layer protocols that form an adaptive wireless network (vs. just an adaptive radio link) [5][18]. In the following of this chapter, we will first review prior work, then discuss the research scenarios and scope for this thesis.

2.2 Prior Work

2.2.1 Current Status on Spectrum Sharing

During the past decade, a number of approaches have been proposed for improved spectrum sharing in both technical and regulatory communities, as discussed in the previous section. The distinctions between unlicensed spectrum regimes, open access and cognitive radio approaches are relatively subtle as they are all based on the concept of technology neutral bands to be used by a variety of services using radio transceivers that meet certain criteria. For example, cognitive radio may be viewed as a special case of open access or unlicensed regimes in which radio transceivers are required to meet a relatively high standard of interference avoidance via physical and/or network layer adaptation. The cognitive radio principles currently under consideration by the FCC and the research community span a fairly wide range of possible functionalities both at physical and network layers.

The phrase "cognitive radio" (CR) was coined by Joseph Mitola in his thesis [1] for a wireless communication system built on software-defined radio [32][33] which is aware of its environment. There are other concepts for cognitive radio, such as in [34], cognitive radio is defined as an intelligent system which can learn and adapt to different situations in spectrum sharing by using machine-readable languages.

Any spectrum sharing mechanism whether distributed or centralized, RF-based or protocol-based must begin with some sort of interference measurement, such as spectrum sensing [35][36] or interference temperature measurement [37][38]. Most of the current work has been focusing on the spectrum sharing between incumbents and spectrally-agile radios [30][39][40][41], where cognitive radio nodes dynamically detect "spectrum holes" of primary spectrum users and opportunistically utilize them in frequency and time [42]. For example, in [42], a spectrum sharing system model is proposed with spectrum resource management and policy enforcement blocks based on measurement of channel busy time for primary spectrum users, while secondary spectrum users fit into the time gaps of each channel. In [43] and [44], dynamic spectrum access techniques relying on a spectrum broker are used for cellular networks, where the spectrum broker controls and provides time-bounded access to a band of spectrum and improves the spectrum utilization based on regional spectrum demand aggregation. There is other work on spectrum efficient MAC protocols using multi-channels such as [45][46][47], where MAC control messages are moved to a control channel which is separated with channels used for data to improve 802.11 MAC. Most of the above work propose basic schemes or algorithms with numerical analysis or simulations, but more detailed system level issues such as co-existing heterogeneous scenarios and protocol designs/validations are not addressed.

In the area of dynamic spectrum access, etiquette and sharing, researchers have been using various analytical tools for modeling. A game theoretic model is proposed in [48][49][50] for adaptive channel allocation and spectrum resource sharing, where spectrum users are modeled as game players and their strategies determine how to select available channels. In [51], both cooperative and non-cooperative (selfish) scenarios are considered and players try to maximize the utility function which is related to the received power and interference to other users. Intelligent power allocation strategies are considered by [52] in their game model. Variable rate link scheduling by a spectrum server is studied in [53] and according pricing and spectrum allocation algorithms are proposed in [54]. There are also other policy related research results, including spectrum regulatory policies for cognitive radio [55] and the economics of collaboration in the spectrum commons [56]. An underlay approach is proposed in [58] to utilize the newly opened VHF/UHF TV frequency band for wireless regional networks, such as IEEE 802.22 [59]. New market and spectrum management concepts enabled by cognitive radio are also studied by [60].

Besides the analytical work, several cognitive radio prototypes and platforms are presented in [61] and [62]. In [63], a multiMAC framework can integrate different MAC protocols such as TDMA, Aloha, and 802.11 for dynamically switching between them to adapt to different network scenarios. A number of current research efforts are also being carried out on the topic of architecture and design of cognitive radio hardware. The NSF-funded network-centric cognitive radio project [64] at WINLAB (in collaboration with Lucent and Georgia Tech) aims to develop a high performance cognitive radio platform with integrated physical and network layer capabilities. The KU agile radio [65] developed at Kansas University utilizes H-OFDM technology for wideband transmitters and receivers. In the commercial market, Vanu Inc. [66] is the first FCC-approved software radio which provides solutions for communication between disparate wireless devices and frequencies. GNU’s open-source software defined radio project [67] also supports a hardware platform using the Universal Software Radio Peripheral (USRP) [68], which is a low cost, high speed USB 2.0 peripheral for the construction of software radios.

2.2.2 New Trends towards Spectrum Sharing

In order to better utilize the scarce spectrum resources, the US Federal Communications Commission (FCC) issued an NPRM 04-113 [69] on the use of VHF/UHF TV band between 54 MHz and 862 MHz by license-exempt devices, aimed at bringing broadband access in rural and remote areas. This is motivated by the low utilization of the VHF and low-UHF bands in sparsely populated areas – these bands have good propagation characteristics and should be useful for data and other services provided the co-existence problem can be solved. IEEE has also initiated the 802.22 WRAN (Wireless Regional Area Network) standard [59] for license-exempt operation in the TV broadcast bands to provide fixed wireless access for rural areas.

Beyond the simple “underlay” scenarios mentioned above, European and US regulators and standardization groups are currently putting more and more emphasis on cognitive radio, which will affect the way spectrum is coordinated and how it will be assigned to wireless communication services in the future. The US FCC NPRM 03-108 [70] in 2003 is aimed to facilitate opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies. In the NPRM, the Commission seeks comments on ways to encourage spectrum sharing and remove regulatory impediments to the deployment of cognitive radio technologies. For example, facilitate licensed spectrum users to deploy cognitive radios for their own use to increase spectrum efficiency, and to facilitate secondary markets, allowing licensees to lease their spectrum access to third parties using such technologies.

The US Defense Advanced Research Projects Agency (DARPA) established the NeXt Generation Communications (XG) program [71], aiming at developing a de-facto standard for cognitive radio and dynamic spectrum regulation. The XG program investigates both key technologies and system concepts to dynamically redistribute allocated spectrum along with new waveforms in order to provide dramatic improvements in assured military communications in support of a full range of worldwide deployments.

2.3 Cognitive Radio Research Scope

2.3.1 Cognitive Radio Scenarios

Spectrum coordination techniques for cognitive radios can be used in a variety of spectrum sharing scenarios, such as co-existing heterogeneous radio systems (shown in Figure 2.3), for example, IEEE 802.11b/g/n [12] and Bluetooth [13] are working in the 2.4GHz ISM band, 802.11a/n and HIPERLAN II in the 5GHz U-NII band [72], and they may also be required to share the spectrum with UWB devices, which may take several GHz bandwidth starting from upper 3GHz. With the fade-out of analog TVs, there are more and more new opportunities in the VHF/UHF TV band (especially 400-800MHz band) which may lead to a new generation of wireless technologies. Recent advanced radio technologies such as 802.16 (WiMax) [14] and 802.22 WRAN may consider cognitive radio methods in their physical layers to explore new spectrum opportunities in both licensed and unlicensed bands. There are several interesting scenarios for mobile cognitive radio users (such as 802.16e) where they can detect and utilize local vacant spectrum for communications as an ad hoc or mesh network. Fixed WiMax deployment such as 802.16a can also use unlicensed band to share the spectrum with existing radio devices such as WiFi (802.11) users and hotspots. The co-existence of long-range WiMax and short-range WiFi networks are of particular interest because WiFi has achieved rapid penetration in wireless local-area networks, and WiMax can provide complementary high-speed data services in a wide area. Figure 2.4 shows a network scenario where WiMax wireless backhaul networks deployed between buildings share the same spectrum with WiFi hotspots which exist in homes, airports, libraries, etc. This typical network will serve as a baseline in our simulation models to study the co-existence of WiFi and WiMax.

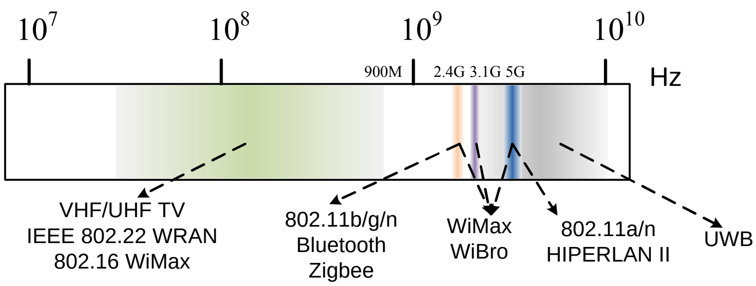


Figure 2.3: Wireless technologies sharing spectrum.

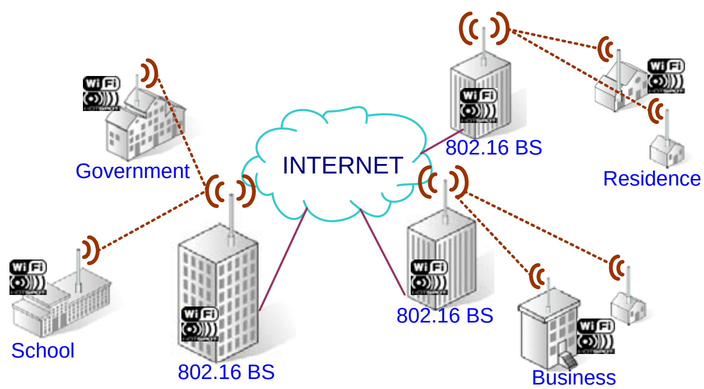


Figure 2.4: A co-existing IEEE 802.11b and 802.16a network.

Despite the scarce and congested nature of the current unlicensed spectrum due to increasing popularity of wireless technologies, the current utilization of precious spectrum resource is very inefficient because the radio hardware has very limited functions in adapting spectrum usage changes. The inefficiency problem can lead to performance degradation especially in a dense network where a lot of different radio devices operate on the same spectrum band. Current spectrum allocation rules are mostly for simple radio transmitters and there are a large safety margins which result in poor utilization. Current spectrum sharing rules such as listen-before-talk [73] are not generally applicable to the new cognitive radio scenarios due to radio heterogeneity and hidden-node problems (shown in Figure 2.5) caused by radios with different power and coverage ranges.

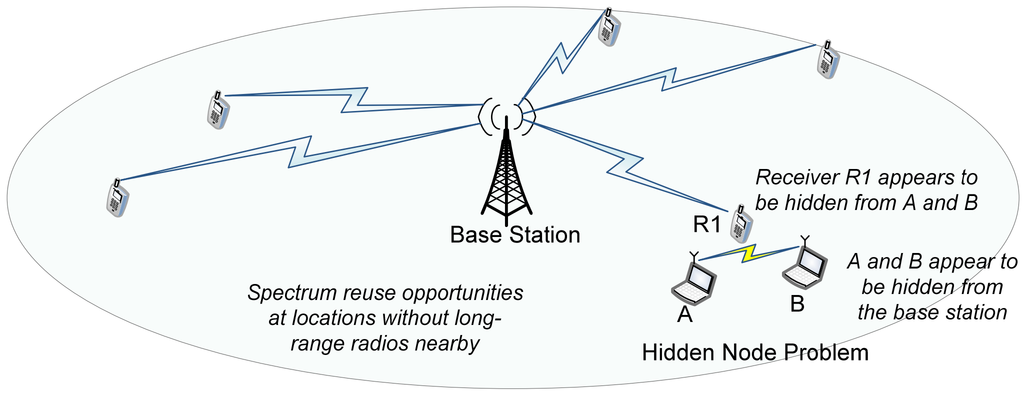


Figure 2.5: Hidden node problems in a heterogeneous network scenario with both long and short range radios.

An example of the hidden node problem in heterogeneous radio systems is shown in Figure 2.5, where a long range radio system (Base Station and R1, etc.) co-exists with a short range radio system (node A and B) and they share the same spectrum. When node R1 is receiving, A and B cannot know R1 is nearby by simply listening on each of the available channels. So any transmissions between A and B will interfere with R1, which seems to be hidden from A and B. On the other side, since A and B only have short-range radios, the Base Station can not sense their existence and they appear to be hidden from the Base Station and thus will suffer from its interference. The two systems use different radio technologies and they will not understand each other without a new mechanism for exchanging spectrum information. This motivates development of spectrum etiquette protocols which enable radios to communicate with each other to negotiate shared use of the band more efficiently. Specific etiquette protocols will be considered further in our work.

2.3.2 Research Scope

It is useful to design and evaluate spectrum sharing schemes for cognitive radio based on the associated hardware and software complexity. In scenarios where wireless nodes have relatively similar interference patterns, simple interference avoidance schemes may be adequate, such as changing operating frequencies based on sensing each available channel, controlling transmit power to reduce interference, or reschedule packet delivery based on wireless channel qualities.

These schemes are "reactive" in the sense that radio nodes react to different interference scenarios or wireless channel quality changes by tuning their runtime parameters such as operating channel, transmit power, rate, etc. Reactive schemes have a low level of hardware and software complexity since no extra equipment is needed and the protocol is simple to implement. But they may have limited performance especially in more complicated cognitive radio scenarios.

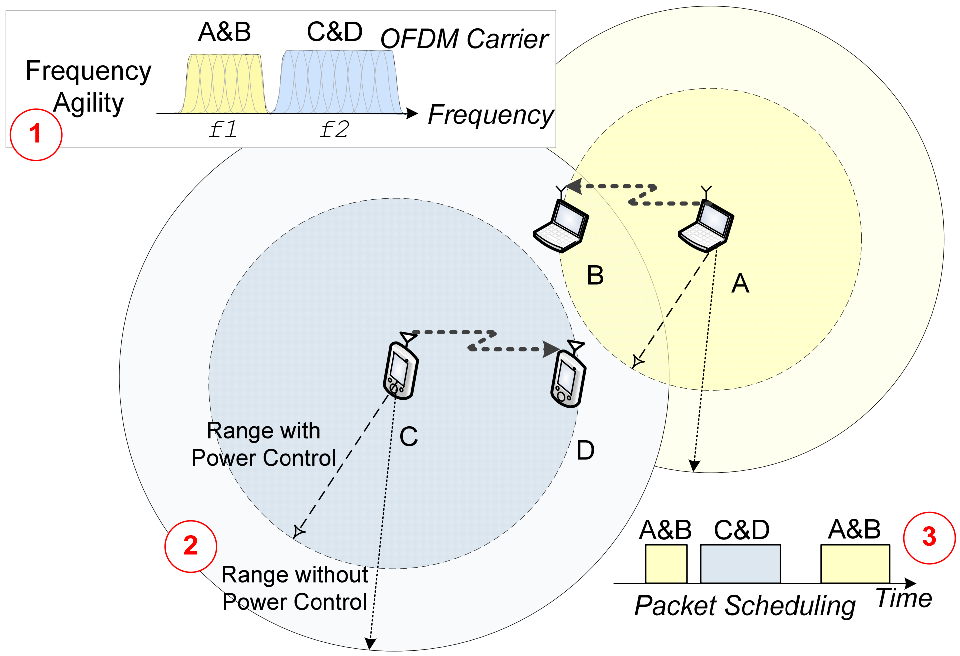


Figure 2.6: Reactive spectrum coordination methods.

Figure 2.6 elaborates on reactive schemes in a network where node A is transmitting to B and node C is transmitting to D. Nodes A and B may use different radio technologies from C and D thus they may not understand each other. Nodes B and D are within the interference range of C and A respectively. When B and/or D experience interference, their reaction can be quite straightforward – sensing the interference level of each available channel and changing to the one with the least interference. For example, the interference will be eliminated if A and B operate at center frequency *f1* and C and D at *f2*. Interference can also be reduced if all nodes lower their transmit power – transmitter A and C control their power to reduce the interference range. To share the same spectrum band, radio nodes can also cooperatively arrange their transmissions sequentially by re-scheduling their packets in time domain to avoid interference.

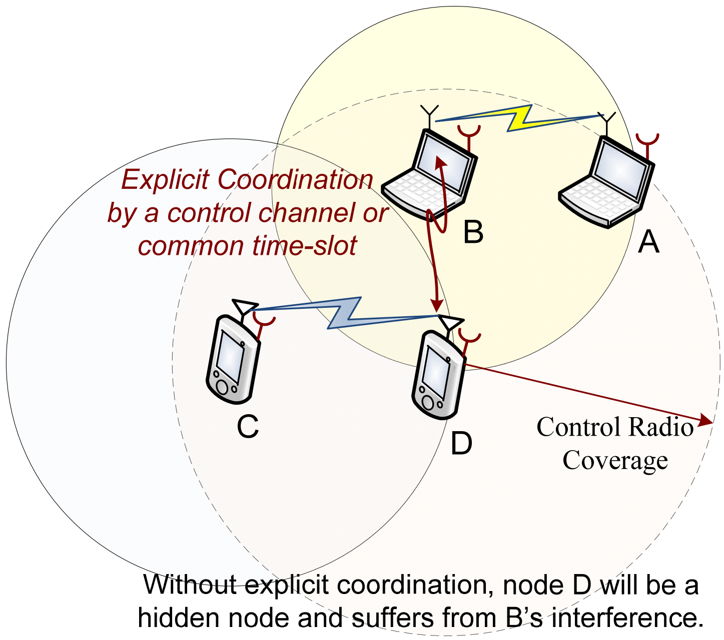


Figure 2.7: Proactive coordination schemes using a control channel.

For more complicated scenarios such as Figure 2.5, simple reactive schemes may not be adequate due to hidden node problems [74][10]. For example, in a similar scenario shown in Figure 2.7, if B is transmitting to A when C is transmitting to D, node D will be interfered by B. This is because nodes are unable to predict future behavior of other nodes and only transmitters can be detected, not receivers, but interference is a receiver property. Here B cannot detect D, which is the hidden node. In such cases, nodes have to actively coordinate with each other to share limited radio resources by using schemes with a higher level of hardware and software complexity. The protocols for active coordination can be called "proactive" as compared with "reactive" ones. Proactive schemes for spectrum sharing enable heterogeneous radio nodes to explicitly execute coordination algorithms and adapt their radio transmit parameters to more complicated interference scenarios by following the spectrum etiquette. In Figure 2.7, a simple control radio installed in each node enables mutual observability of control information between heterogeneous nodes and hence supports explicit coordination functions for efficient spectrum sharing.

It is also interesting to consider general cognitive radio networks, where radio nodes are all agile and can quickly adapt operating frequency, bandwidth, modulation schemes and transmit power to cope with various spectrum sharing scenarios. The key questions are: how do these individual cognitive radio nodes self-organize into networks, initialize/configure their flexible radio parameters and establish communication with each other? How will their naming and addressing schemes be designed in view to support ad hoc and opportunistic formation of networks? What are the algorithms for discovering nodes, services and network topologies? How will radio nodes efficiently share the spectrum with others? To answer these questions, a new network architecture called "*CogNet*" and protocol stacks are proposed based on the concept of a "global control plane (GCP)", extending from the idea of the CSCC protocol, which is separately from the data plane operations. Control protocol components involving spectrum information and multi-hop cross-layer routing are designed. Using the global control plane, cognitive radio nodes which start up or move into a new area can bootstrap and self-organize into ad hoc clusters, and discover each other, find services and obtain addresses. Using this framework, ad hoc collaborations between radio nodes are achieved where multi-hop radio links can be dynamically set up by configuring intermediate nodes hop by hop through the control plane.

Chapter 3 The CSCC Etiquette Protocol

The basic idea of the Common Spectrum Coordination Channel (CSCC) [11] approach is introduced in this chapter together with the demonstration of proof-of-concept experiments for co-existing IEEE 802.11bg and Bluetooth networks in the shared 2.4 GHz unlicensed band.

3.1 Spectrum Etiquette Background

Spectrum etiquette protocols are first proposed to solve the spectrum co-existence problems in unlicensed frequency bands (such as the 2.4 GHz ISM band and the 5 GHz U-NII band), which have played a critical role in enlarging the scope and penetration of wireless technology. The IEEE 802.11 wireless local-area network is the most notable example of proliferating unlicensed band wireless technologies for computer applications. As the popularity of unlicensed radio devices such as 802.11bg and Bluetooth grows, there is increasing concern about the potential for destructive interference between uncoordinated devices, particularly those with different radio access standards. There are increasing reports of problems in coordinating frequency and power settings of 802.11b devices owned by different organizations or individuals, and of destructive interference between Bluetooth and 802.11b devices [13]. These problems have motivated a renewed interest in spectrum etiquette for reducing destructive interference and improving overall spectrum utilization in unlicensed bands. The goal is to avoid the classic “tragedy of the commons” effect where the collective value of a shared resource (in this case, spectrum) is diminished by “overgrazing” due to the lack of cooperative procedures that balance individual needs with overall social utility.

The U.S. FCC in its 1998 U-NII ruling indicated a preference for “technology neutral” spectrum etiquette policy that would permit co-existence and competition of multiple radio technologies, which may each be optimized for different applications. The technology neutral approach also facilitates rapid introduction of emerging radio technologies without the delays associated with traditional standards processes. Recent experience with wireless local-area and personal-area networks has shown that multiple standards are likely to co-exist at any given time, and that the recent "Moore's law" type evolution of radio technologies makes it unlikely that a single radio standard, however popular, will remain unchanged for more than five years (e.g. evolution of 802.11b, a, g, ...). All this argues for a renewed industry effort to standardize a flexible spectrum etiquette policy [24] that would work well with a variety of existing and emerging radio technologies intended for WLAN and WPAN scenarios.

The spectrum etiquette mechanism proposed in this thesis is called the "Common Spectrum Coordination Channel (CSCC)" [11]. We have discussed in Chapter 1 the needs for such a protocol to enable mutual observability between heterogeneous radio devices via a simple common protocol. In this chapter, we will introduce the details of this protocol and study it by applying to a co-existence scenario of IEEE 802.11bg and Bluetooth.

3.2 The CSCC Concept

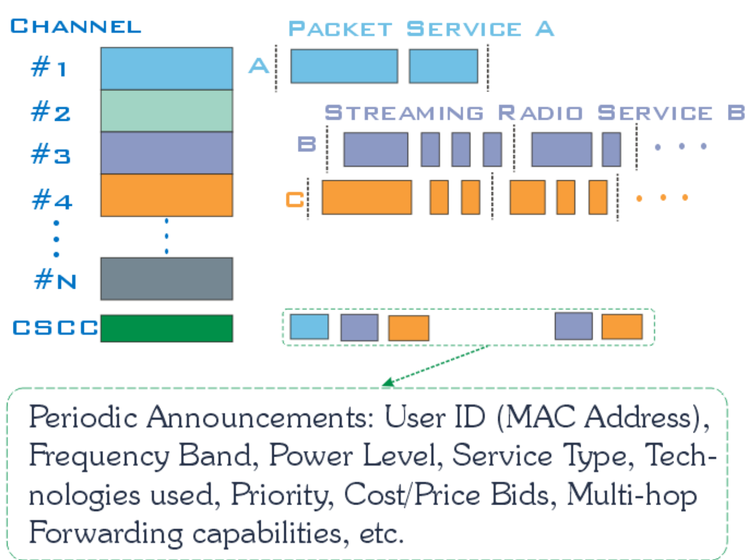


Figure 3.1: Basic principle of the CSCC etiquette protocol.

The basic concept of the "common spectrum coordination channel (CSCC)" is illustrated in Figure 3.1. The CSCC is a narrow control channel shared by all users of the band intended for spectrum coordination purposes. Each device has an extra narrow-band (low bit-rate) radio for exchange of control information over the CSCC channel. When different devices need to use spectrum, the CSCC method requires all users to periodically broadcast spectrum usage information (including: user ID such as IEEE MAC address, frequency band used and transmit power as well as optional parameters such as technology type, service type, multi-hop forwarding capabilities if any, user priority, etc.) using a simple standardized packet transmission protocol in the pre-defined sub-channel at the edge of the unlicensed band. Observation of these announcements permits newly active users to obtain a map of spectrum activity and select available frequencies, if any. All the CSCC broadcast is in an on-demand manner, which means only those devices that have spectrum request or those that are already transmitting will announce their spectrum usage information via the CSCC broadcast. Other users will remain silent and listen to the CSCC information. In the event that no clear channel is available when a device has a new spectrum request, it can transmit a contention message on the coordination channel. This initiates distributed execution of a specified etiquette procedure which results in distributed sharing of radio resources (i.e., frequency, power, time) in the congested region.

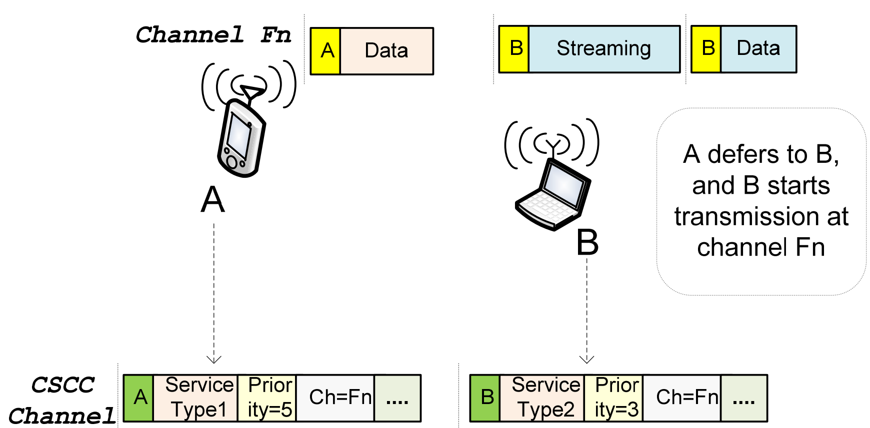


Figure 3.2: Example of CSCC protocol used to execute a priority etiquette policy.

An example in which the CSCC method is used to implement a simple priority-based etiquette policy is shown in Figure 3.2. In this example, user A is already using the channel Fn. When user B has a spectrum request with higher priority than user A, it first listens for CSCC messages, which are broadcast periodically by all active devices within radio range. If no clear channel is available, B may decide to compete with user A for usage of channel Fn. Then user B announces itself by broadcasting a CSCC message in the control channel, informing others its service type, priority, preferred channel number and other information. When A receives this control message from its CSCC radio, it will defer to B and stop transmitting since it has a lower priority than user B. After this process, user B wins the contention and begins transmitting. The same mechanism may be used to implement a broad range of etiquette policies, including dynamic congestion pricing [75] in which contending users place actual price bids for usage of the channel.

The advantage of the CSCC method is that it permits considerable flexibility in spectrum sharing procedures, which can now take into account more complex factors such as type of service or user priority consistent with public policy objectives. More advanced collaborative power control and/or multi-hop routing procedures may also be implemented within this type of framework. In addition, this method provides users with a “program guide” type capability as they enter a new area, thus simplifying terminal start-up procedures for access to network services.

3.3 CSCC Protocol Stack

Figure 3.3 shows the proposed dual-mode spectrum etiquette and data protocol stacks to be implemented by compliant unlicensed band radios. The spectrum etiquette protocol consists of standardized CSCC-PHY and CSCC-MAC layers with an etiquette policy module above. The spectrum etiquette (SE) policy module(s) must also be standardized for specific usage settings (e.g. home, indoor office, outdoor public, etc.) or for different regions, but these standards (including semantics for the parameters involved) can be set independently from the basic CSCC protocol.

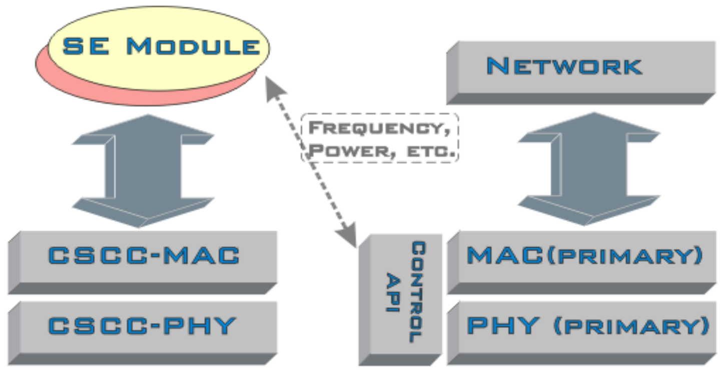


Figure 3.3: CSCC protocol stack.

For the CSCC-PHY, ideally it can be implemented as a generic narrow-band low-rate low-cost radio operating at the edge of an unlicensed band (e.g., 900MHz, 2.4 or 5 GHz). Depending on the coordination scenario requirement for control overhead, it can adopt different transmission rates and powers for different coverage area. In special cases when all the devices have wired connection, such as in ORBIT radio grid testbed, the CSCC-PHY can even be implemented using standard wired Ethernet. For experimental purposes, we can use the basic 1 Mbps 802.11b standard, in order to leverage existing hardware designs, and to keep the complexity to a minimum. The 1 Mbps mode of 802.11 at nominal 10 mW transmit power may be expected to provide ~50-100m coverage in most indoor and outdoor scenarios, sufficient for coordination in most unlicensed WLAN and WPAN scenarios. Lower powered WPAN devices with shorter range may reduce the transmit power on the CSCC-PHY to correspond to a small multiple of their nominal radio range. The CSCC PHY must be standardized for edge-of-band operation in each unlicensed band, although it is also possible to consider a single band at the edge of either 2.4 or 5 GHz unlicensed spectrum with control information at the MAC layer to cover multiple frequency bands.

The CSCC MAC protocol itself is a simple periodic announcement protocol with randomization of the transmit cycle to eliminate repeated collisions. Each station transmits the CSCC packet periodically with a repetition interval of about 100 ms to a few seconds. The exact values depend on desired start-up and system response times.

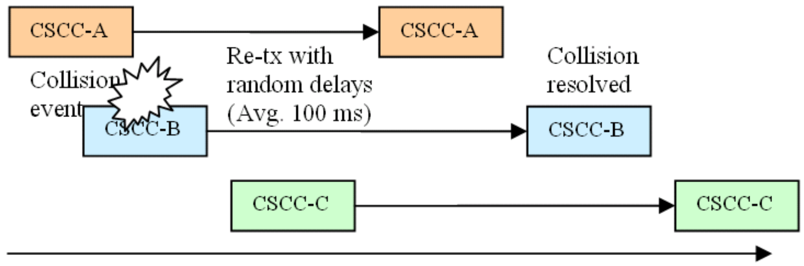


Figure 3.4: CSCC MAC access with randomized periodic transmissions.

The channel access procedure is outlined in Figure 3.4. The CSCC message of user A collides with that of user B, but this collision is resolved in future transmissions via randomization of the transmission interval. Note that this type of one-way broadcast MAC procedure is extremely simple, and requires very little logic for implementation.

3.4 CSCC Packet Format

A possible CSCC-MAC layer packet format is shown in Figure 3.5. A standard Ethernet packet format with control payload extensions is adopted as the basis. The 48-bit MAC address (source address) is used as the unique identifier, along with spectrum etiquette information elements for frequency band, power, etc. The semantics of these information elements is related to specific network conditions, frequency assignment, power control and (potentially) multi-hop collaboration algorithms to be used by a specific SE policy module. The Ethernet destination address is used to denote multicast groups that specify classes of potential neighbors which are expected to participate in the etiquette procedure. Also, the 2-byte type field can be used to indicate the specific SE policy to be used in connection with the information elements received over the CSCC.

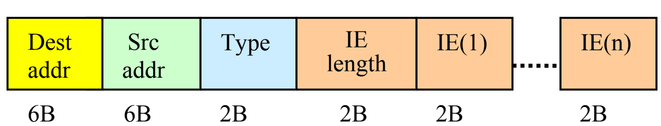


Figure 3.5: Generic CSCC packet format (in bytes).

For example, in the case of a scenario which IEEE 802.11bg devices co-exist with Bluetooth devices in a dense network, we can define several useful information elements: IE(1): Clamed

Channel, IE(2): Priority, IE(3): Pricing based on bid, IE(4): Session Duration, IE(5): Transmitted Power Level, IE(6): Received Signal Strength. Other IE fields to support power control or more complex frequency/time coordination can also be defined as needed.

3.5 Etiquette Policies

As mentioned earlier, various etiquette policies based on sharing the shared use of channel/time/frequency/power, user priorities or even micro-auctions can be considered. Priority is often used as a simple policy for coexistence between different classes of users, e.g. police/fire/ambulance and general-purpose data users. Another interesting policy is based on dynamic pricing [75] based on micro-auctions between contending users. When the channel is congested, each user offers to pay a price for accessing spectrum resources, and the winner of the auction then proceeds to transmit. Efficient use of radio resources via agile radios and/or collaborative multi-hop routing models can also be implemented in this framework since the CSCC provides a map of current usage, eliminating the need for complex and slow frequency scanning procedures. A more advanced use of the CSCC is for “collaborative spectrum usage” in which multiple devices cluster together into a collaborative group that forms an ad-hoc network with multi-hop routing and power control. The CSCC can be used to advertise multi-hop routing capabilities and the willingness to join such a collaborative ad-hoc network of this type.

3.6 Proof-concept Experiment: Coexistence of IEEE 802.11b and Bluetooth

In this section, we present preliminary experimental results for CSCC applied to a co-existing 802.11b and Bluetooth network scenario. The experiments are aimed at evaluating how the concept of the etiquette system works in a realistic environment with uncoordinated devices which potentially interfere with each other. The goals of the experiment are also to validate the protocol’s operation, to evaluate protocol design options, and to study alternative spectrum sharing policies. The network scenario is very simple corresponding to two pairs of incompatible radio devices coexisting in a public space. As Figure 3.6 shows, there are two pairs of radio devices, one 802.11b WLAN and one Bluetooth. Bluetooth1 and WLAN1 are senders and Bluetooth2 and WLAN2 are receivers.

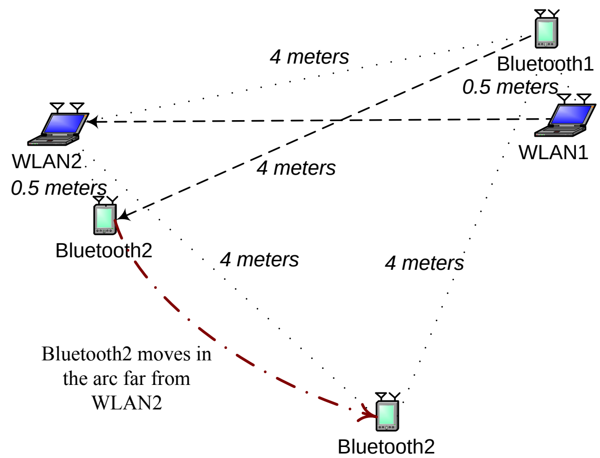


Figure 3.6: Experimental network scenario for devices with dual mode radio.

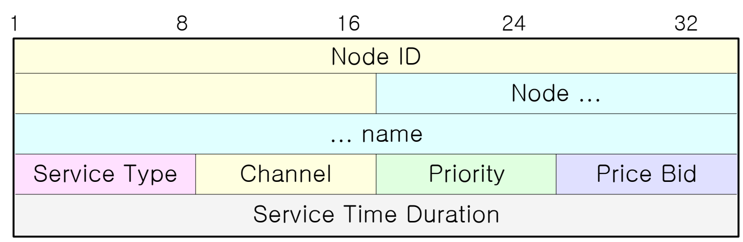
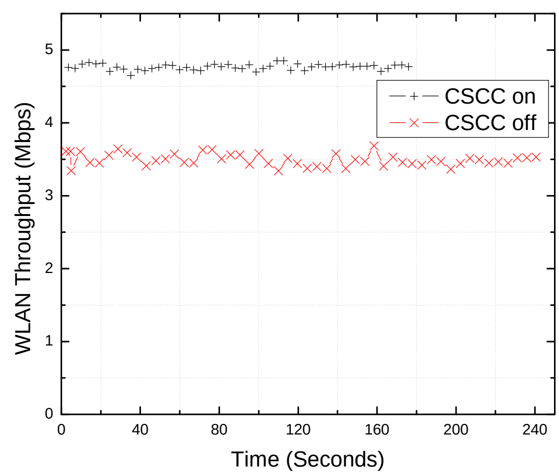


Figure 3.7: CSCC packet format used in the 802.11b/Bluetooth scenario.

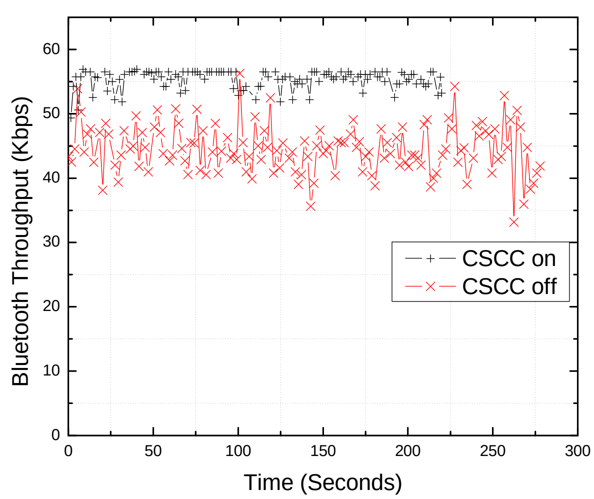
Each of the radio devices is hosted on a laptop computer running Linux. All the devices are equipped with dual mode radios running CSCC, using an 802.11b radio at 1 Mbps tuned at a different channel from the WLAN user card. Initially Bluetooth2 is near to the WLAN2, and then it is moved away from WLAN2 while keeping the same distance from Bluetooth1. In the experiments, the benefit of a priority-based etiquette protocol is evaluated based on TCP file transfer services. The experimental parameters are listed in Table 3.1. The spectrum etiquette protocol itself is implemented in Linux user space, and in this case it consists of a simple priority-based on/off mechanism. The CSCC packet format is shown in Figure 3.7, which is encapsulated in the standard Ethernet packet in order to reuse existing WLAN drivers.

Table 3.1: Experiment parameters for 802.11b and Bluetooth co-existence.

	WLAN nodes	Bluetooth nodes
Mobility	Static without mobility	BT1 static, BT2 position varies
Traffic Model	100MB bytes data by TCP	1.5MB bytes data using stop-and-wait scheme
MAC protocol	IEEE 802.11b at 11Mbps	Bluetooth ACL data link
Wireless Adaptor for data	Cisco Aironet 350 series DSSS (at channel #11)	Ericsson Bluetooth Development Kit (hopping over the whole 2.4GHz band)
CSCC MAC	IEEE 802.11 & periodic announcements at 1Mbps	
CSCC card	Cisco Aironet 350 series DSSS (at channel #1)	



(a) Throughput trace for WLAN session



(b) Throughput trace for BT session

Figure 3.8: Throughput for WLAN or BT session.

Figure 3.8 shows comparative throughput traces vs. time for WLAN and Bluetooth (BT) data sessions with and without CSCC etiquette. When CSCC is turned on, WLAN and Bluetooth devices resolve contentions by using the priority etiquette and the winner continues to transmit without further interference. It is observed that when WLAN users win (Figure 3.8a), their throughputs can improve ~35%, and if BT users win (Figure 3.8b), the throughput improvement is ~30%. Note that since the Bluetooth devices use stop-and-wait scheme, the interference between the two systems is not in its worst case. In a more intense interference case, more throughput improvement can be expected. It is also observed that without CSCC, Bluetooth devices cause periodic interference to WLAN, thus tending to decrease and increase the TCP window repeatedly. The figures confirm that this degradation can be avoided by using the proposed etiquette protocol.

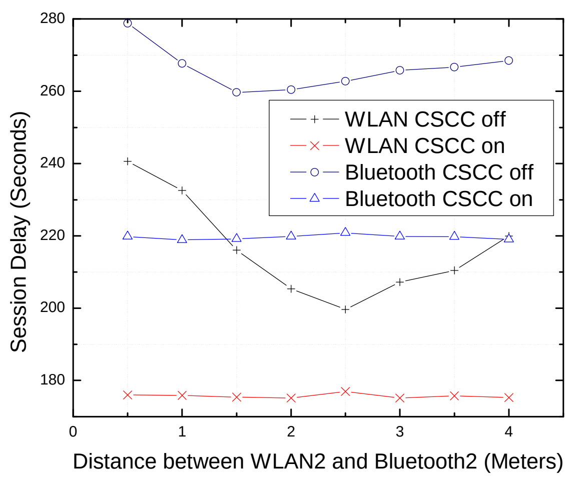


Figure 3.9: Average session delay with and without CSCC vs. distance parameter.

To evaluate the total data session delay with and without CSCC etiquette, BT2 was moved away from WLAN2 as outlined in Figure 3.6. WLAN session delays are reduced 12~30% depending on distance, and BT session delays are reduced 15~22% as shown in Figure 3.9. It is interesting to observe that as we move BT2 far from WLAN2 in an arc (while keeping the distance between BT1 and BT2 constant), the session delays for both WLAN and Bluetooth first decrease and then increase without CSCC. This is because BT2 is moving further from WLAN2 but closer to WLAN1. So their interference first decreases and then increases. When CSCC is turned on, the session delay is almost constant since the two kinds of devices obtain spectrum resources in turn and there is no interference. Figure 3.10 shows the instantaneous packet delay trace for a BT data session. When CSCC is turned on at 230 seconds, the BT user wins the contention with WLAN and its packet delay becomes lower and more stable than without CSCC.

For conclusion, in this section, the CSCC etiquette protocol is proposed which provides a simple way for radio devices with different technologies to announce their own parameters in using a common coordination channel the edge of the unlicensed spectrum band. The CSCC message is periodically broadcast during the data session of the users so that resources such as frequency, power and time can be allocated in a fair and spectrally efficient manner. A proof-of-concept experiment with co-existing 802.11b and Bluetooth devices is conducted and the results show that in the 2.4 GHz ISM band, contending 802.11 and Bluetooth devices can achieve improved throughput and delay for both devices using simple priority-based etiquettes. Alternative spectrum coordination algorithms and etiquette policies will be discussed in the following section.

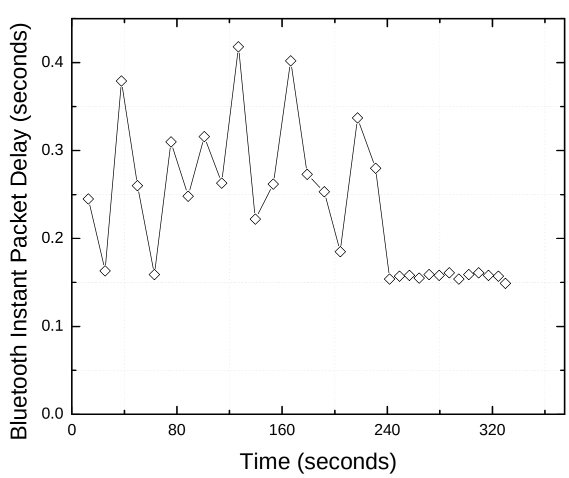
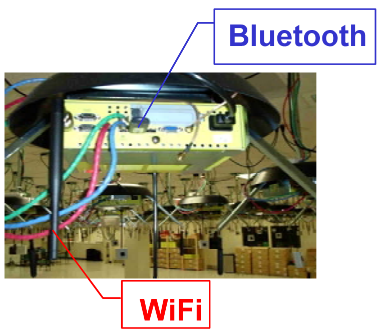


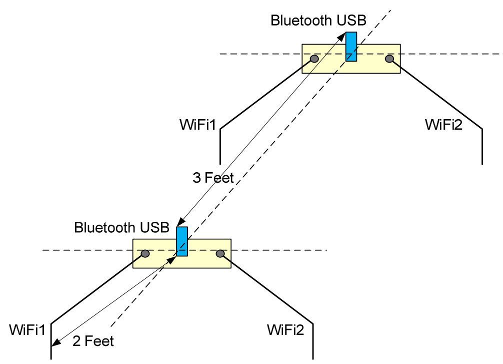
Figure 3.10: Instantaneous packet delay for BT with CSCC turned on at t=230sec.

3.7 ORBIT Experiment: Coexistence of IEEE 802.11g and Bluetooth

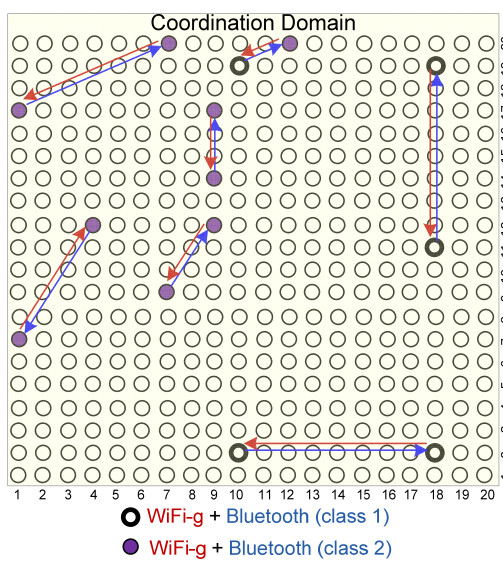
In order to further validate the CSCC protocol in a denser radio environment with IEEE 802.11g and Bluetooth devices, we conducted experiments using the ORBIT radio grid testbed, shown in Figure 3.11. Each ORBIT node [14] has two IEEE 802.11a/b/g radios, one Bluetooth radio and Giga-bit Ethernet connections. Some of the nodes are equipped with Bluetooth USB dongles. In this particular implementation, we use the wired Ethernet to implement all the control functions for CSCC protocols. One WiFi card is tuned at 2.4GHz with 802.11g mode supporting up to 54Mbps bit rate with auto rate fallback controlled by the WiFi driver. A total of 14 nodes are used in this experiment with 7 pairs of WiFi-g links and 7 pairs of Bluetooth links.



(a) ORBIT node



(b) Node setup



(c) Network scenario for ORBIT experiments

Figure 3.11: ORBIT experiment for 802.11g and Bluetooth co-existence.

Table 3.2: ORBIT experiment parameters for 802.11g and Bluetooth co-existence.

	Data Radio Service	
PHY Type	IEEE 802.11g (Atheros AR5212)	Bluetooth (Belkin / IOgear USB Dongles)
Frequency	2427-2447MHz	2402-2483.5MHz
Modulation	OFDM (256 FFT) QAM	GFSK + FHSS (DQPSK for EDR)
Transmit Power	18dBm	4dBm (~20m) (class 2) 20dBm (~100m) (class 1)
PHY Rate	Up to 54Mbps with Auto Rate Fallback by MadWiFi driver	Upto 1Mbps (class 2) Upto 2.1Mbps (class 1 w/ EDR)
Data session	Pareto ON/OFF variable rate CBR: 5 sec random session	Constant audio streaming in UDP (64, 128, 320,512, 1024kbps)
Coordination Algorithms	*Rate-adapt*: Lower Bluetooth service rate for one level when each WiFi receiver is detected. *BT-Backoff*: Shut down Bluetooth radio when any WiFi receiver is detected.	

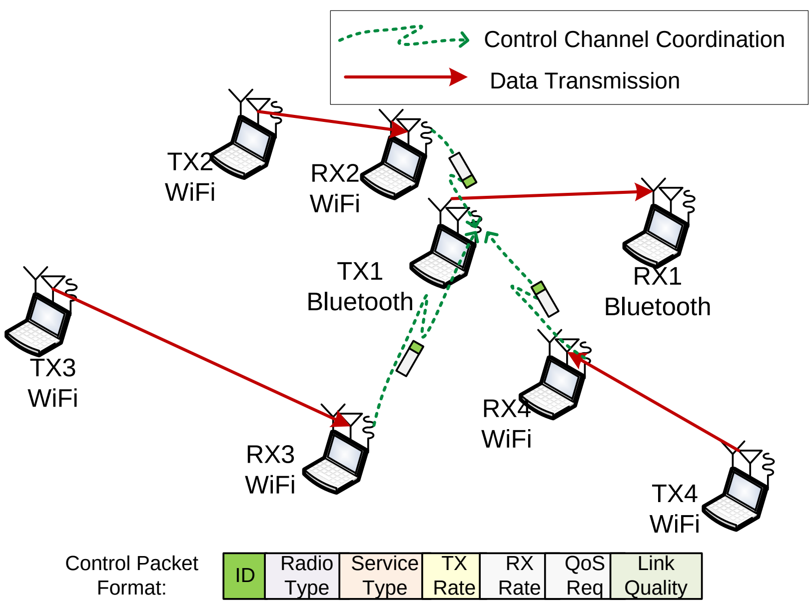


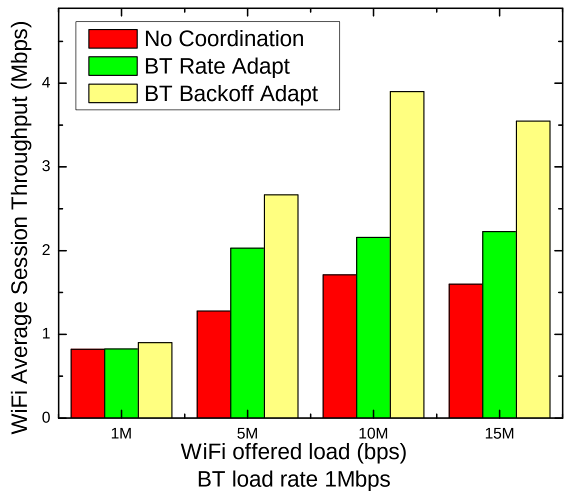
Figure 3.12: Simple rate adaptation and backoff algorithm for 802.11g and Bluetooth.

The experiment parameters are listed in Table 3.2. In this ORBIT [76] experiment, all nodes are running the CSCC protocol with a simple rate adaptation and transmission backoff based spectrum coordination algorithms. The CSCC protocol allows the multi-radio nodes exchanging their rate and traffic information for spectrum coordination. As an example shown in Figure 3.12, a Bluetooth transmitter collects CSCC control packets from three WiFi receivers by listening to the control channel, and it will adjust its own operating parameters (service rate, etc.) based on the interfered WiFi receivers detected. That is, the CSCC protocol helps transmitters to detect the existence of heterogeneous receivers in its neighborhood and thus execute coordination algorithms to avoid interference. Note each node is equipped with both WiFi and Bluetooth radios so the two radios will also interfere with each other in the same platform. Here both interference sources from in-platform radios and between different platforms are considered for coordination.

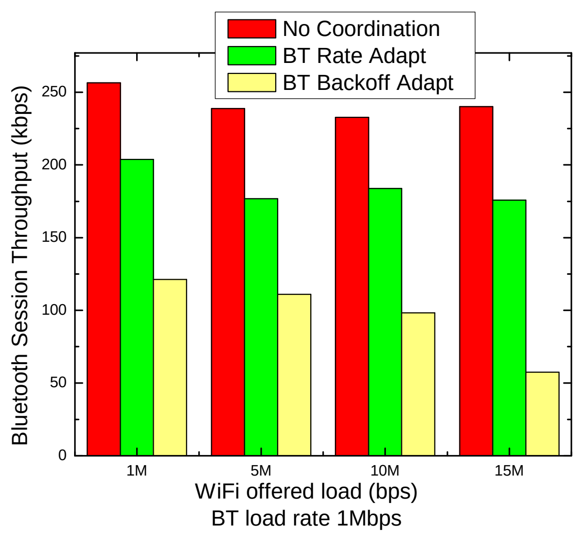
As the Bluetooth radio has a much lower transmission rate than WiFi-g radios, we here consider the algorithms for Bluetooth radios to dynamically adjust its own loading rate based on the number of WiFi-g receivers detected by the CSCC protocol. Two sets of algorithms are considered, the first one is for Bluetooth radio to change its loading rate to avoid WiFi-g radios, and the other is to shut off Bluetooth radio when WiFi-g receivers are detected. We would like to study how much benefit the lower rate system can bring to the whole network when its performance is sacrificed. As explained in Table 3.2, the Bluetooth transmitter will lower its service loading rate by one level (or be shut off) each time a WiFi-g receiver is detected in its control coverage range. When there are no any such receivers detected, the Bluetooth transmitter can increase its own service rate to the highest level to make the best use of the channel.

The average network throughputs measured for WiFi-g data sessions, Bluetooth links and total network throughput are plotted in Figure 3.13(a-c), and the percentage throughput improvement is shown in Figure 3.13(d). In this proof-of-concept setup, have used a relatively simple priority backoff approach in which BT transmitters try to avoid high rate WiFi-g system using two alternative schemes: "BT-Rate" scheme will force Bluetooth transmitters to lower its transmission rate for one level when one active WiFi-g receiver is detected by the CSCC protocol; "BT-BO" scheme will force Bluetooth transmitters to temporarily turn off whenever any active Wifi receiver is detected. From Figure 3.13(d), it is observed that by reducing Bluetooth throughput, we can obtain between 30-100% improvement in total network throughput.

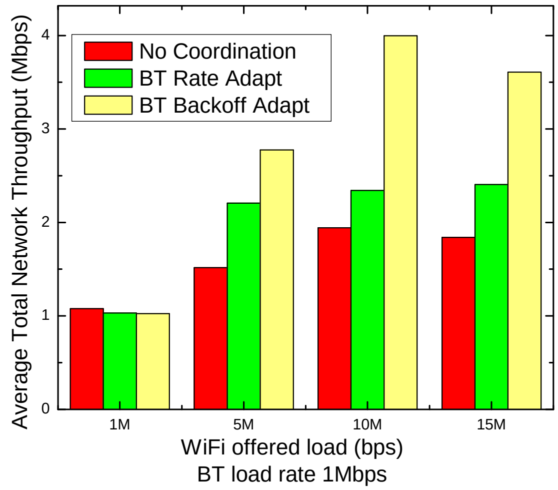
The “BT-Rate” scheme achieves better performance balance for both systems, with a moderate 20% degradation for Bluetooth throughput, while WiFi-g throughput improves up to 50%.



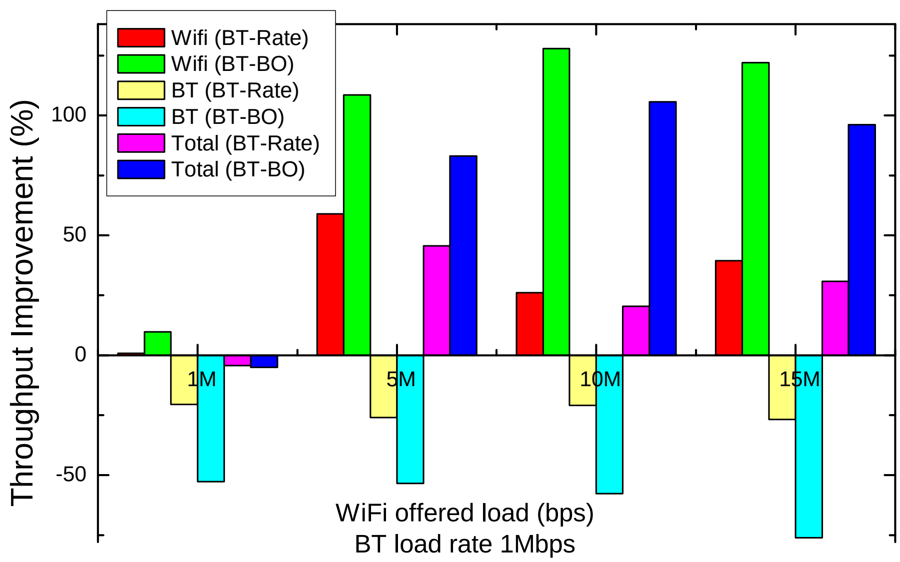
(a)Average WiFi session throughput



(b) Average Bluetooth throughput



(c) Average total network throughput



(d) Throughput improvement for each case

Figure 3.13: Experiment results for network throughput vs. WiFi-g loading rate.

The percentages of system throughput improvement in terms of WiFi throughput, Bluetooth throughput and total network throughput are compared in Figure 3.14 with different numbers of nodes (varying number of links). We can observe that the simple rate algorithms favor WiFi and sacrifice Bluetooth mostly due to the fact that WiFi radios usually carry intermittent traffic type with ON/OFF periods, while we only consider constant streaming type traffic for Bluetooth radios. In experiments with different pairs of communication links, the simple algorithm embedded with the CSCC etiquette protocol can always significantly improve WiFi throughput at a moderate degradation of Bluetooth throughput. The time back-off algorithm shuts off Bluetooth radio periodically, which is greedier favoring WiFi. The rate adaptation algorithm balances the two systems by guaranteeing Bluetooth performance for a certain level and improving WiFi performance by about 60-80%. There is a trade-off between how much WiFi can gain but how much Bluetooth degrades.

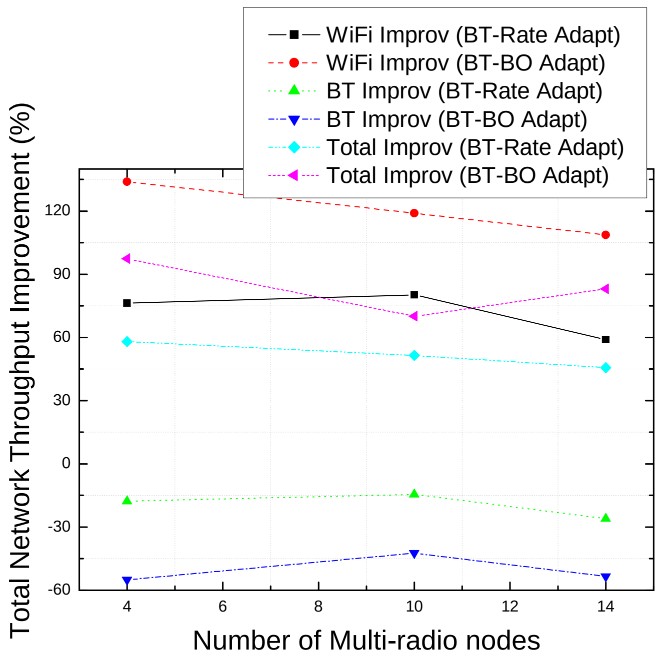


Figure 3.14: Throughput improvement for different pairs of links, WiFi load rate = 5Mbps, Bluetooth load rate = 1Mbps.

3.8 Conclusion

In this section, we have proposed a spectrum etiquette protocol to coordinate heterogeneous or cognitive radio devices sharing the same spectrum bands. The proposed CSCC etiquette protocol provides a simple way for radio devices with different technologies or operating parameters to announce their self states using a common coordination channel the edge of the unlicensed spectrum band. The CSCC message is periodically broadcast during the data session of the users so that resources such as frequency, power and time can be allocated in a fair and spectrally efficient manner. Different etiquette policies are also discussed depending on different network service conditions. Experimental results show that in the 2.4 GHz ISM band, contending 802.11 and Bluetooth devices can achieve improved throughput and delay for both devices using simple priority-based etiquettes. Larger scale experiments using ORBIT testbed are also conducted and results show by adapting Bluetooth service rates, the 802.11g devices can benefit much more and the total network throughput is significantly improved.

Chapter 4 Reactive and Proactive Spectrum Coordination Algorithms

4.1 Introduction

Spectrum coordination approaches discussed in Chapter 2 can be applied to different radio co-existence scenarios. In this chapter, we investigate the feasibility of spectrum co-existence between IEEE 802.11b (Wi-Fi) [12] and 802.16a (Wi-Max) [14][76] networks using both reactive interference avoidance methods and the CSCC etiquette protocol. The CSCC has been proposed as an explicit spectrum etiquette protocol which uses a common edge-of-band control channel for coordination between transceivers using different radio technologies. In Chapter 3, it was shown that a simple CSCC implementation can be used to significantly reduce interference between 802.11bg and Bluetooth devices operating in close proximity. This motivated us to next consider the important emerging scenario in which both wide-area 802.16 and short-range 802.11 radio technologies could co-exist in the same unlicensed band with a small amount of coordination, either explicit or implicit. It is generally accepted that current unlicensed band etiquettes (such as listen-before-talk) are not applicable to the wide-area/short-range hybrid scenario under consideration due to hidden-receiver problems and the need to support stream services such as VoIP or video. As a result, we believe that it is appropriate to consider new "cognitive radio" [3] techniques which allow dynamic sharing of spectral resources between multiple radio devices in the same band.

Co-existence of short-range IEEE 802.11b WLAN and 802.16a WMAN is of great interest, because in future wireless networks, IEEE 802.16a can provide wireless backhaul connectivity to homes and offices, while 802.11b offers complementary local area network capability within a home, office or campus. Since the IEEE 802.16a standard can operate in unlicensed spectrum bands, spectral resources may have to be shared with other wireless systems. Currently there are limited spectrum sharing rules (based on listen-before-talk) in the unlicensed bands but they are considered inadequate for achieving co-existence between higher power services such as 802.16a and lower power ones such as 802.11b. Therefore a cognitive radio scenario with “smart” transceivers which scan the spectrum and try to avoid interference is of particular interest. Many characteristics of 802.11b and 802.16a allow easy adaptation for spectrum sharing, e.g., both systems consume limited bandwidth; their signals have simple spectral density shape (DSSS and OFDM); and multiple modulation levels with different bit rates are supported.

Reactive cognitive radio techniques are based on channel sensing and distributed adaptation of transmit parameters such as frequency, power, bit-rate and time occupancy. Reactive adjustment of PHY parameters is based only on local observations, which may sometimes be insufficient such as in scenarios where there are “hidden nodes”. The hidden node problem occurs when a receiver is located in between two potential transmitters which cannot sense each other’s presence and hence may cause unintended interference at the receiver. The CSCC protocol coordinates radio nodes in a proactive way, where a common spectrum coordination channel at the edge of available spectrum bands is allocated for announcement of radio parameters such as frequency, power, modulation, duration, interference margin, service type, etc. The hidden node problem mentioned above can also be solved because the range of CSCC control can be designed to exceed that of regular service data, and receivers can also explicitly announce their presence to further optimize spectrum use. The overall goal of this work is to systematically evaluate the incremental benefit of each increase in spectrum coordination complexity, aiming for results that will assist in making design trade-offs between performance and cost.

The specific problem studied in this chapter is that of evaluating both reactive and proactive etiquette policies for co-existence between Wi-Fi and Wi-Max networks sharing the 2.4GHz ISM band. Both simple scenarios with one 802.16a cell and one 802.11b hotspot and more realistic scenarios with multiple hotspots are simulated using an *ns-2* system model. Variations of node geographic distribution (clustered vs. uniform) are studied. The density of radio nodes in the coverage region and their degree of spatial clustering are key parameters in the system evaluation.

Clustering regimes where CSCC can significantly improve the network throughput by solving the hidden-receiver problem are identified.

4.2 Reactive Spectrum Coordination Techniques

Three basic reactive coordination methods will be studied, namely Dynamic Frequency Selection (DFS), which utilizes agility in operating frequency; Reactive Transmit Power Control (RTPC), which adjusts transmit power based on observed interference; and Time Agility (TA), which re-schedules transmissions to avoid interference based on traffic patterns in time.

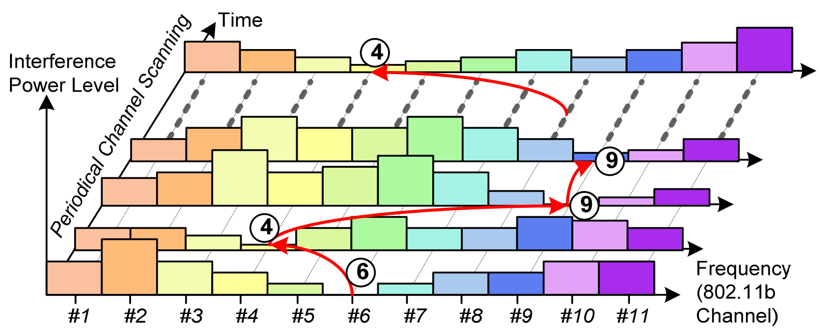


Figure 4.1: An example of the Dynamic Frequency Selection algorithm.

4.2.1 Dynamic Frequency Selection (DFS)

In the DFS scheme, radio nodes periodically scan the operating spectrum bands and measure interference power level in each available channel. When radio nodes have data to transfer, they choose the channel with the least interference power. The concept is illustrated in Figure 4.1, in which each node keeps a record of the interference power level of each channel and selects a sequence of channel #6, #9, #9, …, #4, etc for communication. The updating interval can be determined by the statistics of the traffic, e.g., randomly chosen in the order of a short 802.11 data session (~100ms for about 50 packets with size of 512 Bytes at 2Mbps bit-rate). Note that too frequent channel switching may cause packet loss due to link-level interruptions. On the other hand, infrequent switching may result in a slow response to channel condition changes. To prevent unnecessary channel switching, a new channel is used only if interference power of a clearer channel is at least 10% less than current interference level.

However, this scheme requires each node to stay in a default channel when it is idle, where sender and receiver can switch to other channels for data transmission. In Figure 2.6, node pair AB and CD can choose different frequencies for their OFDM carriers to avoid interference. The drawbacks of this scheme are also obvious: there may be chances that the link is broken due to unsynchronized channel switching; and the hidden node problem where a transmitter may choose a channel which potentially interferes with a receiver nearby due to the inability of detecting such a hidden node. For example, when node B is receiving from A, it may suffer from interference from C because node C can not sense the existence of node B only by comparing signal strengths and scanning over each channels.

4.2.2 Reactive Transmit Power Control (RTPC)

It is important for radio nodes to not only exploit available resources, but also at the same time emit the least interference to others. The RTPC algorithm achieves this by allowing transmitters to use the minimum transmit power possible for data transfer. Since interference is a receiver property, in the RTPC scheme, each receiver will estimate the minimum transmit power to maintain adequate link quality, based on its own QoS requirements and path loss estimates. This recommended transmit power level is fed back to transmitters by utilizing MAC packet headers (e.g., ACK header). As illustrated in Figure 4.2, the receiver can sense interference power changes PI_e since the last measurement, and the received power of current received packet P_{rx}. By knowing the target received power P_{target}, determined by the QoS requirement of the receiver (e.g., a level of bit error rate less than 10^{-6}), it then can calculate the recommended next transmit power using equation (4.1). Transmit power is updated on a packet-by-packet basis and $P_{tx}(n)$ for the *n*th packet is calculated by

$$P_{tx}(n) = P_{tx}(n-1) + (\gamma_{target} + RSSI(n-1) - P_{rx}(n-1)) + (RSSI(n) - RSSI(n-1))$$
$$= P_{tx}(n-1) - P_{rx}(n-1) + \gamma_{target} + RSSI(n) \quad (4.1)$$

where γ_{target} is the expected target SINR (all terms measured in dB or dBm), and $P_{target} = \gamma_{target} + RSSI$ is the target received power, $PI_e = RSSI(n) - RSSI(n-1)$ is the sensed interference power change between the *n*th and (*n-1*)th transmission. The new transmit power can also be understood by adding the estimated path loss to the target received power. Here the *RSSI* is a value reported by the wireless driver of current experienced total noise plus interference power. In Figure 4.2, the "TX Power Adjustment" block is controlled by energy constraints, which may contribute a term to control transmit power and this is not considered in current study.

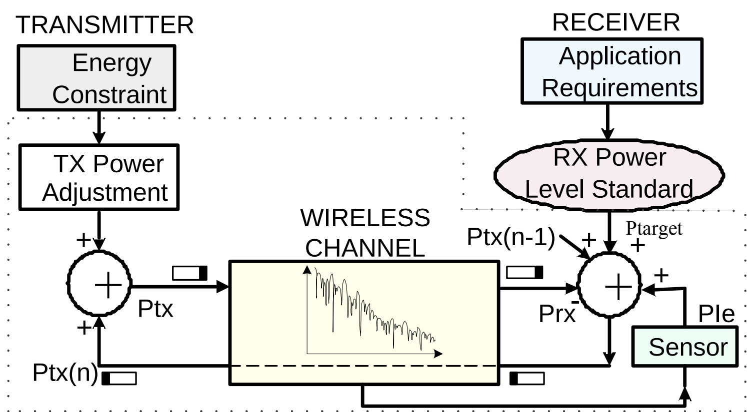


Figure 4.2: Reactive transmit power control algorithm.

For implementation, the power value (in dBm) can be quantized to 256 levels stored in an 8-bit field in the MAC header, which is piggybacked between the transmitter and receiver. In case of piggyback packet loss, a power roll-back mechanism is used to avoid deadlock situations by increasing the (recommended) transmit power by a certain amount (e.g., 20% of current power level) each time a packet is lost until reaching the maximum value.

However, nodes using this scheme may be interfered by uncoordinated transmitters because the packet reception is more vulnerable to interference due to reduced signal strength. This is mostly due to the fact that this scheme reactively control the transmit power from coarse receiver feedback, which is only based on heuristics but does not quantitatively indicate what's happening at the nodes' neighbors. Thus hidden node problem still exists in this case when there are uncoordinated receivers in a transmitter's minimum coverage area, which will be explained in details in section 4.3.

4.2.3 Time Agility (TA)

Reactive interference avoidance can also be realized by controlling transmit probability or re-scheduling MAC packet transmissions in an interference-varying environment. The Time Agility algorithm explores gaps in the time dimension by avoiding transmissions (and thus potential re-transmissions) when channel conditions are bad (i.e., interference level is high) and encouraging transmissions when channel condition is good. This is realized by changing transmitters' transmit probability $Prob_{tx}$ as a function of the interference power and SINR at the preferred receiver. This algorithm implicitly allows nodes to adapt to each other's traffic pattern by listening on the channel and controlling $Prob_{tx}$. An example of the algorithm is shown in Figure 4.3 where $P_{interference}$ is the interference power. Note that the communication threshold is assumed to be at BER ≈ 10^{-6} or SINR ≈ 12dB with QPSK modulation.

If *SINR>>12dB* ***then*** $Prob_{tx} = 1$
If *SINR>≈12dB* ***then*** $Prob_{tx} \sim 1/P_{interference}$
If *SINR<12dB* ***then*** $Prob_{tx} \sim SINR/max\{SINR\}$

Figure 4.3: Time agility algorithm.

Similar to the RTPC scheme, the receiver listens on the channel and updates the recommended transmit probability $Prob_{tx}$ which is quantized to 8 bits and piggybacked in MAC headers. For the algorithm shown in Figure 4.3, a SINR near to the threshold (12dB) means that the channel condition is still good but there may be potential close interferers around. In order to avoid interfering more severely with the potential interferers, the transmit probability is proportional to the inverse of sensed interference power. When the SINR level is less than the threshold, the node can infer that either the signal strength is too weak, or that the interference power is too strong, or both. Thus it is preferable to control the transmit probability to be proportional to the current SINR value (in dB) to avoid re-transmissions and mutual interference.

Note that in terms of traffic engineering, when the traffic pattern is easy to learn (e.g. Pareto ON/OFF traffic model [79] with relatively long OFF periods), such a time agility algorithm can help radios to adapt to each other's traffic pattern and effectively utilize the available degree of "freedom" in time. $Prob_{tx}$ is increased when the interferer's traffic load is low (or off), and decreased when the interferer's traffic load is high. This algorithm is traffic-type-independent, and the difference is in the degree of difficulty in adapting to the specific traffic patterns on the channel. For example, it is easier to adapt to Pareto ON/OFF traffic than CBR traffic with the same load, due to the extended OFF period.

However, reactive controls of radio parameters at transmitters are mostly based on local channel scanning, interference sensing and power estimation, thus they also suffer from "hidden node" problems as discussed in Chapter 2, due to the lack of information at receivers who suffer from interference. Transmission parameter adjustment is a reaction of experienced interference changes, which may lead to stability problems. For example, nodes may uncoordinatedly vacant from a congested channel to another same channel which results in congestion in the new channel; increasing transmit power (or transmit opportunities) unilaterally may also deteriorate the interference problems; reactive transmission time control is also based on local interference power sensing and heuristics of channel congestion condition which do not reflect the global interference scenario. These kinds of adaptation are based on local channel observation, thus there may be oscillations when nodes control their transmission behaviors based on locally sensing signal strength and interference. Therefore, explicit (or proactive) spectrum coordination protocols are needed which will be discussed in the next section.

4.3 Proactive Spectrum Etiquette Protocols

4.3.1 CSCC Etiquette Protocol – A General Case

The basic CSCC concept was discussed earlier in Chapter 3. In a more general case, radio nodes can proactively announce their existence and coordinate with each other by executing coordination algorithms. Information in the CSCC message, such as node ID, center frequency, bandwidth, transmit power, data rate, modulation type, data burst duration, interference margin (IM), service type, etc., is used by neighboring nodes to coordinate and share the spectrum in an efficient way. Note that the CSCC protocol mechanism is independent of the spectrum coordination policy itself, which can be implemented to reflect regional or application-specific requirements. This is explained further in Figure 3.3 which shows that a separate CSCC control stack consisting of CSCC PHY and MAC operate in parallel with the data service. The spectrum etiquette module runs on top of the CSCC protocol stack and can be specified in a completely general way as long as necessary parameters are carried by the CSCC packet. Since interference needs to be considered at receivers rather than transmitters, CSCC announcements may be made by receivers involved in active data sessions by one-hop broadcast, and contention can be resolved by periodic repetition with some randomization of transmit time to avoid multiple collisions.

When a node receives a CSCC message, it will know that there is a data session going on between neighboring nodes at a specified frequency slot for some duration. Then, a coordination procedure is initiated either by switching to other bands with lower interference or by limiting transmit power to avoid interference with existing radio links following specified coordination policies.

The explicit coordination by CSCC protocol can help to solve the hidden-node problem, as illustrated in Figure 4.4. R_{cscc} is the coverage range of control radio which is generally ~1-2x the minimum service data radio range. When TX2 initiates a data session to RX2, it first notifies RX2 of the transmit power and the estimated data burst duration T2 by broadcasting a message in the control channel. Then RX2 claims the current spectrum, i.e., *Band#2*, for the duration of T2 by broadcast a CSCC message in the control channel. When TX1 receives the CSCC message from RX2, it will know the spectrum *Band#2* is taken by RX2 and TX1 will either switch to other available bands or coordinate with RX2 at *Band#2* by reducing its transmit power, i.e., coverage range from R1 to R1'.

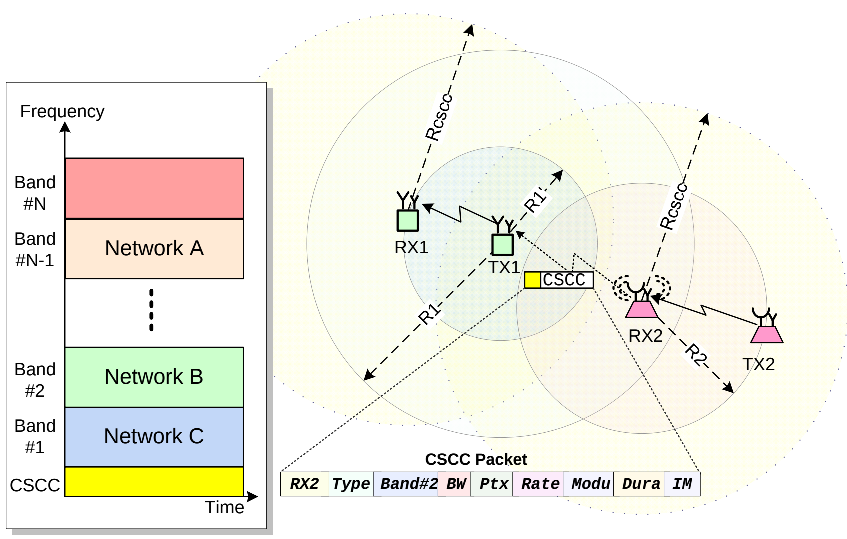


Figure 4.4: Illustration of the CSCC protocol and how it helps to solve the hidden-node problem.

Without explicit coordination from the CSCC protocol (or some other similar mechanism), node RX2 would become "hidden" to the interference from TX1. Similar to the well-known hidden terminal problem in IEEE 802.11 networks [74], the hidden-node problem exists in networks with heterogeneous radios. Initially TX1 covers a range of R1, and RX2 covers a range of R2. There is no way for TX1 to notice the existence of RX2 only by reactive scanning or sensing, especially when R2<R1, and therefore the transmission of TX1 will interfere with RX2 if they share the spectrum. Note TX1/RX1 and TX2/RX2 use different radio technologies for data communication and thus they require a common spectrum coordination channel as in the CSCC method proposed here. TX1 then receives CSCC messages from RX2 which is no longer

“hidden” to TX1, and TX1 can switch to a different frequency or reduce its power to avoid interference.

4.3.2 Proactive Spectrum Coordination Algorithms

Spectrum coordination policies refer to specific algorithmic procedures used for adaptation of frequency or power based on the in-band interference power. Alternative coordination policies will also be discussed.

4.3.2.1 Coordination by Adaptation in Frequency

Radio nodes can change operating frequencies to avoid interference by the CSCC protocol. Following the example of Figure 4.4, when TX1 and RX1 have on-going data communication, RX1 broadcasts a CSCC message in the CSCC channel stating it will take *Band#2* for some duration, as shown in Figure 4.5. After a while, TX2 notifies RX2 that it has data to send, and then RX2 broadcasts a CSCC message stating it wishes to use *Band#2* for data transfer. In the event that RX2 has a higher priority, it will take over *Band#2* and starts communication, while TX1 is forced to change its data channel to a clear channel, e.g., *Band#1* and notifies RX1 by either broadcasting a CSCC message or piggybacking in the data packet. Then RX1 will broadcast a CSCC message to claim *Band#1*.

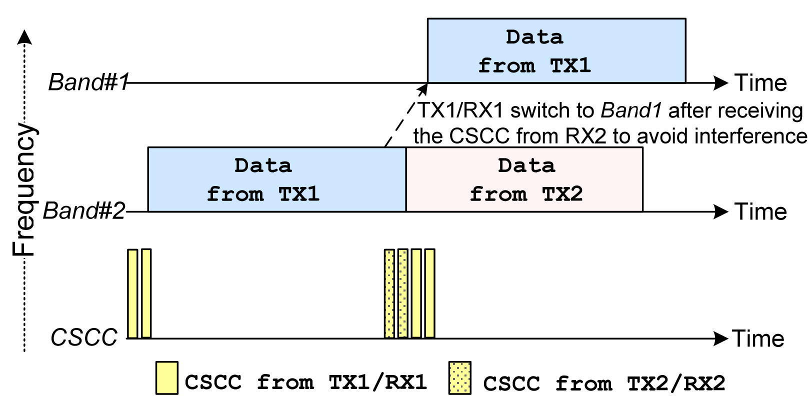


Figure 4.5: Coordination by adaptation in frequency.

4.3.2.2 Coordination by Adaptation in Power

When the spectral band is heavily loaded and frequency selection alone cannot be used to avoid interference between simultaneous users, adaptation of transmit power is an efficient way to reduce interference. By listening to CSCC messages, radio nodes can determine appropriate transmit power levels required to reduce interference in a specific frequency band. In this case the CSCC message carries a field called the receiver's interference margin (IM). The IM is defined as the maximum interference power a receiver (the one broadcasting the CSCC message) can tolerate without disturbing its on-going data communication. When the IM value is changed, it will be updated to neighboring nodes by CSCC messages.

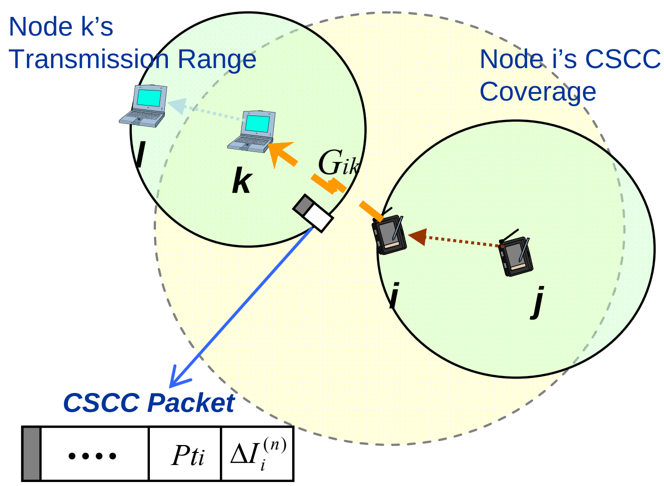


Figure 4.6: Power adaptation algorithms using the CSCC protocol.

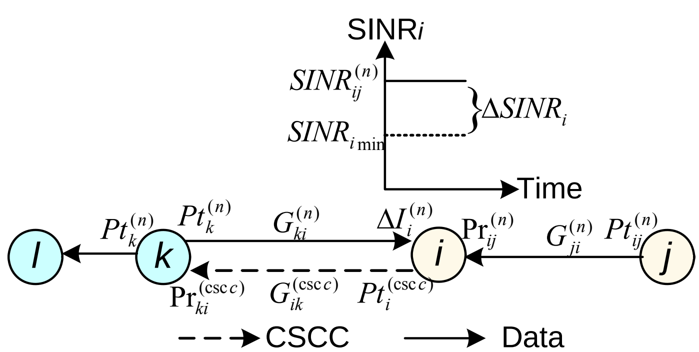


Figure 4.7: Coordination by adaptation in power.

The power adaptation algorithm is illustrated in Figure 4.6 and Figure 4.7. Assume at the data channel #*n*, the received power at node *i* from node *j* is $\Pr_{ij}^{(n)}$ and its current signal to interference and noise radio (SINR) is $SINR_{ij}^{(n)}$, the interference margin can be calculated by

$$\Delta I_i^{(n)} = (\frac{1}{SINR_{i\min}} - \frac{1}{SINR_{ij}^{(n)}}) \cdot \Pr_{ij}^{(n)} \tag{4.2}$$

where $SINR_{i\min}$ is the minimum SINR required to maintain the on-going communication at node *i*, e.g., maintain a minimum bit error rate of 10^{-6} for TCP traffic. Node *i* will broadcast a CSCC message with power $Pt_i^{(cscc)}$ at the CSCC channel. The IM $\Delta I_i^{(n)}$ and $Pt_i^{(cscc)}$ are both contained in the CSCC message. Assume that node k receives the CSCC message at the control channel, and the path loss gain of the control channel from node *i* to node k is $G_{ik}^{(cscc)}$. Then we have $Pt_i^{(cscc)} G_{ik}^{(cscc)} = \Pr_{ki}^{(cscc)}$, and $\Pr_{ki}^{(cscc)}$ can be reported by the PHY of node *k*. Assume the CSCC channel is symmetric, so $G_{ki}^{(cscc)} = G_{ik}^{(cscc)} = \Pr_{ki}^{(cscc)} / Pt_i^{(cscc)}$. Since the control channel is usually close to the data channel in frequency, the path loss gain at the CSCC channel is a good estimation of that at the data channels, i.e., $G_{ki}^{(n)} = G_{ik}^{(n)} \approx G_{ik}^{(cscc)}$. The maximum transmit power of node *k* at data channel #*n* then is bounded by the constraint in order not to disturb the signals received at node *i*:

$$Pt_k^{(n)} G_{ki}^{(n)} \le \Delta I_i^{(n)} \tag{4.3}$$

$$Pt_k^{(n)} \le \frac{\Delta I_i^{(n)}}{G_{ki}^{(n)}} \approx \frac{\Delta I_i^{(n)} Pt_i^{(cscc)}}{\Pr_{ki}^{(cscc)}} \tag{4.4}$$

If $Pt_k^{(n)}$ is too small for node *k* to reach its receiver, say node *l*, it should either switch channels seeking a band with less interference (i.e., more IM available), or just keep silent by backing off its transmissions following a defined back-off policy. In the example of Figure 4.4, TX1 can calculate its maximum transmit power at *Band#2* by equation (4.4) and reduce its transmission range from R1 to R1’, keeping the interference power experienced at RX2 less than its IM.

4.3.2.3 Spectrum Etiquette Policies

A wide variety of spectrum etiquette policies can be applied within the CSCC protocol framework. The policies define rules that radio nodes must follow when they are competing for spectrum resources. A simple access rule is First-Come-First-Served (FCFS), which means the first one coming into a channel will claim the spectrum for some duration by CSCC protocol. Another approach is priority-based, where nodes have different pre-assigned priorities based on their carried traffic type, and high priority nodes will take precedence over low priority ones when there is contention for the same piece of spectrum. A dynamic pricing auction policy [75] in which users bid on available spectrum is another choice. Radio nodes can offer their prices for using the spectrum and the allocation can be done in a distributed way by CSCC protocol to maximize the system revenue. We have applied the priority-based spectrum etiquette to the co-existence of WiFi and Bluetooth in Chapter 3. Here for the study of WiFi and WiMax co-exsitence, we use the FCFS etiquette.

4.4 Co-existence of IEEE 802.11b and 802.16a

A co-existing system with IEEE 802.11b hotspots and 802.16a cells in the same shared spectrum is considered to evaluate the effectiveness of proposed reactive and proactive spectrum coordination policies.

4.4.1 System Framework

An example of the co-existence network is shown in Figure 2.4, which consists of IEEE 802.11b hotspots, with one Access Point (AP) and multiple clients in each hotspot, and 802.16a cells, with one Base Station (BS) and multiple Subscriber Stations (SS) per cell. WiFi hotspots can cover a range of ~500 meters as wireless local area networks and WiMax cells cover a longer range of ~3km as wireless metropolitan area networks. Both systems are deployed in one geographic area and 802.11b hotspots are inside 802.16a cells. This is a typical cognitive radio scenario where 802.16a SS may be clustered with 802.11b hotspots and they overlap in space. We assume that both systems share a current or future unlicensed, or “cognitive radio” band, and will need to co-exist by coordinating with each other.

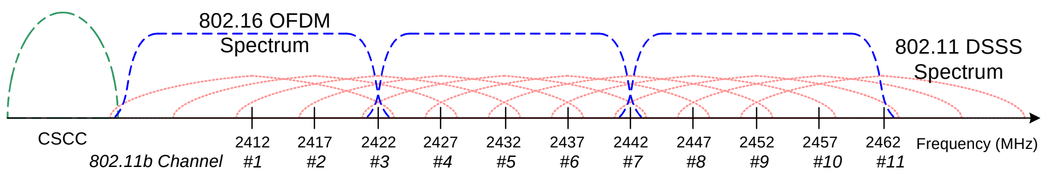


Figure 4.8: Channel allocation for IEEE 802.11b and 802.16a

Figure 4.8 shows a sketch of the channel allocation for the two systems. WiFi radio uses DSSS with 22MHz bandwidth, and there are 11 overlapping channels with center frequencies from 2412MHz to 2462MHz. OFDM is used in WiMax radios with 20MHz bandwidth, and in this study we assume there are three non-overlapping channels centered at 2412, 2432 and 2452MHz. To simplify the simulation, bandwidth and rate are fixed for both systems, and QPSK modulation is used with 2Mbps data rate for 802.11b and 14Mbps for 802.16a radios. We also assume that the CSCC channel is allocated at the left edge of the whole spectrum and is orthogonal to other data channels.

In order to capture the interference effects between the two systems, a physical-layer interference model is constructed to calculate the SINR at a receiver. Packet reception is based on simulated packet error rate (PER), which is calculated from bit error rate (BER) knowing the packet length in bits. The BER is obtained from the modulation performance curve [78] by knowledge of SINR. Assume at data channel #*n*, node *i* transmits to node *j* with transmit power $Pt_{ij}^{(n)}$, the path loss gain between them is $G_{ij}^{(n)}$, and the in-band background noise observed at node *j* is $N_j^{(n)}$, then the SINR at the receiver *j* can be expressed as:

$$SINR_j^{(n)} = \frac{Pt_{ij}^{(n)} G_{ij}^{(n)}}{N_j^{(n)} + \sum_{l \neq i} \alpha_{lj}^{(n)} Pt_l G_{lj}^{(n)}} \tag{4.5}$$

where $0 \leq \alpha_{lj}^{(n)} \leq 1$ is the spectrum overlapping ratio of node l and j at channel #n. The interference powers (in watts) from all transmitted signals (DSSS and/or OFDM) are summed over overlapped regions (in frequency). Here we assume the transmissions of nodes other than node i are additive interference.

4.4.2 Implementation in *ns-2*

Both reactive (DFS, RTPC and TA) and proactive spectrum coordination algorithms are implemented in Network Simulator version 2.27 (*ns-2*) [12]. For DFS, ideal channel switching is assumed for 802.11b hotpots, i.e., the AP in the hotspot selects new channels and all clients in the hotspot will be notified by a broadcast message and immediately switch to the same new channel which AP selected. The penalty of switching channels is the loss of the current packet if any, and we assume every node can successfully switch to the new channel. The typical frequency scanning interval is assumed to be uniformly distributed between 100ms and 200ms, which is the same order of magnitude as the transmission time for a short data session (~50 packets with size of 512 bytes at 2Mbps).

For RTPC, when a MAC packet is initiated at the sender, the current transmit power level (quantized to an 8-bit integer number between 0 and 255) is placed into 802.11b RTS or 802.16a frame header. The receiver then can obtain the received power of this packet and the sender's transmit power from the header. We will use a constant target SINR of 12dB, which approximately corresponds to a BER of 10^{-6} when using QPSK modulation. Then the receiver can compute the recommended transmit power from equation (1) and piggyback in the MAC header to the sender. Maximum transmit power is used for 802.11 RTS/CTS due to their short length and RTPC is applied to both 802.16a BS and SS (both downlink and uplink). The TA algorithm is implemented similar to RTPC. Receivers calculate the recommended transmission probabilities by Figure 4.3, which are then piggybacked in MAC headers to the transmitters. In cases of packet loss, transmitters will transmit with probability 1 if there is data to send.

Bit 1	8	16	24	32
Source ID				
Destination ID				
Data Burst Session Duration				
NodeType	Priority	BandWidth	Modulation	
Center Frequency				
CSCC Message Transmit Power				
Interference Margin at Data Band				

Figure 4.9: CSCC packet format for WiFi/WiMax co-existence.

The CSCC etiquette protocol is implemented with a dual radio structure in each node. The spectrum coordination agent is between network and MAC layers, which monitors both data radio (IEEE 802.11b or 802.16a) and control radio (1Mbps 802.11-type). The control radio is fixed at the CSCC channel. The packet format for CSCC messages is shown in Figure 4.9. A Pareto ON/OFF traffic model [79] is used to simulate Internet traffic, and a CSCC message is broadcast per data burst session (Pareto ON session). Only best-effort traffic with UDP packets is considered here. The estimated burst duration in milliseconds is included in the CSCC message. A FCFS-based policy is used when there are contentions, i.e., the first node claiming the spectrum will take it and subsequent transmissions from other nodes must coordinate with the first one by switching channels or bounding their transmit powers satisfying the interference margin of the first node.

4.5 Simulations

Scenarios with single or multiple 802.11b hotspots are simulated and various 802.16a SS node geographic distributions are also studied. DFS, RTPC, TA and the CSCC protocol are evaluated and compared in the scenarios considered.

4.5.1 Simulation Parameters

The parameters used in the simulations are summarized in Table 4.1. The interference model of equation (4.5) is implemented in *ns-2*. For each transmission event, every node will update the impact of that transmission by calculating a new sum of interference power and signal to interference and noise ratio if a packet is being received. The transmission in the case may from either WiFi transmitters or WiMax transmitters. If the interference is from a heterogeneous radio type, the overlapped portion of their spectrum is considered with updating the interference power. In this study, we assume the CSCC control radio uses a constant power and its coverage area is constant.

Table 4.1: Simulation parameters for WiFi/WiMax co-existence.

	IEEE 802.16a	IEEE 802.11b
MAC protocol	TDMA	IEEE 802.11b BSS mode
Channel Model	AWGN, two ray ground propagation model	
Bandwidth/ channels	20 MHz / 3 non-overlapping channels	22MHz / 11 overlapping channels
Raw Bit Rate	14Mbps	2Mbps
Radio parameters	OFDM (256-FFT, QPSK)	DSSS (QPSK)
Background Noise Density	-174 dBm/Hz	
Receiver Noise Figure	9 dB	9 dB
Receiver Sensitivity	-80dBm (@BER 10^{-6}, 14Mbps)	-82dBm (@BER 10^{-5}, 2Mbps)*
Antenna Height	BS 15m, SS 1.5m	All 1.5m
CSCC Coverage	600 meters	
Maximum Coverage	~3Km (@BS 33dBm)	~500m (@20dBm)
Transmitter Power Range	BS 0-33dBm, SS 0-23dBm	0-20dBm

**From CNWLC-811 Wireless 802.11b PC Card specification.*

4.5.2 Simulation Results - Single 802.16a Cell and Single 802.11b Hotspot Case

Each coordination algorithm is first evaluated in a simple network scenario with one 802.16a cell (one BS and one SS) and one 802.11b hotspot (1 AP in the center and 1-4 clients A, B, C and D placed 100m away from the AP), as shown in Figure 4.10. $D_{BS\text{-}AP}$ is the distance between 802.16a BS and 802.11b AP and $D_{SS\text{-}AP}$ is the distance between 802.16a SS and 802.11b AP.

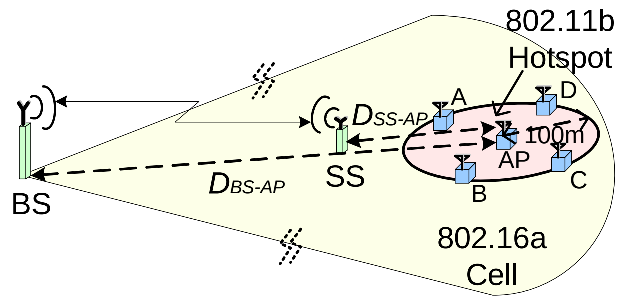
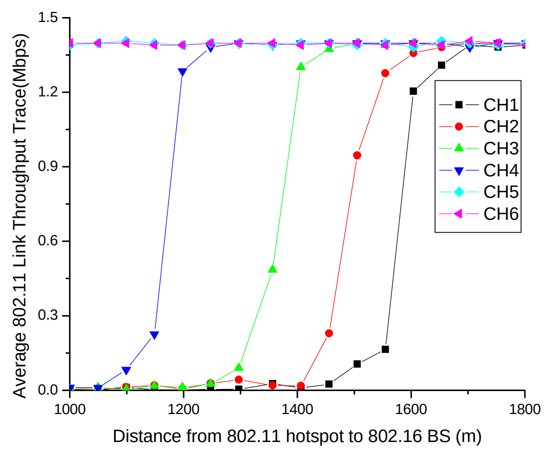
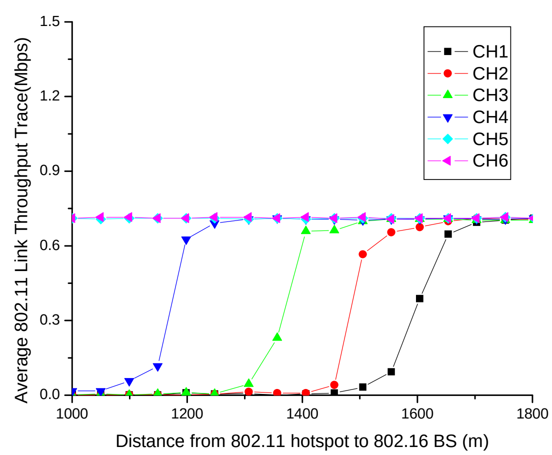


Figure 4.10: Network scenario for single cell case.



(a) With one 802.11b traffic flow



(b) With two 802.11b traffic flows

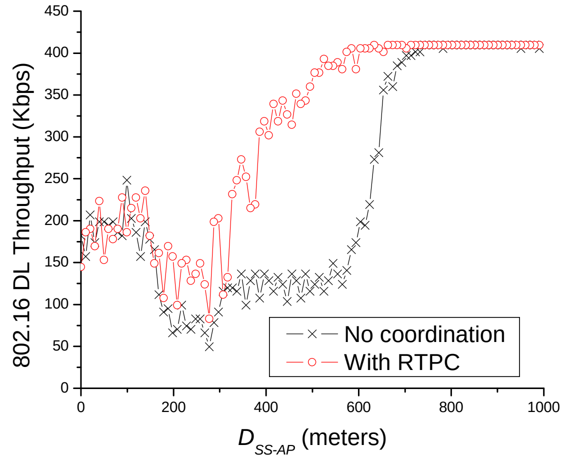
Figure 4.11: Average 802.11b throughput vs. $D_{BS\text{-}AP}$ at different channels, when both systems have overloaded CBR traffic.

4.5.2.1 Effect of DFS for Spectrum Overlapping

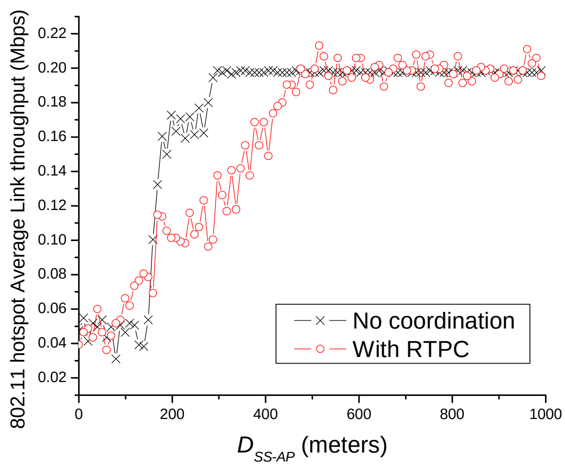
In this simulation, we assume the center frequency of 802.16a cell is fixed at 2412MHz, which overlaps the most with 802.11b channel #*1*, partially overlaps with 802.11b channel #*2*, #*3*, or #*4*, and does not overlap beyond channel #*5*. DFS enables 802.11b devices to avoid interference by switching their operating channels dynamically. Figure 4.11 shows the benefit of switching to different channels. We define the interference radius (IR) as the distance between two systems when their throughputs begin to degrade due to interference. When both 802.16a DL and 802.11 links are overloaded with CBR traffic (the most severely interfering case), IR will be 1.7km if 802.11b is at channel #*1*, but IR can be reduced to 1.6km, 1.4km and 1.2km by switching 802.11b channel to #*2*, #*3* or #*4* respectively. By operating at channel #*5* or beyond, there will be no interference between the two systems (IR is zero). Similar results are observed with two 802.11b traffic flows (in Figure 4.11b).

4.5.2.2 Effect of RTPC

The same scenario shown in Figure 4.10 is used and $D_{BS\text{-}AP}$ is fixed at 3km. RTPC is applied to both 802.11b links and 802.16a uplink and $D_{SS\text{-}AP}$ is varied (the closer the 802.16a SS to 802.11b hotspot, the stronger the interference). Note that since the interference from 802.16a BS is fixed, RTPC is not applied to the 802.16a downlink here. Figure 4.12 shows the benefit by applying RTPC: the 802.16a SS throughput can increase up to 4 times at the expense of slight degradation in 802.11b throughput. When the SS node is close to the hotspot (strong interference), 802.11b node tends to more back-offs which will benefit 802.16a SS (throughput increase when $D_{SS\text{-}AP}$ is small) by less interference. In this case, DFS will have more benefit when there is no more degree of “freedom” to explore in the dimension of power.



(a) 802.16a DL throughput



(b) 802.11b hotspot throughput

Figure 4.12: Average link throughput trace, 4 links for hotspot, each has Poisson arrival rate with inter-arrival mean time 3ms.

4.5.2.3 Effect of Time Agility

The TA algorithm is implemented for both systems to fill available gaps and avoid busy period in time domain by setting transmit probabilities to transmitters. Pareto ON/OFF traffic [79] is used for 802.16a links and the duty cycle (ON to OFF ratio) is kept constant at 1:1. 802.11b nodes (using CBR traffic) will try to adapt to the 802.16a traffic pattern by decreasing transmit probability when 802.16a traffic is ON and increasing it when 802.16a traffic is OFF by measuring SINR levels. Figure 4.13 shows that the TA algorithm can help to improve the hotspot link throughput by up to 30% when the interferer traffic ON time is of the order of one second. Although the simple time agility only performs well under limited circumstances, this experiment serves as an example of the spectral "freedom" usage pattern dependence of coordination algorithms.

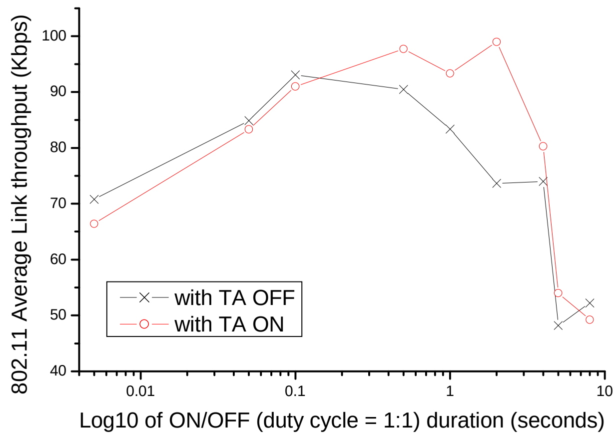
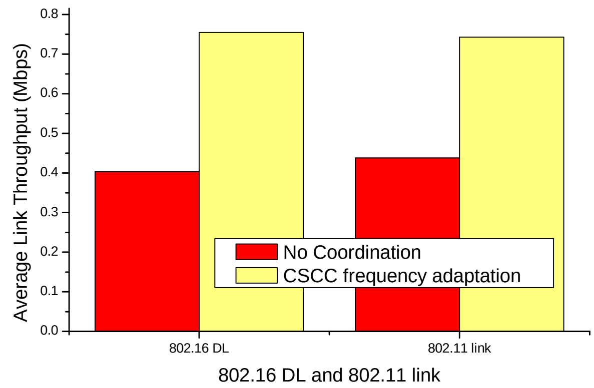


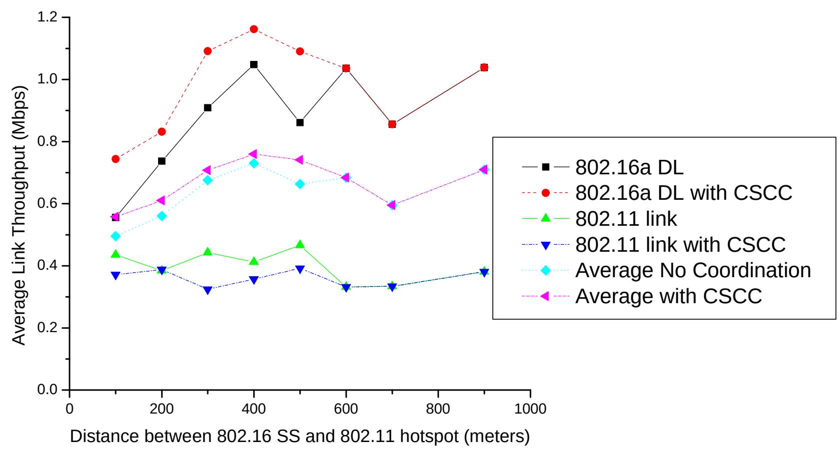
Figure 4.13: Time agility by varying 802.16a Pareto traffic ON time, 802.11b nodes use CBR traffic with load 200Kbps, and 802.16a node load is 1.3Mbps.

4.5.2.4 Evaluation of the CSCC approach

The network scenario is the same as Figure 4.10, which is a typical hidden-node scenario. In the hotspot, traffic goes from AP to node A, and for 802.16a, only downlink (DL) traffic is considered so that the 802.16a SS becomes "hidden" to 802.11b interferers. All nodes are static and $D_{BS\text{-}AP}$ is 1km. The WiMax subscriber station (downlink) will be interfered by the WiFi hotspot due to their close proximity. If there is uplink traffic from the subscriber station, the WiFi client nodes will also suffer from the interference of the subscriber station. We will study both the CSCC frequency adaptation and power adaption algorithms.



(a) CSCC frequency adaptation when $D_{SS\text{-}AP}$=200m



(b) Results for power adaptation

Figure 4.14: Network throughput by using CSCC frequency or power adaptation when both systems have Pareto traffic with ON/OFF time = 500ms/500ms and traffic load 2Mbps.

The throughputs for both systems are plotted in Figure 4.14. By applying CSCC frequency adaptation (Figure 4.14a), both 802.16a DL and 802.11b throughput can almost be doubled since in this scenario there is enough vacant spectrum to use with CSCC coordination. To evaluate CSCC-based power adaptation algorithm in the highest interference case, we consider both systems' center frequencies fixed at 2412MHz (they overlap mostly in frequency as shown in Figure 4.8). Figure 4.14b shows 802.l6a DL throughput is improved by ~35% which varies by $D_{SS\text{-}AP}$. Since the 802.16a BS is 1km away (out of CSCC range), 802.11b hotspot throughput is slightly degraded, but the average network throughput for both systems is still improved by about

5% to 15%. When the 802.16a SS is out of the hotspot CSCC range, the link throughput is the same for the case with or without CSCC, as might be expected. Since the BS is always out of the hotspot CSCC range, we would expect greater improvement for 802.11b throughput in cases with shorter links.

4.5.3 Simulation Results - Multiple 802.11b Hotspots and 802.16a SS Case

We consider a network with four 802.11b hotspots (with 4 clients and 1 AP per hotspot) placed in one 802.16a cell with coordinates (1km, 0), (0, 1km), (-1km, 0) and (0, -1km) relative to the BS at (0, 0), illustrated in Figure 4.15. 802.11b nodes are randomly placed inside the hotspot with the distance to AP less than R_{max11} meters. Various geographic distributions of 802.16a SS were studied: (i), randomly (uniformly) distributed inside the 802.16a cell with radius 1.5km; (ii), clustered around each hotspot with the distance to each AP less than R_c. The "clustering index" C_i is defined as the ratio of R_{max11} and R_c, which is between 0 and 1, and obviously the larger the clustering index, the more closely the cluster couples spatially with hotspots (and thus the higher the interference between the two systems). The total number of 802.16a SS is kept the same as the total number of 802.11b clients in the network.

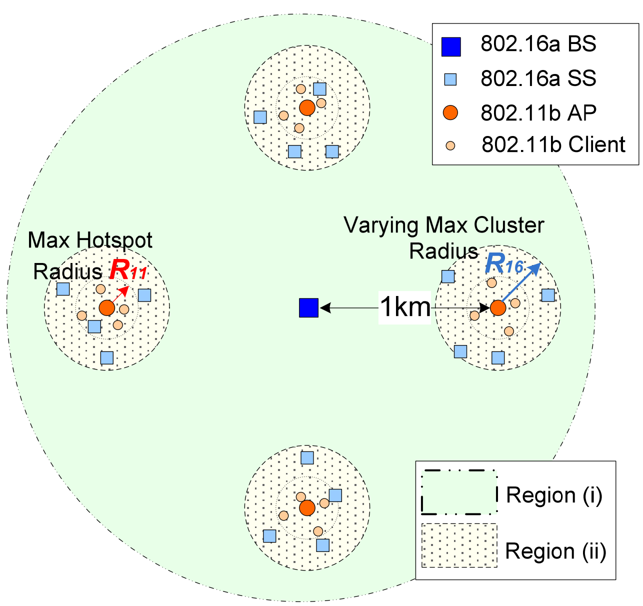


Figure 4.15: Uniform and clustering-distributed 802.16a SS.

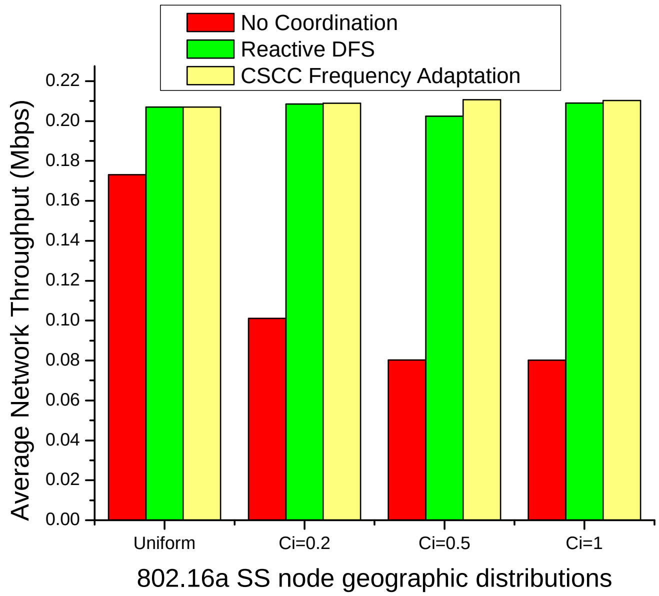
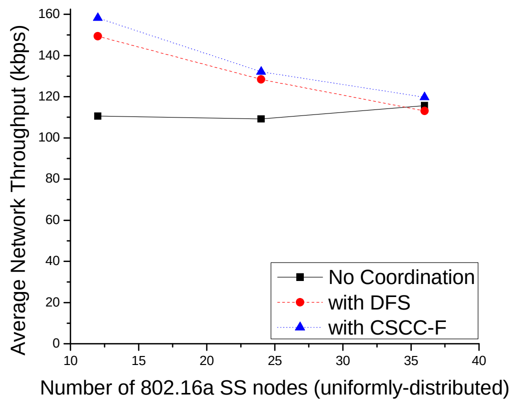
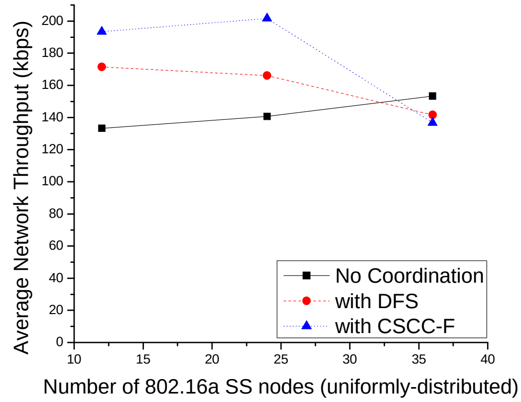


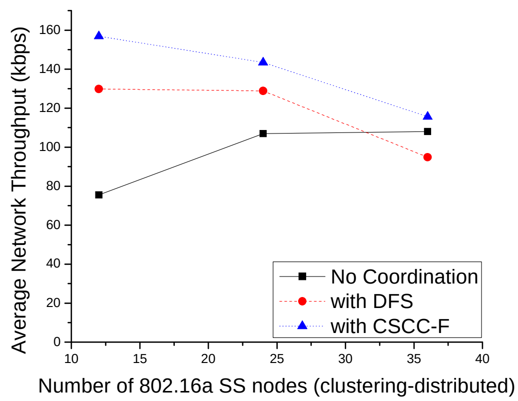
Figure 4.16: Throughput comparison for (i) uniformly and (ii) clustering distributed 802.16a SS nodes with adaptation in frequency, when R_{max11}=50m and Pareto traffic with ON/OFF time = 500ms/500ms and traffic load 1Mbps.

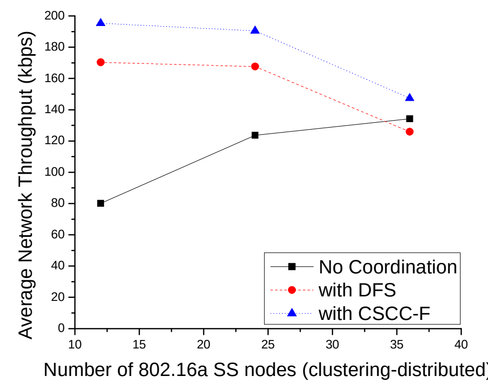
First the results for adaptation in frequency are compared with reactive dynamic frequency selection (DFS) and the no coordination case, shown in Figure 4.16. Both 802.16a DL/UL traffics are considered. Since in this network there is sufficient vacant spectrum for the two systems to operate in different channels, and by CSCC coordination or reactive DFS, radio nodes can switch to channels with less interference and improve the system throughput by about 15% in the uniform-distributed case (with less interference between nodes) and up to 160% in the clustering case varying by the clustering index. In a more crowded network with multiple 802.16a cells taking more spectrum bands, this improvement may be less due to high interference in each available channel.





(a) uniformly-distributed case, load = 400kbps (b) uniformly-distributed case, load = 600kbps

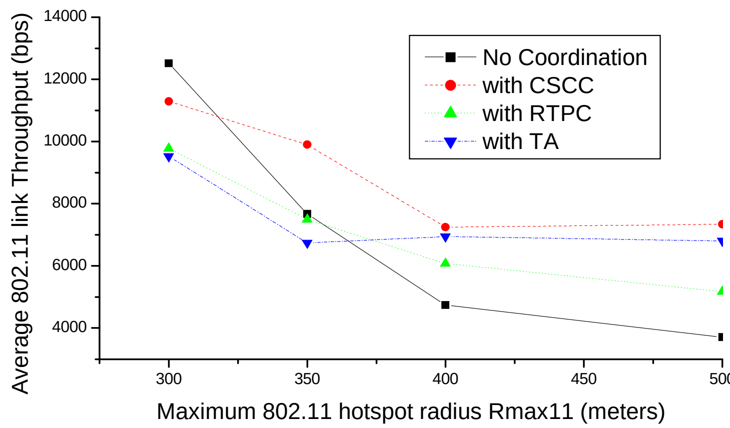




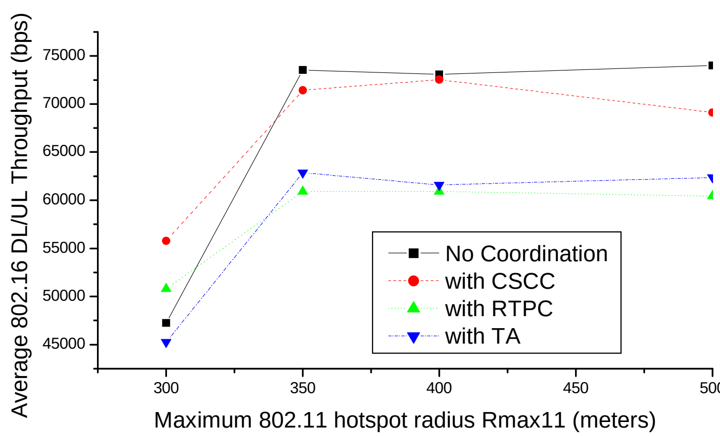
(c) clustering-distributed case, load = 400kbps (d) clustering-distributed case, load = 600kbps

Figure 4.17: Throughput for uniformly (a, b) and clustering (c, d) distributed 802.16a SS nodes (with 12 nodes in each 802.16a channel), when R_{max11}=100m, R_c=200m and Pareto traffic with ON/OFF time = 500ms/500ms.

Another set of results for CSCC adaptation in frequency (denoted as CSCC-F in the figures) are plotted in Figure 4.17. Both 802.16a DL and UL traffics are considered. In Figure 4.17, (a) and (b) are the cases with uniformly-distributed 802.16a SS (region (i) in Figure 4.15); (c) and (d) are the cases with clustering-distributed SS nodes (region (ii) in Figure 4.15). The results show CSCC-F can significantly improve the average network throughput (up to ~50% in uniformly distributed case and ~140% in the clustering case). It also performs better than reactive DFS when the 802.16a SS node density is not very high, which means there is vacant spectrum for the two systems to operate in different channels. Comparing Figure 4.17 (a) with (b), the improvement amount is higher with more traffic load. When 802.16a SS nodes take all available spectrum bands (i.e., 36 nodes taking all 3 available 802.16a channels), the coordination in frequency may be insufficient due to lack of available spectrum, while adaptation in power will be explored.



(a) Average hotspot throughput



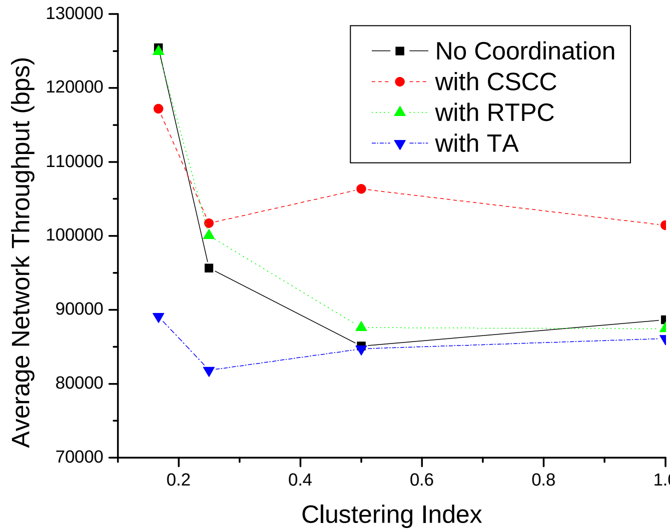
(b) Average 802.16a DL/UL throughput

Figure 4.18: Throughput for 802.16a SS random distribution in region (i) with varying hotspot radius R_{max11}, and numbers of 802.16a SS nodes : 802.11b nodes = 2:1, load 600kbps.

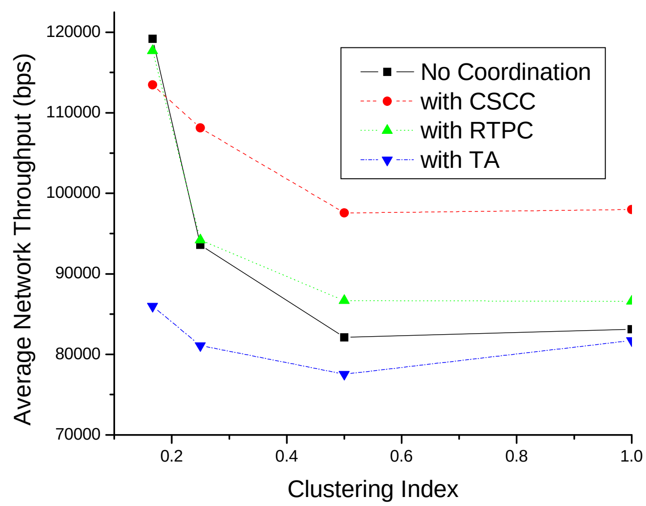
To evaluate the coordination by power adaptation, we assume a high interference case with fixed center frequency at 2412MHz for both systems (no adaptation in frequency). The CSCC based power adaptation algorithm is compared with reactive ones and the baseline case without any coordination. The results for uniform distribution of 802.16a SS nodes in region (i) are shown in Figure 4.18 with average hotspot and 802.16a DL/UL throughputs plotted separately. In this case the SS nodes are sparsely distributed in the cell and there is a lower probability of "hidden receivers". Figure 4.18(a) shows that when the hotspot size is larger, its throughput is severely affected by the interference from 802.16a DL/UL, but CSCC protocol can help improve the hotspot throughput by ~70-100% when R_{max11} is greater than 350 meters, by a slight degradation of 802.16a average throughput. The CSCC protocol performs better than the reactive RTPC and TA because the reactive schemes can also improve the hotspot throughput but degrade 802.16a throughput more.

The network throughputs for clustering of 802.16a SS nodes in region (ii) are shown in Figure 4.19. X-axis is the clustering index $C_i = R_{max11}/R_c$, and Y-axis is the average network throughput of both systems. The R_{max11} is fixed at 50m and C_i is varied by changing R_c. By applying CSCC, average network throughput can be improved up to ~20% when the clustering index is greater than about 0.2 and the amount of improvement increases with C_i, which means higher interference between the two systems. The more intense the traffic load (600kbps vs. 1Mbps), the larger the improvement. The CSCC protocol also performs better than reactive methods in cases with significant clustering, mainly due to the fact that it can deal with the hidden-node problem discussed earlier.

In summary, when there is vacant spectrum to use frequency adaptation, CSCC protocol can significantly improve the network throughput by ~1-2x especially in the clustering case when in-band interference is high. For the fixed channel allocation case, the CSCC-based power adaptation algorithm can also benefit the hotspot throughput when the hotspot size is large with uniformly distributed 802.16a SS. In the clustering case, CSCC protocol can significantly improve average network throughput over reactive schemes when the clustering index is large, which indicates a high spatial coupling between the 802.16a SS clusters and hotspots.



(a) 600kbps load



(b) 1Mbps load

Figure 4.19: Throughputs for power adaptation with clustering-distributed 802.16a SS in region (ii), with numbers of 802.16a SS : 802.11b nodes = 1:1, and Pareto traffic with ON/OFF time = 500ms/500ms.

4.6 Conclusion

Spectrum co-existence of IEEE 802.11b and 802.16a networks has been studied using both reactive and proactive spectrum coordination algorithms to coordinate and reduce interference. Specifically, reactive algorithms such as DFS, RTPC and TA and proactive CSCC etiquette protocols are studied. The hidden-node scenario in which reactive algorithms may not work well was identified, and it was shown that the CSCC approach can help to solve this problem. Proposed reactive and proactive coordination policies were simulated in representative WiFi and WiMax co-existence scenarios, and system performance based on average throughput was evaluated and compared. Various 802.16a SS node density and geographic distributions were studied leading to an identification of spatial clustering regimes where CSCC coordination can significantly improve system throughput by solving the hidden-receiver problem. Our results demonstrate that CSCC power adaptation can help maintain 802.16 service quality at the expense of a modest decrease in 802.11 throughput in the hidden-receiver scenario considered. Overall system throughput can be significantly improved over reactive schemes depending on the degree of spatial clustering.

Chapter 5 Protocols for Cognitive Radio Networks

In this chapter we discuss the inter-networking issues for cognitive radio nodes and propose a new network architecture *CogNet* and protocol stack for cognitive radio networks. Control protocols such as bootstrapping, self-organizing, node/service discovery, naming/addressing, multi-hop routing, etc. will be introduced in details.

5.1 Introduction

Recent progress in cognitive radio techniques makes it possible to consider an adaptive wireless network [5] which can self-organize into ad hoc multi-hop networks to achieve the best utilization of radio resources such as spectrum. Radio nodes in the network can also self-optimize their transmit parameters and exchange link state information to establish the best path for data communications.

We examine an adaptive network architecture based on separation of control and data planes. Current wireless network architectures involve control signaling and data traffic sharing a common plane, resulting in a variety of inefficiencies [80]. Extending the idea of the CSCC proposed earlier, it is possible to use the CSCC to create a separate control plane for distributing control information, thereby providing a simplified pipe-like design for the data plane. The control and data planes are sufficiently generic to allow for implementation on a variety of radios with different available resources. For example, the control and data planes may either be implemented by employing orthogonal time slots or by taking advantage of additional channels if they are supported by the radio.

In this chapter, we introduce the cognitive radio protocol stack which implements the control plane functionalities by using a common spectrum coordination channel [11]. The bootstrapping process enables nodes to be aware of itself, the surrounding nodes and current network status when it starts up. It can help new nodes to discover available networks and services by listening to bootstrapping beacons which are periodically broadcast locally in the control channel by existing nodes. The discovery protocol allows nodes to have a global view of the network, services and available links. Naming and addressing services are provided distributedly for translation of node name and address. Multi-hop data paths can be established based on end-to-end link weight calculation in the control plane along with configuration of cross-layer parameters for data plane such as radio frequency, power, rate, etc.

5.2 *CogNet* Network Architecture

5.2.1 Considerations for Cognitive Radio Networks

As discussed earlier in Chapter 2, collaborative networks of cognitive radios have the potential of achieving significantly higher performance relative to the reactive or proactive spectrum etiquette protocol approaches. In particular, such networks reduce spectral interference by encouraging high speed/low power transmissions to nearby radio nodes, with collaborative multi-hop forwarding of packets to their desired destination.

Cognitive radio networks have a number of new and interesting capabilities:

- Spectrum agility and fast spectrum scanning over multiple frequency bands, providing local awareness of radio interference and the ability to change frequency bands on a per-packet basis
- Fast PHY adaptation, or the ability to change physical-layer waveforms on a per-packet basis and PHY collaboration modes such as network coding
- Spectrum etiquette protocol and dynamic spectrum policy implementation on a per-session basis
- Fully programmable MAC layer, with the option of dynamic adaptation to meet service needs

- Cross-layer protocol implementation capabilities based on integrated PHY, MAC, network algorithms
- Ad hoc cluster formation, involving multi-hop packet forwarding among peer groups of radio nodes

Adaptive wireless networks of cognitive radios will require a general protocol framework with control and management support for cross-layer collaboration between radio nodes [17]. For example, collaborative PHY mechanisms such as network coding require control mechanisms to identify participating nodes, specify path diversity routes and eventually indicate (or download) applicable forward error correction algorithms. Similarly, for flexibility at the MAC layer, the control protocol should be able to distribute status necessary to infer current network topology and congestion conditions, together with the ability to coordinate changes in MAC functionality between a selected group of radio nodes. At the network layer, radio nodes should be able to organize into voluntary ad hoc network clusters that agree to forward packets between themselves – this requires control protocol support for neighbor discovery, address assignment and routing table exchange. Cross-layer adaptation algorithms also require exchange of PHY and MAC level status information between nodes which participate in an ad hoc network cluster.

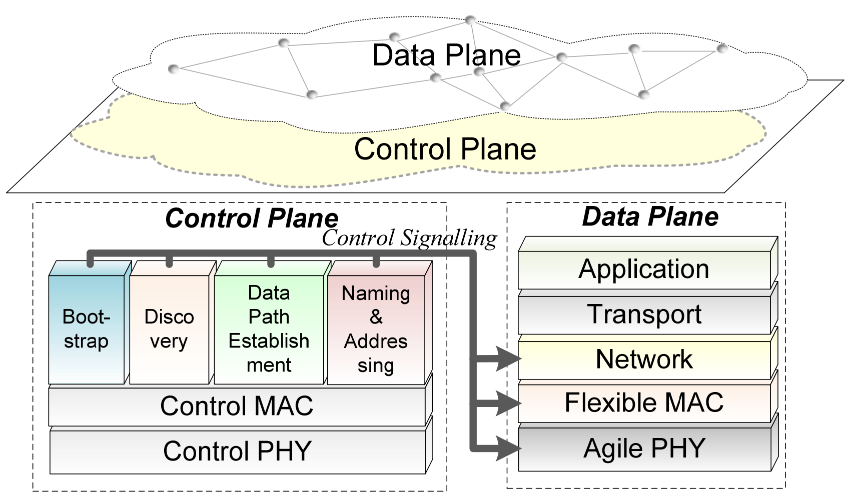


Figure 5.1: *CogNet* architecture using a global control plane for cognitive radio networks.

In view of the complexity and range of control and management functions required, it is becoming increasingly clear that we should partition the protocol functionality of the cognitive network in an explicitly-defined control plane and a data plane [81]. The *CogNet* protocol architecture [18] is shown in Figure 5.1 which allows individual cognitive radio nodes to organize into adaptive wireless networks by providing a protocol framework with control and management support for cross-layer collaboration between radio nodes.

5.2.2 Global Control Plane (GCP)

The global control architecture allows cognitive radio nodes to initialize and dynamically adapt their PHY, MAC and network level parameters. The control plane is made up of several key components: bootstrapping [82], discovery, cross-layer routing [83][84] and naming/addressing [81][87][88][89][90][91][92]. The radio bootstrapping function allows for detecting local links and configuring PHY/MAC parameters when cognitive radio nodes first boot up. After initialization, nodes execute a discovery protocol based on periodic reporting of local link states of neighboring nodes using a controlled one-hop broadcast mechanism. The discovery protocol also interacts with cross-layer routing module that provides end-to-end reachability and path information across multiple hops, which are dynamically configured with cross-layer parameters including frequency, power, rate, etc. The fourth key component is the support for distributed naming and addressing by which network nodes map their permanent “names” to dynamically assigned network addresses which may change with network structure and mobility.

To implement the GCP, we extend the concept of CSCC protocol to serve as the control plane for cognitive radio nodes by utilizing a low-cost control radio (e.g. 802.11b or similar) operating at the edge of the shared spectrum band. The control radio used is a generic low-rate 802.11-type radio fixed at one specific channel to implement the control plane functions and configure the data plane which is quite generic and flexible in adapting to different spectrum and interference scenarios.

5.2.3 Data Plane

The data plane protocol stack on each node contains modules needed to support data communication between the wireless nodes and it exposes a set of controls for each module which interact with the control plane through APIs to monitor, configure and adapt the data plane modules. The data plane has an agile physical layer which can sense spectrum opportunities, report to GCP and rapidly move to newly available bands. The flexible MAC layer supports for switching between different media access mechanisms to achieve the best performance under different network topology and traffic conditions, e.g., in a sparse network, CSMA-based MAC may be appropriate, while in a dense network, it is preferable to use a TDMA-like MAC for scheduling to avoid excessive channel contention.

The GCP provides a generic framework to exchange control information to implement these and other network adaptation functions. The separation of control and data planes gives the flexibility to optimize each function so that the data plane can use a “pipe-like” design [81] to fully utilize radio resources and minimize protocol overheads. The multi-hop “data pipe” from end-to-end source and destination can be established and configured by the control planes of nodes along the “pipe” (data path), where all the control signaling for setting up the pipe is carried through the GCP and data planes just focus on transmit/forward data packets along the pipe (path). The control plane generally uses a low-rate radio PHY with wider coverage than the data signal, and can thus be used to efficiently distribute control information with fewer hops than would be required during data transfer. The data plane parameters can be optimized for end-to-end performance by setting up frequency, power, bandwidth, rate, etc. at each data forwarding hop to improve spectrum efficiency.

5.3 *CogNet* Control Protocols

The protocols for control plane operation are introduced in this section, including a bootstrapping protocol, a discovery protocol, a data path setup protocol and a naming/addressing scheme.

5.3.1 The Bootstrapping Protocol

The bootstrapping protocol [18] operating at the control plane is aimed for nodes to obtain basic PHY/MAC parameters, local reachability and link state information when they first boot up or move to a network area.

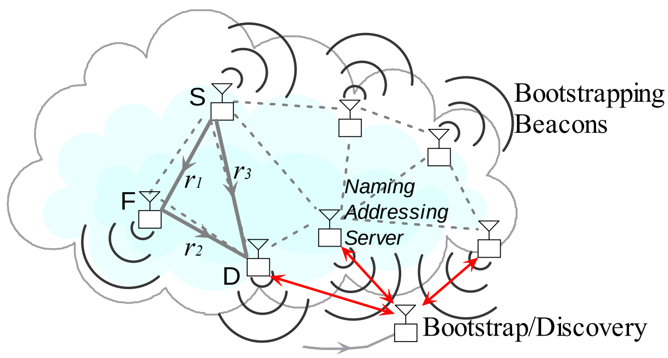


Figure 5.2: The bootstrapping protocol.

In the network of Figure 5.2, existing nodes periodically broadcast up-to-date bootstrapping beacons (*BSB*) on a specific control channel. When a new node boots up or moves nearby, it will first listen on the predefined control channel using default control plane radio configuration to collect bootstrapping beacons for a random period of time. A local link state table can thus be built up with the estimation of wireless link quality to neighbor nodes from their bootstrapping beacons. After the beacon collection process, the new node will start discovery process by exchanging all the link states with neighbor nodes to obtain a global view of the network. During the bootstrap, the new node can also detect naming/addressing services if available. After the bootstrap, new nodes begins to periodically broadcast self-states in their own beacons.

1 8 16 24 32

MSG Type	Flags	Sequence Number	
Source…			
…Identifier		Max PHY Rate	
Max Transmit Power		Beacon Transmit Power	
Num of Reach	MAC Type	MAC Busy Indicator	

8 10 12 14 16

Flags:								
	NA	CF	FD	0	0	0	0	0

Figure 5.3: Bootstrapping beacon format.

The bootstrapping beacon is implemented as a low layer (PHY or MAC) broadcast within only one hop, which provides minimal required information of node states shown in Figure 5.3. The beacon transmit power (quantized using 16 bits from 0 to 50dBm) is useful for beacon receivers to derive link quality between two nodes. MAC profile includes MAC type and MAC busy indicator, which indicates how busy the sender's data plane MAC is by periodical measurement of data MAC busy time per interval. It is normalized between 0 and 1 (indicated by a 16-bit integer) which is a good estimate of the sender's forwarding ability. A "flags" field usually has control or service information, e.g., "NA" bit indicates naming and addressing service. The collision of beacon messages is resolved by the control plane MAC, e.g. CSMA if 802.11 MAC is used. Control overhead will be evaluated using simulations.

Based on the beacons a node collects, a local link state table is built up with link state vectors (*LSV*) for each direct wireless link. Each *LSV* is a tuple of destination node ID, link (or end-to-end path) weight, next hop ID and hop count, e.g., $<DestID_k, w_{jk}, NextHopID_k, HopCount_{jk}>$ for node j describing the link from node j to k. The link weight is a performance metric assigned to direct links and end-to-end path weight is a metric of paths involving multi-hop relays. During the bootstrap, direct link weight can be obtained, which is an estimate of the maximum achievable PHY bit rate between two nodes by mapping estimated data signal to noise ratio (*SNR*) to physical transmission rate. Node i can estimate the path loss and thus *SNR* for data packets from a beacon of node j by:

$$SNR_{ij} = \frac{Pt_{\max i} \cdot \Pr_{ji}^{(B)}}{Pt_{ji}^{(B)} \cdot N_0} \tag{5.1}$$

Pt_{maxi} is the maximum data transmit power of node *i,* $Pr_{ji}^{(B)}$ and $Pt_{ji}^{(B)}$ are respectively the received and transmit power of the beacon message, and N_0 is the noise power experienced at the data plane (estimated using 20MHz bandwidth). Here we assume the path loss between node *i* and *j* is the same as that of node *j* and *i*. Note if the data channel is close to the control channel, the path loss estimated by beacon messages is a good estimate for the data channel. Otherwise the path loss estimation is different (e.g., about 8dB more from 2GHz to 5GHz by Friis model), but the estimation at control channel can still be used as a quantity to evaluate the quality of a link. Note at the time of estimation there may not be a data transmission so the frequency to be used by data plane is not determined, and thus interference is not counted either in equation (5.1). By orthogonal channel allocation, the interference can be minimized or eliminated. The achievable physical bit-rate for data transmission can be estimated by the *SNR* to rate mapping function f_{map} known to the node's data plane. The maximum achievable link rate $R_{\max ij}$ can be obtained by:

$$R_{\max ij} = \min\{R_{\max i}, R_{\max j}\} = \min\{f_{map}(SNR_{ij}), R_{\max j}\} \tag{5.2}$$

Taking MAC busy indicator into consideration, if the available bandwidth ($R_{\max ij}$) at a node is shared by transmissions for different data traffic, we define the link weight L_{ij} from node *i* to *j* as the "available" portion of the bandwidth as:

$$L_{ij} = R_{\max ij} \cdot \min\{\rho_{MACi}, \rho_{MACj}\} \tag{5.3}$$

where ρ_{MAC} ($0< \rho_{MAC} <1$) is the MAC idle ratio (derived from the MAC busy indicator). The link weight L_{ij} is proportional to the maximum achievable rate from node *i* to *j*. The larger the weight, the higher data rate can be supported by the link.

5.3.2 The Discovery Protocol

It is important for cognitive radio nodes to discover the network after bootstrap, because in order to quickly setup adaptive links/paths, a node has to have knowledge of the rest of the network and a path to reach a certain destination node.

Active discovery can be started by a new node or a node recovered from failure. A link state aggregation (*LSA*) message (see Figure 5.4) is used to poll neighbor nodes for aggregating local link states. Upon receiving a poll message ("PR" bit disabled), neighbor nodes then send all their *LSVs* in a *LSA* response ("PR" bit enabled). The *LSV* records path metrics to other nodes in the network. For example, *LSV* $<k, w_{jk}, k', C_{jk}>$ sent from node j means, node k can be reached by an end-to-end (E2E) path weight w_{jk} through next hop node k' with a hop count C_{jk}. Note that the requester can also piggyback its own link states in the poll message for suppression. To further reduce control overhead, only changes in link state vectors are propagated to the network in *LSA*.

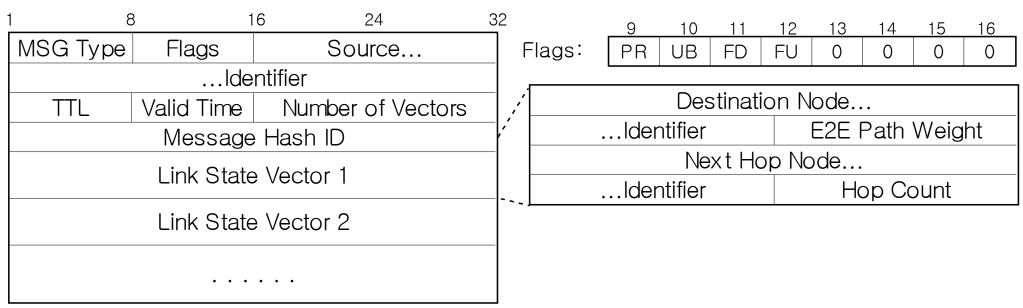


Figure 5.4: Link state aggregation (*LSA*) message format.

When a *LSA* response is received, the link state table is updated and new entries are added by calculating end-to-end path weight if new paths/nodes are discovered. In the network of Figure 5.2, when node S wants to transmit data to D, it can either directly reach D by rate r_3 or use node F as relay. The estimated per bit delay for both cases are:

$$E(D_1) = \frac{1}{r_3} \qquad\qquad E(D_2) = \frac{1}{r_1} + \frac{1}{r_2} \tag{5.4}$$

Compared to transmission delay (especially for large data packets), processing/propagation delay and channel switching delay at node F can be ignored. Channel accessing delay is not counted here either as data forwarding can be completed in consecutive time slots or in orthogonal channels with minimum channel contention. Under the condition $E(D_1) > E(D_2)$, i.e., $r_3 < r_1 r_2 /(r_1 + r_2)$, node S would prefer relay rather than direct communication to D. Based on the analysis above, the end-to-end path weight is defined as the reverse of the summation of the reversing individual link weights along the path, i.e., when node *i* receives a link state vector <*k, w*$_{jk}$*, k', C*$_{jk}$> from *j*, the new end-to-end path weight from node *i* to *k* is calculated as:

$$w_{ik} = \frac{1}{\sum_{m \to n \in \Re_{ik}} \frac{1}{L_{m \to n}}} = \frac{1}{\frac{1}{w_{jk}} + \frac{1}{L_{ij}}} \tag{5.5}$$

where $\Re_{ik}$ is the link set of all hops (i.e. link $m \to n \in \Re_{ik}$) along the multi-hop path between node *i* and *k*. As the direct link weight L_{ij} is an estimate of the link rate supported by each hop between node *i* and *j*, the end-to-end path weight w_{ik} will be a good estimate of the achievable end-to-end rate using intermediate traffic relays. The relationship between link weight and path weight is demonstrated in Figure 5.5.

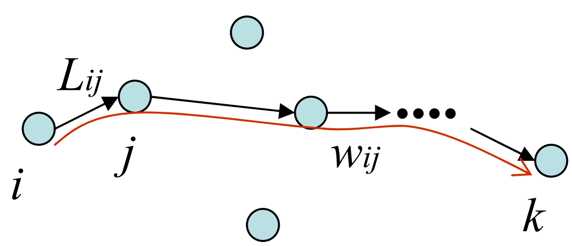


Figure 5.5: Calculating end-to-end path weight from link weights.

From equation (5.5) we know that the higher each direct link weight, the higher the end-to-end path weight. The algorithm for updating link state table after calculating the new weight is shown in Figure 5.6. If node *k* does not exist in the table, a new entry to destination *k* will be created and the link state vector <*k, w*$_{ik}$*, j, C*$_{jk}$+1> is added. If there exists an entry to node *k* (e.g., <*k, w*$_{ik}'$*, l, C*$_{ik}$>), the vector with the higher end-to-end path weight will be kept.

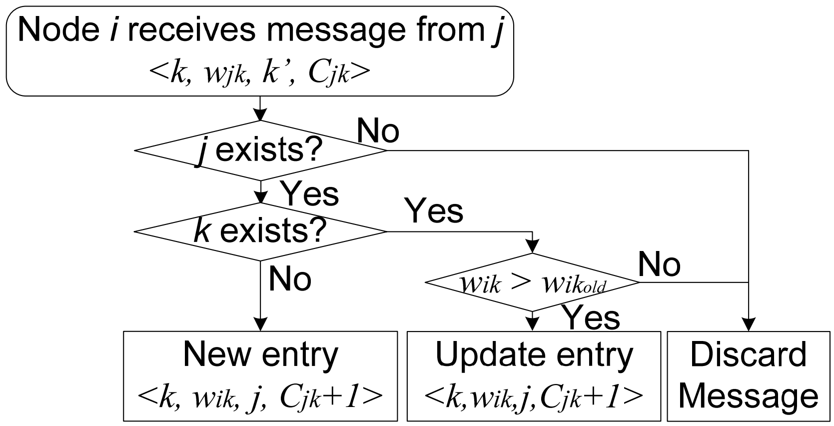


Figure 5.6: Flow chart for processing link state vector message.

When there is no link failure, this algorithm is loop-free due to the definition of end-to-end path weight. If a destination node is discovered, the origin node will never update with a path going through itself, because from equation (5.5), any looping path going through the same link will cause the weight to decrease, while paths with only higher weight are updated. When there are link failures, the discovery protocol can also guarantee loop-free. When a wireless link is down, according entries in the link state table will not be deleted immediately; instead, the weight will be set to 0 during the next update interval and propagated to the network. When a zero-weight *LSV* is received, the relating path weights will be set to zero and the process is repeated. After the validity interval passes, obsolete *LSVs* will then be deleted. In this way, instant loops may exist but in the long run they will be eliminated after zero-weight *LSVs* are propagated.

The discovery process repeats periodically to keep the consistency and freshness of global information. The aggregation interval (5-10 seconds) is usually designed to be multiples of the *BSB* interval (2-5 seconds), in order to balance the trade-off between the speed of information propagation and control overhead. Note the aggregation is only a local one-hop broadcast which does not require global flooding [85]. The unique message ID can also prevent re-processing of the same information.

5.3.3 The Data Path Setup Protocol

The *Data Path Setup (DPS)* protocol [81] is used for cross-layer routing when actual data traffic is initiated, and the source explicitly establishes the path to reach a destination, by configuring hop-by-hop cross-layer parameters of the data plane at each forwarding node. This is different from ad hoc routing protocols for the followings reasons: (1) the *DPS* protocol does not only find a path from source to designation (optimized by achievable end-to-end rate), more importantly, it sets up the per-hop data plane parameters (frequency, power, rate, bandwidth, etc.) to utilize local spectrum opportunities to achieve such end-to-end performance; (2) the path setup signaling is carried through the GCP; (3) this protocol utilizes the results from the discovery process. Different radio resource allocation algorithms can be carried in the *DPS* protocol, which is a session-based three-way handshake between hop senders and receivers. Here, we describe a baseline algorithm for joint frequency/power/rate allocation in a channelized cognitive radio system with fixed bandwidth and MAC protocol.

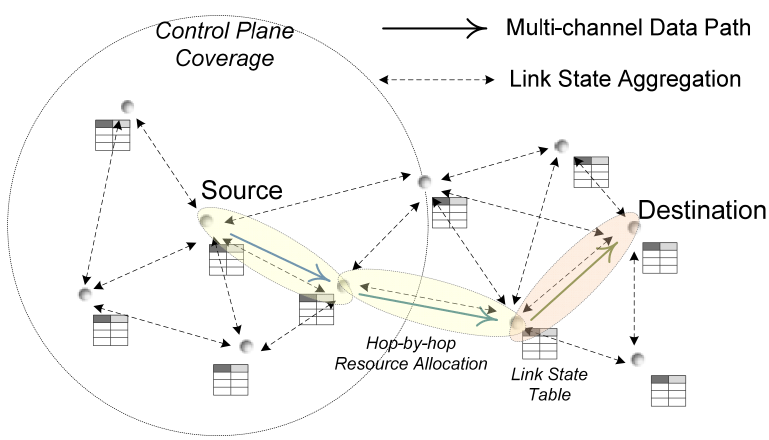


Figure 5.7: Multi-hop data path setup concept.

Each cognitive radio node discovers other nodes in the network during the discovery by maintaining a path weight to reach a destination node. When there is real data traffic initiated, the source node has to explicitly establish the data path to reach the destination, along which per-hop cross-layer parameters have to be configured for data planes at each intermediate data-forwarding node, as shown in Figure 5.7. Each node can negotiate the radio resource to be used for data transmission with their neighbors by the control plane. The setup of each hop along the data path gives the data plane a pipe-like design where data traffic will be forwarded using the pre-configured parameters (frequency, power, rate, MAC, etc.) in the data "pipe" established. A unified *DPS* message (Figure 5.8) is used for negotiation and setup of per-hop parameters. For each hop, a session-based three-way handshake is used for senders and receivers to agree on the PHY and MAC parameters. The *DPS* message is only unicasted at the traffic source and in other cases it is a one-hop multicast (indicated in the flags field of the message). The receiver of each hop is responsible for determining the radio parameters to be used and acknowledges with the sender, while at the same time, begin the next-hop negotiation with the same *DPS* message. When multiple hops are involved, this process will repeat at each hop to establish the "pipe" between traffic source and destination.

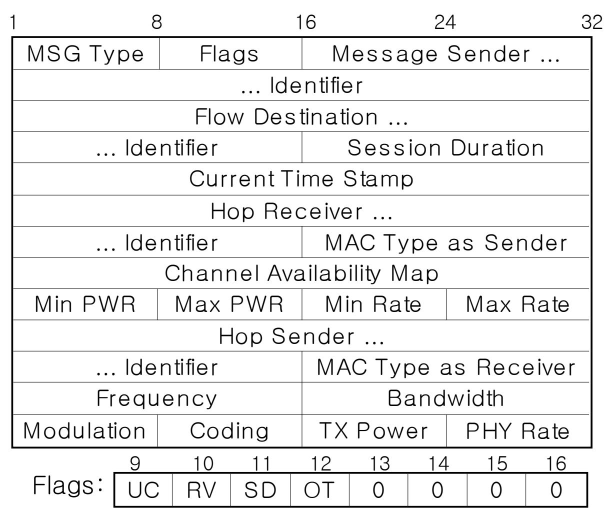


Figure 5.8: Data Path Setup (*DPS*) message format.

The control "Flags" field of *DPS* defines the message content, e.g., "UC" bit indicates unicast, "RV" or "SD" bit means there is content for a hop receiver or sender, and "OT" bit means the information is for nodes other than a sender or receiver. By this way, an intermediate node can use one message to both notify a previous-hop sender and at the same time to start a next-hop negotiation, which expedites the setup process and reduces control overhead.

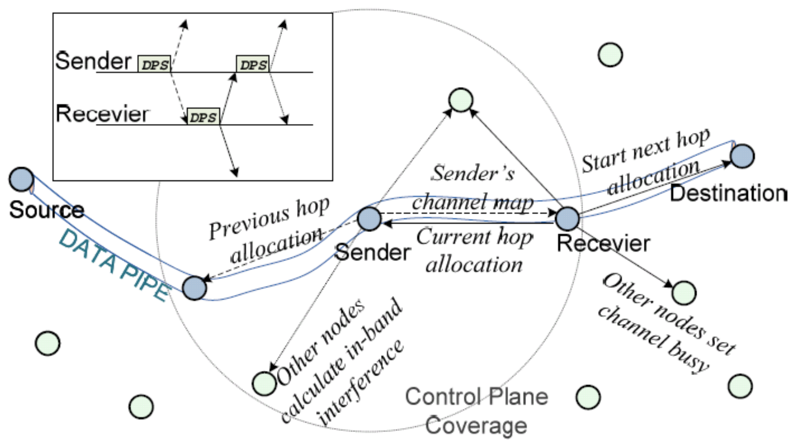


Figure 5.9: Hop-by-hop resource allocation for data path setup protocol.

During the data path setup process shown in Figure 5.9, cross-layer parameters are setup at each hop along the path, including various PHY and MAC parameters. The radio resource negotiation between sender and receiver at each hop is carried through the control plane, and other nodes overhearing the negotiation will mark the claimed spectrum resource. For data path with multiple hops, different frequency can be used at each hop which enables concurrent packet forwarding for hops using non-conflicting frequencies. System throughput can be significantly improved by setting up maximum-rate and multi-channel links along the data pipe.

A joint frequency/power/rate allocation algorithm is proposed where we consider a channelized cognitive radio system with fixed bandwidth. There are multiple channels available for data transmission. As shown in Figure 5.9 and summarized in Table 5.1, for each hop, the sender will send its channel availability map (which uses bit-map to indicate the availability of each data channel) and maximum power/rate supported. The hop receiver is responsible to match a clear data channel and calculate the minimum required transmit power to achieve the maximum possible PHY rate for data transmission. The allocated frequency, power and rate parameters are sent back to the sender in a *DPS* message, which at the same time starts the next hop allocation if necessary. The sender then has to re-announce the parameters chosen with a *DPS* message enabling the "OT" bit, which delivers the information to other nodes so that they can calculate the in-band interference caused by the sender. The "OT" bit is also enabled by a hop receiver so that the receiver's neighbors can process the information to mark the resource used for this data session. By the 3-way handshake at each hop, an end-to-end data path is set up from traffic source to destination and the data plane of each node then focus on forwarding data traffic in the data "pipe".

Table 5.1: Summary of the joint frequency/power/rate allocation algorithm.

For each hop:
Sender:
Sends a *DPS* message with self-state, such as the channel availability map and max data radio power
Receiver:
(1) Matches channels with the least interference, if no available TX/RX channel overlapping, then prefers RX channel
(2) Calculates the min required transmit power to achieve the highest PHY rate at current interference level
(3) Broadcasts a *DPS* message:
(a) Notifies sender with allocated frequency, power and rate
(b) Include self-state as a sender for next hop setup
Sender:
Acknowledges by broadcasting a *DPS* to repeat the parameters
Other Nodes:
Others overhearing any *DPS* message will record channel usages and calculate interference level impacted at its location (assisted by the path loss measured from bootstrapping beacons)

5.3.4 Naming and Addressing

The control functions for cognitive radio networks support for naming and addressing of each node. A distributed scheme is proposed to achieve auto-configuration of each node with IP addresses and name-to-address translation.

5.3.4.1 Distributed Naming/Addressing Server Election

One of the key ideas of this scheme is to elect distributed naming/addressing servers, which are responsible for allocating unique IP addresses to those nodes covered by a server's control plane while also maintaining node name registration and translation to addresses. In the dynamic networks formed by cognitive radio nodes, it is infeasible to have a centralized server for address allocation. We propose a distributed naming/addressing (NA) service with multiple NA servers involved which divide the network into logical sub-networks for address allocation and name registration.

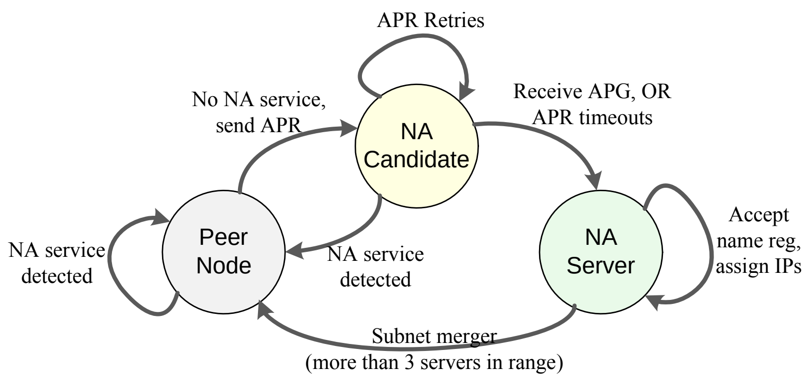


Figure 5.10: Naming/addressing server election.

Figure 5.10 shows the NA server election process, which guarantees that each node in the network has access to at least one server through the control plane. If a new node fails to collect any beacons (with “NA” bit enabled) from NA servers during its bootstrap, it will begin to elect itself as an NA server by broadcasting *Address Pool Request (APR)* messages to obtain available IP address pools from existing NA servers in the network. Upon receiving any NA beacons during the election process, the node will cancel its election and register with the detected NA server. The *APR* message uses an expanding ring mechanism which starts as a 2-hop broadcast and increases the TTL hop count for subsequent retries. In a network with uniformly distributed nodes, there is a high probability that an *APR* message will reach NA servers within two hops. Only non-server nodes rebroadcast *APR* messages. Any NA server receiving an *APR* message will use a binary splitting mechanism [88] to tentatively allocate half of its own free IP address pool to the requester by unicasting an *Address Pool Grant (APG)* message. The requester will then accept the pool with the largest space by sending an *Address Pool Accepted (APA)* message. Non-acknowledged pools will be reclaimed by the owner after an *APG* timeout. If no *APG*’s are received after several retries, the requester will choose a random IP segment (e.g. 10.31.*.*) to become an NA server by enabling "NA" bit in the beacons. Later during the periodical NA aggregation process, name and address information will exchanged through all distributed NA servers to detect and resolve collisions. The network thus is formed into multiple logical subnets, as the example shown in Figure 5.11. The dark nodes are elected NA servers and they maintain a mutually non-overlapping available IP address pools, which are used to assign unique IP address to associated client nodes. Each client node can find at least one server and request to associate by registering its name to the server. The server will also maintain the uniqueness of node names by rejecting conflict name registrations in its logical subnet. Information of node address, ID and name translation will be periodically aggregated and cached between NA servers. In such a way, each node can be reached by its node name plus the server name it is associated to. The details of naming scheme will be discussed in the next section.

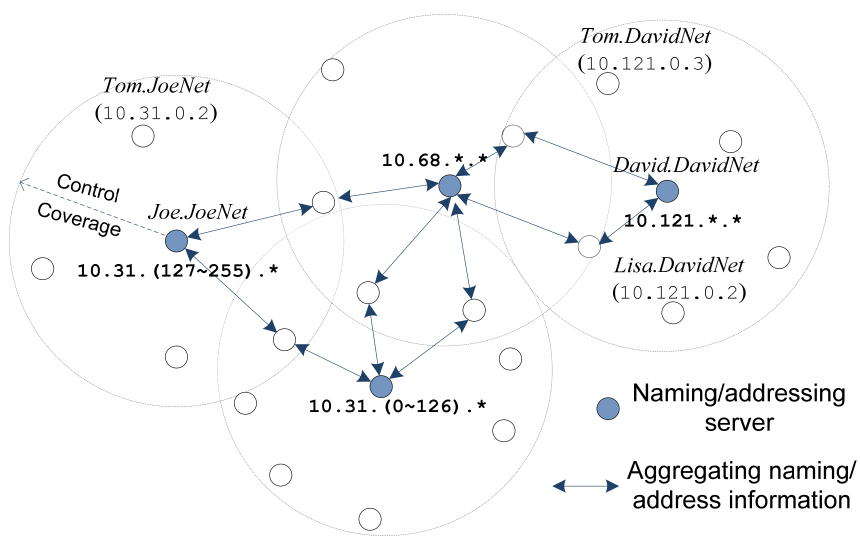


Figure 5.11: Naming and addressing scheme in an example network.

5.3.4.2 Name/Address/ID Translation

During the bootstrap, when a new node receives beacons from NA servers, it selects the one with the maximum link weight and sends a *Name Registration Request (NRR)* message to register its name to the server. If the server's IP address pool is non-empty, it will check if there is any conflict with the node name registrations it already received. If there is no conflict, the server will accept the new node name registration by assigning an IP address from the available pool and keep the node name to address and ID translation information into the translation table. A *Name Address Grant (NAG)* message will be sent to the request node with the assigned IP addresses. If the same name already exists in the table, the server will send a *Name Registration Denial (NRD)* message and the requester will then retry the registration by a new name (e.g., suffixing the name with a random number). If the server's address pool is empty, an *NRD* message will also be sent indicating no address available. If the *NRR* message times out after *NRR_Timeout* seconds, the requester can either register to other available servers or retries for a maximum of *NRR_Retries* times. If the reason of *NRD* is no address available, the requester will try another server with NA service, or wait *NRR_Timeout* seconds and then retries if no other servers available. In the rare cases when the server runs out of address, it will restart the *APR* process to get more available addresses from other servers.

The name to address and ID translation information maintained at each server is periodically aggregated between NA servers. NA servers' names (subnet names) are guaranteed to be unique during the aggregation process by the conflict resolution procedure. Thus each node can be uniquely identified by joint node and subnet name. Applications which communicate using node names are thus supported where the resolution of name to address/ID is achieved by distributed NA servers. During the aggregation process, each server will periodically aggregate the information in its translation table to the network by *Name Address Aggregation (NAA)* messages (shown in Figure 5.12). Upon receiving an *NAA* message, the NA server will update the information in *NAA* to its own name/address/ID translation table.

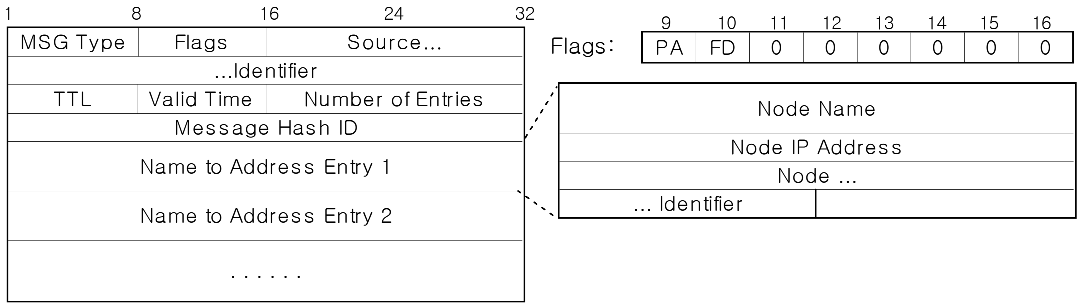


Figure 5.12: Name and address aggregation (*NAA*) message

To reduce the amount of information flooded to the network, a special aggregation rule is used. Each time NA servers only aggregate new or changed entries in its translation table or the whole translation table only upon the request of a new NA server (with the "Poll" bit enabled). After an NA server broadcast an NAA message, everyone registered under this server will rebroadcast the message. Then after the first hop, only those registered under a different NA server rebroadcast the message, and the NAA message ends at any NA server. This rule will ensure the neighbor NA servers get the new update without flooding the whole network. Then the new update will later reach the whole network by each server's aggregation process. The unique message content hash ID also helps to reduce control traffic under the rule that each node will not forward any message with the same hash ID (thus the same content) during one aggregation period, which prevents the re-processing of the same update coming back from neighbor NA servers.

5.4 Experiment Results using ORBIT Testbed

The bootstrapping protocol is validated using experiments conducted in the ORBIT radio grid testbed [12][93] with Debian Linux installed in each node, which has two wireless cards. The nodes with Intel Pro-wireless 2915-based 802.11a/b/g cards are used. One wireless card is fixed at channel 1 using IEEE 802.11b radio for all the control functions and the other interface uses 802.11a for data transmission with 8 channels available (for Intel 2915 card) at 5 GHz unlicensed band. In this experiment, we only consider the scenarios where nodes are within one hop, and a dynamic channel allocation algorithm is used which allows transmitters and receivers to pre-setup their data communication channel during bootstrapping process. Basically we implemented part of the data path setup protocol in a one-hop case, with the frequency allocation algorithm (discussed in section 5.3.3). The algorithm helps each sender and receiver to agree on the vacant 802.11a channel by listening to bootstrapping beacons at the control plane.

Table 5.2: Experiment parameters for bootstrapping and channel assignment.

	Control Plane	Data Plane
Data session	-	5 sec session duration, random interval (between 5 to 10 sec), CBR traffic
Packet type	Raw 802.11 packet, variable length	UDP packet with fixed length 1024 bytes
Radio type	IEEE 802.11b	IEEE 802.11a
Channels	Fixed at channel 1	36, 40, 44, 48, 149, 153, 157, 161
Rate	1Mbps	54Mbps with Auto-Rate-Fallback (by wireless driver)

The experiment parameters are listed in Table 5.2, network topology is shown in Figure 5.13 and results are demonstrated in Figure 5.14. Several experiments are conducted with different number of transmission node pairs and varying offered load. When all 8 pairs (16 nodes) are fixed at one channel, the per-session throughput will degrade when the channel is saturated after 20Mbps load. With the dynamic channel allocation scheme, nodes are able to setup different channels for their data sessions and the throughput can be improved by about 200% for 8 pairs of nodes when load is larger than 10Mbps. The top curve shows the maximum achievable throughput when only one pair of nodes communicate using current ON/OFF traffic model.

Figure 5.13: Network topology (Intel wireless cards only) in ORBIT experiments.

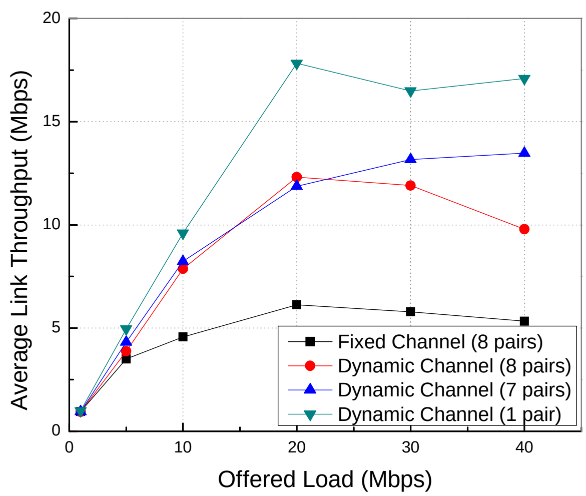


Figure 5.14: Average link throughput for varying communication pairs.

5.5 Simulation Results using *ns-2*

The global control plane architecture and each *CogNet* control protocol component are implemented in *ns-2* where the control radio uses 802.11b operating at fixed channel 1 with 2Mbps rate covering about 250m. The control MAC uses the IEEE 802.11 standard without RTS/CTS. The data radio can be implemented with generic radios (using varying frequency, bandwidth, modulation, power and rate parameters), but without loss of generality, we utilize 802.11a OFDM radio parameters at 5GHz for data plane with 8 channels of 20MHz each. PHY rates are 6, 9, 12, 18, 24, 36, 28 and 54Mbps and transmit power varies from 0 to 20dBm. A network scenario of 1 km x 1 km with varying numbers of cognitive radio nodes is simulated where nodes are randomly placed in the network and boot up at random times, shown in Figure 5.15. The bootstrapping and discovery protocols are evaluated in terms of network setup time, control overhead used and estimated achievable end-to-end rate. The maximum network setup time is the time from the start of the first node to the time all nodes in the network achieve global awareness by completing the discovery process. To evaluate the *DPS* protocol, different traffic source/destination pairs are chosen randomly to perform data ON/OFF sessions with ON/OFF duration uniformly distributed from 5 to 10 seconds.

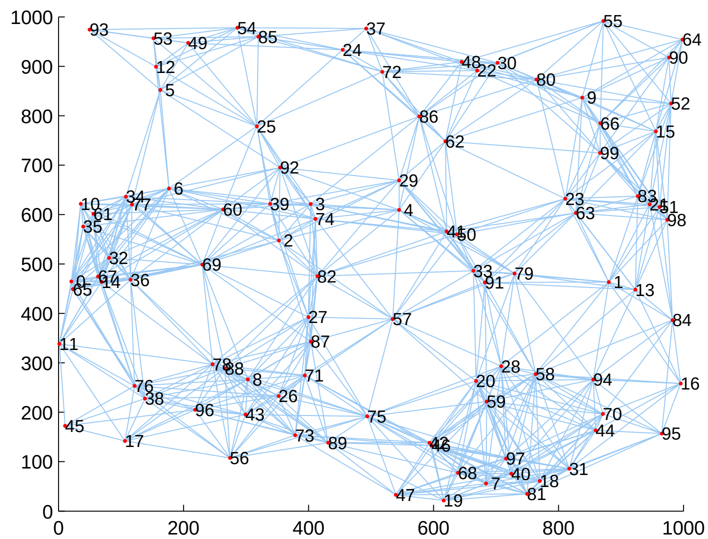
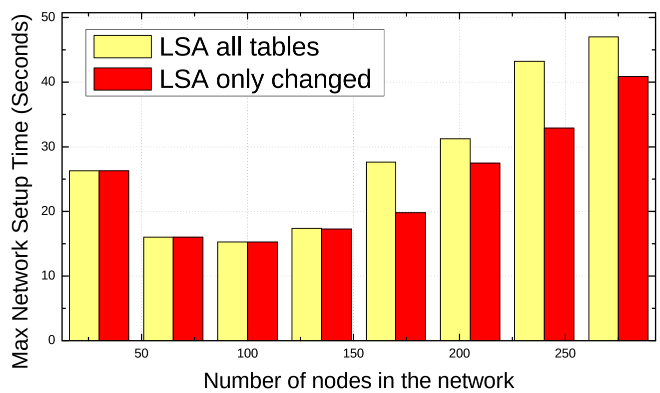
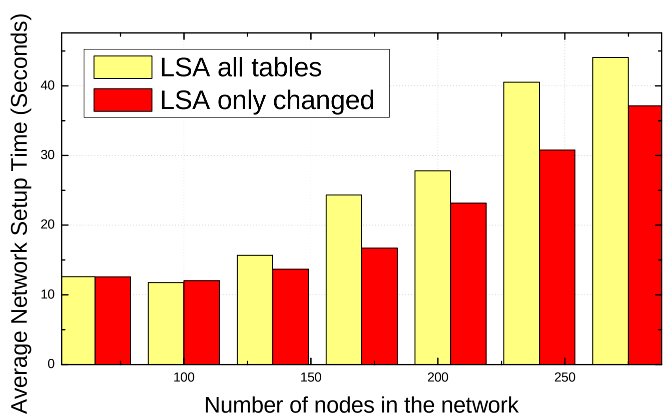


Figure 5.15: An example of random network topology (100 nodes in 1km x 1km network).

The simulation results are compared for cases in which all link states are sent periodically ("*LSA* all tables"), or alternatively only when changes occur ("*LSA* changes only"). The maximum and average network setup time are shown in Figure 5.16 where nodes random boot up from 0 to 4 seconds. With increasing number of nodes in the network, the network setup time first decreases and then increases, reaching its minimum at a node density of about 100nodes/km^2, because when the network is sparse, more *LSA* steps are needed to discover the whole network, while in a very dense network, the size and number of *LSVs* are large, and it takes about 3-8 *LSA* steps to discover the network. It is observed that when only changed link states are propagated, the network converges faster due to reduced control packets contending for the control channel.



(a) Maximum network setup time



(b) Average network setup time

Figure 5.16: Network setup time (*BSB* interval 2sec, LSA interval 5sec).

The average control traffic per node during discovery process is shown in Figure 5.17 with both bootstrapping beacons and *LSA* messages counted as control traffic. The average per node control traffic rate increases as the node number increases but the curve flattens out when the node number becomes large, converging to about 55-65kbps, which is well below the control channel capacity. When only changed link states are propagated, the control traffic rate is about 10kbps less than the case by sending all link states. The estimated theoretical end-to-end rate is also calculated using equation (5.5) during discovery. Each node is randomly assigned a MAC idle ratio to simulate its busy condition. From Figure 5.18, each node discovers paths to every other node in the network with average achievable end-to-end rate as high as 18Mbps for an 802.11a-type network involving multi-hop relays (usually 1-8 hops). The busier a node, the lower the end-to-end rate achieved due to reduced forwarding ability.

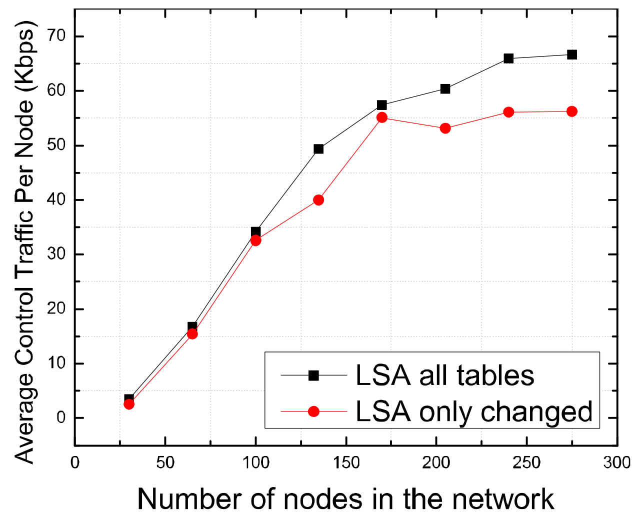


Figure 5.17: Average control traffic per node for network setup.

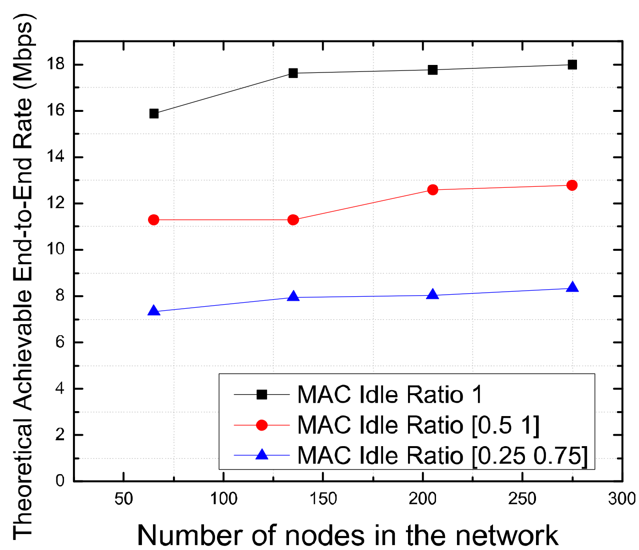


Figure 5.18: Estimated theoretical achievable end-to-end rate.

Simulation results for the *DPS* protocol and joint frequency/power/rate allocation algorithm are shown in Figure 5.19 and Table 5.3. The average frequency allocation success ratio decreases with increasing numbers of source and destination pairs in the network. The *DPS* protocol succeeds if every hop is configured with a matching frequency between hop sender and receiver. Apparently when there is less traffic in the network, it is easier for the *DPS* protocol to set up the end to end parameters, but if the is more traffic loaded, the network will become more congested. It is observed that with increasing node density, this ratio improves mainly because the joint frequency/power/rate allocation algorithm allocates minimum required power for achieving the maximum supported bit rate, which potentially increases the space reuse of the limited 8 data channels. The *DPS* protocol latency (the duration from start of source to the acknowledgement of the destination indicating completion of hop-by-hop setup) and control overhead are given in Table 5.3, where end-to-end path setup only takes an average of 7 milliseconds with modest total control traffic of about 1.4KBytes.

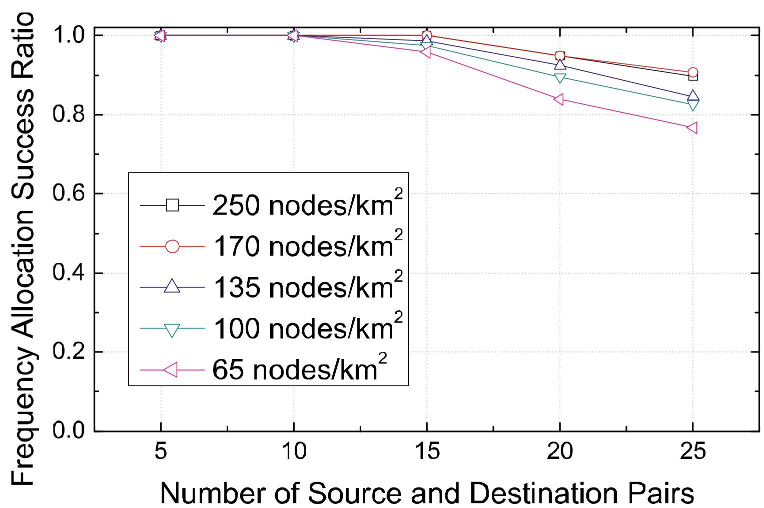
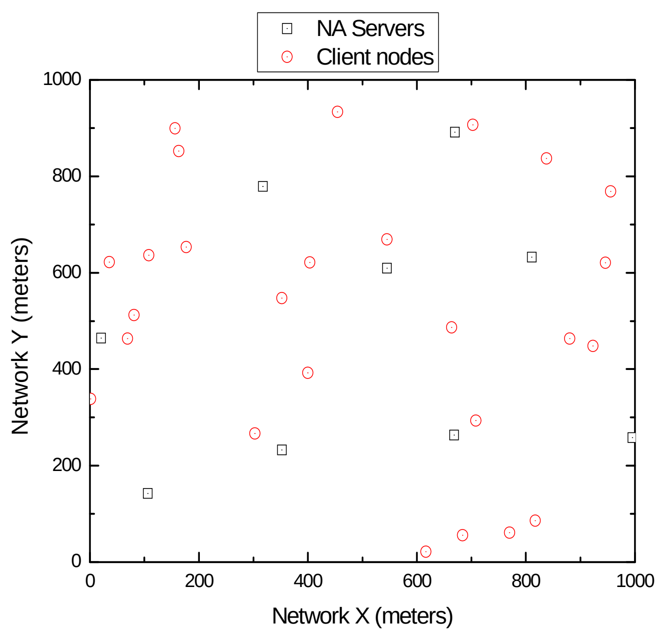


Figure 5.19: Frequency allocation success ratio for the *DPS* protocol.

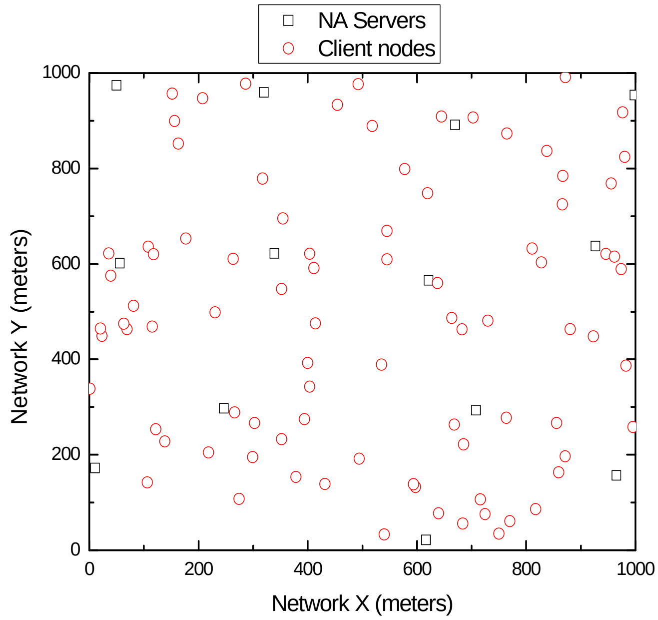
Table 5.3: Simulation Results for the *DPS* protocol.

Node density (per km^2)		65 nodes	135 nodes	205 nodes
Latency (milliseconds)	5 flows	6.49	6.96	7.62
	15 flows	6.52	6.64	7.38
Overhead (Kbytes)	5 flows	1.3	1.4	1.5
	15 flows	1.4	1.4	1.3

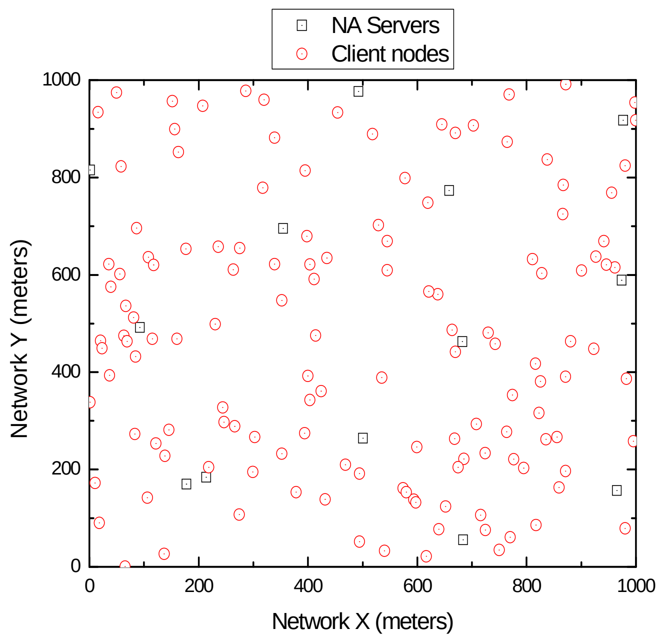
The distributed naming and addressing scheme for cognitive radio networks is also validated using *ns-2* simulations in networks with different node density. The simulation results for the NA server election are demonstrated in Figure 5.20, where three networks with 35, 100 and 150 nodes are studied. The NA scheme elects distributed NA servers by distributing and exchanging control messages in the control plane such that it is guaranteed that any node in the network can reach at least one NA server in its control plane coverage. In Figure 5.20, the red circle stands for regular nodes and the black square stands for elected NA servers. The results show for a network of one square kilometer, 9 servers are elected among a total of 35 nodes and 13 servers are enough to cover the whole network area when the total number of nodes exceeds 100. The NA server election scheme guarantees the server coverage but at the same time elects as less servers as possible during the random startup process of the network. We also observe when the node density is larger than 100 nodes/km^2, the number of required servers to cover the whole network does not change, which demonstrates a good scalability of this server election scheme.



(a) 35 nodes (9 servers)



(b) 100 nodes (13 servers)



(b) 150 nodes (13 servers)

Figure 5.20: Simulation results for distributed naming/addressing scheme.

Table 5.4 shows an example of the allocated IPv4 address pools in the network with 9 NA servers elected. Similar results for the 100-node and 150-node networks are shown in Table 5.5 and Table 5.6. The ID of each NA server is listed together with the available IP address pool allocated using the distributed scheme. We use the IP segment 10.x.x.x for experimental purposes and the self-elected server randomly picks a subnet (e.g., 10.62.x.x) while subsequent servers use binary-split methods to obtain and divide available IP address pools from existing NA servers. It is observed for a large network the number of elected servers converges and 255 subnets are large enough to accommodate all the address pool requests in this network.

Table 5.4: Example of the distributed address pool allocation for a 35-node network.

Server ID	IP Pool Start	IP Pool End
23	10.62.127.0	10.62.190.254
16	10.62.191.0	10.62.255.254
0	10.166.0.0	10.166.126.254
4	10.62.63.0	10.62.126.254
20	10.62.0.0	10.62.62.254
22	10.97.127.0	10.97.255.254
17	10.166.127.0	10.166.190.254
26	10.166.191.0	10.166.255.254
25	10.97.0.0	10.97.126.254

Table 5.5: Example of the distributed address pool allocation for a 100-node network.

Server ID	IP Pool Start	IP Pool End
64	10.224.191.0	10.224.255.254
22	10.224.63.0	10.224.126.254
41	10.224.0.0	10.224.62.254
95	10.35.127.0	10.35.255.254
28	10.35.0.0	10.35.126.254
45	10.11.0.0	10.11.255.254
83	10.224.127.0	10.224.190.254
78	10.103.0.0	10.103.62.254
39	10.103.63.0	10.103.126.254
85	10.16.0.0	10.16.126.254
93	10.16.127.0	10.16.255.254
61	10.103.127.0	10.103.255.254
19	10.38.0.0	10.38.255.254

Table 5.6: Example of the distributed address pool allocation for a 150-node network.

Server ID	IP Pool Start	IP Pool End
7	10.120.0.0	10.120.255.254
124	10.172.127.0	10.172.255.254
115	10.172.0.0	10.172.126.254
102	10.74.0.0	10.74.62.254
98	10.180.0.0	10.180.126.254
91	10.16.127.0	10.16.255.254
128	10.16.0.0	10.16.126.254
116	10.74.127.0	10.74.255.254
37	10.87.127.0	10.87.255.254
92	10.87.0.0	10.87.126.254
90	10.180.127.0	10.180.255.254
139	10.74.63.0	10.74.126.254
95	10.70.0.0	10.70.255.254

5.6 Conclusion

In this chapter we have proposed and validated a novel network architecture for cognitive radio networks in which control and data plane operations are separated. Control plane protocols for bootstrapping, discovery, cross-layer routing and naming/addressing functions have been described. The bootstrapping protocol enables self-organizing of cognitive radio nodes to networks by building up local link state tables. Further, the discovery protocol helps nodes to achieve global awareness by periodically aggregating and propagating link states across the network. The data path setup protocol helps to establish the actual data pipe by setting up hop-by-hop operating parameters when traffic is generated between a source and destination node. The naming/addressing service assigns network addresses to nodes with permanent "names", and maintains name-to-address translations. These control protocols are validated using a simple ORBIT experiment setup and larger scale *ns-2* simulations. In the ORBIT experiments, control protocols help 802.11a nodes to setup individual links with different channels and system throughput is greatly improved. In the *ns-2* simulations, we focus on a larger scale network to evaluate the network setup time and control overhead used for the proposed protocols. Data path setup protocol is also evaluated with different node density for its successful ratio. Naming and addressing scheme is validated by varying node density while server election and address allocation results are demonstrated.

Chapter 6 Conclusion and Future Work

6.1 Thesis Summary

Cognitive radio technology has the potential to dramatically improve spectral efficiency and performance in the next generation of wireless networks. In this thesis, we have studied the spectrum coordination protocols and algorithms for future cognitive radio networks. We start by identifying the design space for cognitive radio schemes as ranging from simple reactive algorithms to proactive spectrum etiquettes and finally to collaborative adaptive wireless networks, with different levels of software/protocol and hardware complexities. In particular, the rest of this thesis focuses on the problem of efficiently sharing spectrum resources in wireless networks through the use of appropriate spectrum etiquette protocols and related coordination algorithms, and the design of network architecture and protocols for cognitive radio nodes to organize into a form of adaptive wireless networks to achieve high spectrum efficiency.

A "common spectrum coordination channel (CSCC)" approach is proposed as a mechanism to enable efficient spectrum coordination between heterogeneous wireless networks or future cognitive radio networks. Specific spectrum coordination algorithms and etiquette policies are designed using the CSCC protocol when applied to different spectrum sharing scenarios. The spectrum etiquette protocol is based on the Common Spectrum Coordination Channel (CSCC) approach which allows explicit coordination for spectrum usage among heterogeneous wireless radio nodes by announcement of their operation parameters such as frequency, power, rate, interference, etiquette policies, etc. The performance of the proposed class of spectrum etiquette protocols is evaluated in various wireless network scenarios and compared with simpler reactive interference avoidance schemes, including reactive frequency, power and transmission time control. We first validate the CSCC protocol in a typical co-existence scenario of IEEE 802.11bg and Bluetooth at 2.4GHz. Proof-of-concept experiments are conducted using both a simple indoor setup and a denser radio environment in ORBIT radio grid testbed, where a priority based spectrum etiquette policy is used with Bluetooth rate control and backoff algorithms to avoid interference. The results have demonstrated significant performance gains with CSCC as compared to the case with no coordination.

To further study the CSCC etiquette protocol and spectrum coordination algorithms, we compare it with simpler reactive interference avoidance schemes in a co-existence scenario of IEEE 802.11b (WiFi) and 802.16a (WiMax) sharing the same spectrum. Simple reactive coordination methods does not require modification of hardware, where radio nodes adjust their transmit parameters such as frequency, power and transmission time based on local observations, but may suffer from severe hidden-node problems in certain scenarios where transmitters are unable to identify the existence of heterogeneous receivers nearby. We present a detailed comparison between reactive algorithms and proactive schemes based on the CSCC etiquette protocol using *ns-2* simulations. Various 802.16a SS node density and geographic distributions were studied leading to an identification of spatial clustering regimes where CSCC coordination can significantly improve system throughput by solving the hidden-receiver problem. Our results demonstrate that CSCC power adaptation can help maintain 802.16 service quality at the expense of a modest decrease in 802.11 throughput in the hidden-receiver scenario considered. Overall system throughput can be significantly improved over reactive schemes depending on the degree of spatial clustering.

After validating the utility for spectrum coordination between existing wireless standards (IEEE 802.11/WiFi, Bluetooth, and 802.16/WiMax), the spectrum etiquette protocol is extended to serve as the foundation for a more complete adaptive wireless network where radio nodes may cooperate by forming or joining autonomous ad hoc clusters with multi-hop routing. Collaborative networks of cognitive radios are required to achieve the next level of performance, and we have proposed a specific *CogNet* protocol architecture to enable the formation and operation of these adaptive wireless networks. The new network architecture for cognitive radios separates the operations of control plane from data plane, were the CSCC protocol serves as the foundation to implement control functions such as bootstrapping, network discovery, cross-layer routing, resource coordination and naming/addressing services involved in ad hoc collaboration. The global control plane helps cognitive radio nodes to self-organize into collaborative ad hoc networks and self-configure themselves with proper communication parameters for data transmissions carried on in the data plane. Control protocol components are validated using a combination of ORBIT experiments and *ns-2* simulations and evaluated in terms of network formation latency, control overhead used, etc.

6.2 Future Directions

This thesis has studied both spectrum etiquette protocols and various coordination policies and algorithms for co-existing heterogeneous wireless networks and future cognitive radio networks. The proposed CSCC approach can serve as a foundation to solve many other wireless network problems including resource allocation and network cooperation.

In future work, different spectrum etiquette policies can be further designed and studied, such as spectrum auction and brokerage using dynamic pricing or game theory to resolve resource contentions between users. When the channel is congested, each user can offer to pay a price, or distributing tokens for accessing spectrum resources, and the winner of the auction then proceeds to transmit. Fairness issues for resource allocation can also be further studied. Our current work is mostly based on simple priority-based, or first come first serve based policies to resolve contention. Even the priority-based policies can be carefully designed where all the traffic in the network is classified with different access priority (e.g., streaming traffic has a higher priority than web traffic), and QoS requirements can also be considered as part of the policy. It is important to embed individual traffic QoS requirement in future designs. The proposed spectrum etiquette protocol, together with related policies and algorithms can also be made available to future spectrum policy and standardization processes concerned with efficient use of the spectrum.

We have proposed a new network architecture with control protocol components for future cognitive radios to form into adaptive wireless networks. This thesis focuses on the basic control protocol design for ad hoc collaborations between cognitive radios nodes, but the integration of cognitive radio networks into future Internet is also an important topic which can be explored in future work. The network integration will need more complex protocol designs regarding nodes' naming and addressing, global service and QoS issues. Another important aspect is to apply the proposed network architecture and cognitive radio protocols to a realistic application scenarios. With the fade-out of analog TVs, there are more and more new opportunities in the VHF/UHF TV bands, especially from 400MHz to 800MHz. It is possible to develop several particular cognitive radio applications such as high speed wireless communication in dense radio environments, or in the mobile vehicular wireless communication scope. In the indoor wireless scenarios, the density of the radio (including multi-radio devices) is continuing to increase in the near future. So the cognitive radio network protocols can be applied in such scenarios to allow network collaboration to improve end-to-end performance. If new cognitive radio hardware is available, the new radio could utilize the vacant TV bands to provide very high speed communication by taking a larger chunk of spectrum for data transfer. In the outdoor usage scenarios, mobile vehicular communication can also utilize the concept of cognitive radios. For example, in the highway, cars can be equipped with new cognitive radios to communicate with neighbors for either traffic information exchange or high speed multi-media transfer, because usually in a highway there are more vacant spectrum opportunities due to the locations.

In this thesis, the proposed protocols are validated mostly using simulations or ORBIT experiments, and we assume the data plane has a set of configurable parameters. In the ORBIT experiments we have to use multi-channel 802.11a nodes for protocol validation. These are due to the fact that currently there is a lack of actual cognitive radio platforms to use. In future work, the proposed protocols can be implemented as a software package on newly developed cognitive radio hardware, e.g., the WiNC2R platform [64][81] being developed in WINLAB, or GNU/USRP2 [67][68] software radios. Then more interesting network scenarios can be created for evaluation. When the software and hardware are available, controlled experiments can be planned in the future on the ORBIT testbed, eventually leading to larger scale outdoor trials.

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