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Medium Access Control Protocols
for Cognitive Radio based Dynamic Spectrum Access Networks

A dissertation submitted in partial satisfaction of the

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by

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To my parents and grand parents

Table of Contents

List of Figures

List of Tables

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ABSTRACT OF THE DISSERTATION

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With the knowledge that a majority of licensed spectrum is underutilized in both time and frequency, the concept of dynamic spectrum access (DSA) has been proposed to alleviate the spectrum scarcity problem that wireless communications face today. In DSA networks (DSAN), as being standardized in IEEE 802.22, Cognitive Radio (CR) has been employed as an enabling technology to allow unlicensed radio transceivers to operate in the licensed bands at locations where that spectrum is temporally not in use.

One of the key challenges of the CR-based DSANs is to address two conflicting requirements: QoS assurance for DSANs and reliable protection for licensed user. This problem is overcome by a technique proposed in IEEE 802.22 called Dynamic Frequency Hopping (DFH) where data transmission of a DSAN is performed in parallel with spectrum sensing. We present the principle of DFH and the coordination mechanisms that allow multiple DSANs operating in DFH mode to achieve efficient spectrum usage and reliable spectrum sensing. Seemingly, dynamic sharing of the scarce spectrum among the collocated networks is another challenge of DSANs. We describe a distributed spectrum sharing protocol called On-demand Spectrum Contention (ODSC) that uses interactive MAC messaging to enable efficient, scalable, and fair inter-network spectrum sharing. Additionally, in order to support coordinated DFH, ODSC, and other inter-network coordination functions, we introduce a beacon-based inter-network communication protocol called Beacon Period Framing (BPF) that realizes reliable, efficient, and scalable over-the-air inter-network communications.

1 Introduction

Nowadays, the explosive growth in the wireless services industry has resulted in steady increase in demands for spectral bandwidth despite the fact that radio spectrum is a finite natural resource. In order to avoid a potential spectrum scarcity problem while satisfying the spectral needs of both current and future wireless services and applications, new solutions for spectrum policy making and wireless technology development that would help provide more available radio spectrum are being critically studied.

To facilitate the coexistence of difference wireless services that cause minimal interference to one another, the current policies of spectrum allocation is based on static band assignments designated for a particular service. Considering the fact that bandwidth demands may vary significantly in both time and space, such fixed spectrum allocation may result in a large amount of “white space” [1] (allocated spectrum that is not in use) and poor spectrum utilization – even though frequency assignment data show there is little or no unassigned spectrum in most bands of interest.

There are many reasons for the white space [2]. Some is due to the large peak-to-average use ratio of many systems that have dedicated spectrum, such as those used for public safety mobile users. Another reason is that spectrum assignments are designed to accommodate the practical receiver limitations, such as limited adjacent channel and image frequency rejection. Some white space is caused by spatially non-uniform population and hence demands for the spectrum.

With the knowledge that a large amount of licensed spectrum is underutilized in both time and frequency, the concept of dynamic spectrum access (DSA) has been proposed as a promising solution to the potential spectrum scarcity problem, where unlicensed devices (the secondary uses) temporarily "borrow" frequency bands from spectrum licensees (the primary users) while at the same time respecting the rights of the incumbent license holders.

In particular, the DSA approach requires that the secondary users shall not cause any harmful interference to the primary users as well as the other unlicensed users sharing the same portion of the spectrum. Since primary users hold exclusive rights to the spectrum, it is not obligated for them to mitigate any additional interference caused by the operation of the secondary devices. The unlicensed devices will have to periodically sense the spectrum to detect the incumbents and other secondary users' transmission and should be able to adapt to the varying spectrum conditions for mutual interference avoidance [3].

To meet the requirements of awareness and adaptation for the secondary operations, cognitive radios [4] have been identified as a key enabling technology for DSA based wireless networks, where the operating parameters (such as frequency, power, and modulation) of the unlicensed device can be rapidly reconfigured to the changing communication requirements and spectrum conditions of the transmission environment. Based on software-defined radio (SDR) technology [5], cognitive radios are able to provide greater flexibility and access to spectrum, and improve the spectrum utilization by seeking and opportunistically utilizing radio resources in time, frequency and space domains on a real time basis.

In the past, cognitive radios have been limited to the spectrum occupied by unlicensed devices [2]. However, a significant change in how cognitive radios technology is applied can be foreseen. In May 2004, the Federal Communication Commission (FCC), following up on its landmark Spectrum Policy Task Force (SPTF) report in 2003, released a proposal in Docket 04-186 [1] that recommends the possible use of cognitive radio technology for low power unlicensed devices to share spectrum in the VHF and UHF television bands.

The FCC's proposal favors TV bands for the initial effort of cognitive radio based DSA network due to a number of reasons as follows [2]:

- There is a substantial amount of unused spectrum available in the TV bands.
- The propagation properties of the frequencies in the TV bands benefit long range, non-line-of-sign (NLOS) communications and provide excellent building penetration, comparing to the microwave frequencies used for, e.g. IEEE 802.11 unlicensed wireless LAN technology.
- TV broadcast systems usually use high antennas, and the intended receivers need greater than 10 dB signal-to-noise ratio (SNR) to operate (higher for analog NTSC). These large SNR ratios simplify the technology needed to detect the presence of TV services on a TV channel.

- TV transmitters have deterministic usage patterns in time (left on more or less continuously), location, and frequency. Thus, it appears that it would be simpler to use cognitive radio in TV bands than in any other band.
- The 6MHz bandwidth of TV channels makes the TV spectrum very attractive for the use of wireless broadband services.
- Since there is only a small portion of households that depend on over-the-air TV broadcast, the impact of having the harmful interference to TV users would be small in TV bands.

Based on cognitive radio technology, IEEE802.22 [6], following the FCC Notice of Proposed Rulemaking (NPRM) [1] in 2004, is an emerging standard based on the concept of Dynamic Spectrum Access for Wireless Regional Area Networks (WRAN) that operate on unlicensed and non-interference basis in the TV bands (between 47-910 MHz). It aims at providing alternative broadband wireless Internet access in rural areas without creating harmful interference to licensed TV broadcast.

An IEEE 802.22 WRAN system (or a WRAN cell) consists of a Base Station (BS) and the associated Customer Premise Equipments (CPE) that communicate to the BS via a fixed point-to-multi-point radio air interface. The typical radius of the coverage area is 33 km. Apart from coexisting with TV broadcast services, IEEE 802.22 systems also have to be aware of FCC Part 74 devices (such as licensed wireless microphones) and other licensed devices in the TV bands. It is envisioned that channel (frequency) availability for data transmission of a WRAN system is determined by referring to an up-to-date incumbent database augmented by distributed spectrum sensing performed continuously both by the BS and the CPEs [6].

One of the key challenges of the cognitive radio based Dynamic Spectrum Access Networks (such as IEEE 802.22 Wireless Regional Area Networks) is to address two apparently conflicting requirements: assuring Quality of Services (QoS) satisfaction for DSA network services, while providing reliable spectrum sensing for guaranteeing licensed user protection [7]. To perform reliable sensing, in the basic operation mode on a single frequency band (the so called “listen-before-talk” mode) one has to allocate Quiet Times, in which no data transmission is permitted. Such periodic interruption of data transmission could impair the QoS of DSA networks.

This critical issue can be addressed by an alternative operation mode that we have proposed in IEEE 802.22 called Dynamic Frequency Hopping (DFH) [8] where data transmission of the DSA networks are performed in parallel with spectrum sensing without any interruption. However, efficient frequency usage and mutual interference-free spectrum sensing could only be achieved if multiple neighboring DSA network cells operating in the DFH mode coordinate their frequency hopping behaviors.

Motivated by this requirement we further propose the concept of coordinated DFH and assess its advantages. The key idea of the coordinated DFH is that neighboring DSA network cells form cooperating communities, which choose their hopping frequencies and perform DFH operation in a coordinated manner. In addition, we develop concepts of fundamental mechanisms for managing such cooperative DFH operations in this work [7].

Although avoiding harmful interference to licensed incumbents is the prime concern for the system design, another key design challenge to cognitive radio based DSA systems is how to dynamically share the scare spectrum among the collocated DSA network cells so that performance degradation, due to mutual co-channel interference, is effectively mitigated. Moreover, it's important that the inter-network spectrum sharing scheme should be developed to maintain efficient spectrum usage, accommodate a large scale of networks with various coexistence scenarios, and provide fairness in spectrum access among the coexisting DSA network cells [10].

To that end, we describe in this work a distributed, cooperative, and real-time spectrum sharing protocol called On-Demand Spectrum Contention (ODSC) [8, 11] that has been proposed to IEEE 802.22. On-Demand Spectrum Contention (ODSC) employs interactive MAC messaging on an inter-network communication channel and provide efficient, scalable, and fair inter-network spectrum sharing among the coexisting 802.22 cells [10].

Apparently, the effectiveness of both the coordinated DFH and ODSC protocols relies on the availability of an efficient and reliable inter-network communication channel for the interactive MAC message exchanges among network cells. In fact, a reliable inter-network communication channel is also indispensable to many other inter-network coordinated functions for cognitive radio based DSA networks (e.g. inter-network synchronization of quiet periods for spectrum sensing). As the third contribution in this dissertation, we introduce a beacon-based inter-network communication protocol called Beacon Period Framing (BPF) Protocol that realizes a reliable, efficient, and scalable inter-network communication channel reusing the RF channels occupied by the DSA network cells for their data services.

This dissertation is organized as follows. Chapter 2 gives a comprehensive overview on Cognitive Radio based Dynamic Spectrum Access networks, highlighting the fundamental concepts, management models, system architectures, techniques, and design challenges. In Chapter 3, the emerging IEEE 802.22 standard is then introduced with design details on many key aspects including the physical (PHY) layer, the medium access control (MAC) layer, the system models, and the cognitive spectrum management functions. The Dynamic Frequency Hopping techniques and the coordinated frequency hopping protocols are detailed in Chapter 4. Further analyses on DFH are provided in Chapter 5, which evaluates the operation performance of a distributed hopping approach as compared to a centralized management scheme. Chapter 6 addresses the design challenges on the inter-network coexistence and inter-network communications. Detailed descriptions and performance evaluations are provided for the ODSC protocol and BPF protocol. Chapter 7 discusses a number of related design issues, proposes the future work, and concludes the dissertation.

2 Dynamic Spectrum Access Networks

2.1 Introduction

The increase in spectrum demand, which has occurred, internationally, in the last 10-15 years as a consequence of booming wireless communications, has placed considerable pressure on traditional (administrative, command-and-control) regulatory arrangements for spectrum access and use.

In the commend-and-control mode, the available radio spectrum is divided into fixed and non-overlapping segments separated by guard bands and assigned to different services and wireless technologies. These spectrum segments are licensed for exclusive use to carriers, radio and TV broadcasters, specialized wireless service providers, corporations, the military, and public safety agencies.

The static partitioning of spectrum has left very little useful spectrum to allocate both for new technologies and services and for expansion of existing services. On the other hand, extensive spectrum usage measurements in the USA [12] and Europe [13] show that considerable parts of the spectrum, although dedicated to specific services, are actually not used for significant periods of time, ranging from seconds to minutes [35], as depicted in Figure 2-1. This has brought to light the inefficiency of the existing regulatory model of spectrum management. Consequently, regulatory bodies around the world are in the process of re-thinking their spectrum policies, and are seeking alternative spectrum management models, which allow a much more efficient and flexible utilization of the spectrum.

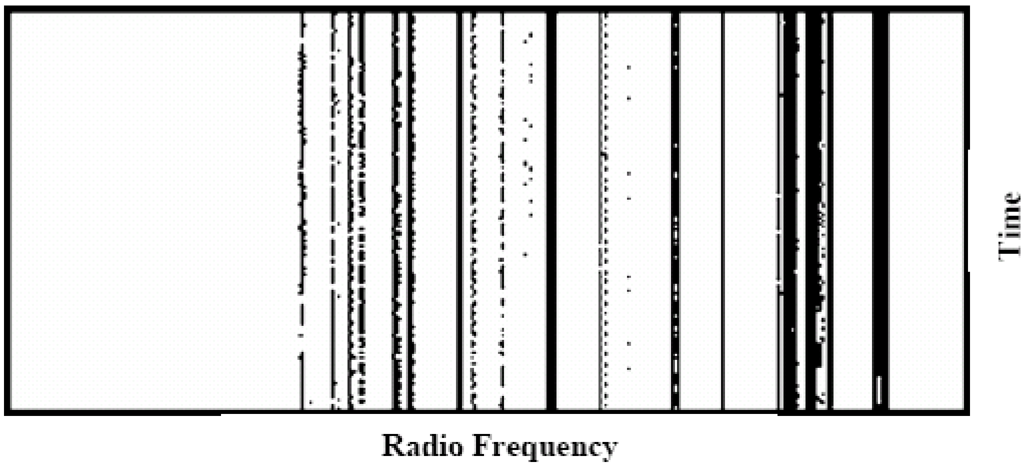

Figure 2-1 Spectrum usage of approximately 700 MHz below 1 GHz during 1 hour in Atlanta in June 2002, a black dot denotes "in use" [17]

Three distinct new models for spectrum management being considered [14, 15] are:

- The market model,
- The license-exempt model (open spectrum),
- Secondary usage of licensed spectrum.

The market model enables the allocation and use of spectrum be decided by market players through spectrum trading. This includes, for example, a partial transfer of a licensee's rights to spectrum (for example a TV broadcaster or 3G operator) either for a limited period of time and/or a portion of the spectrum designated in the license, and the possibility of partitioning and aggregating spectrum according to user's needs [35].

In the license-exempt (open spectrum) model [16], regulators allocate segments of the spectrum that is open to be used by any radio system under a minimum set of restrictions called spectrum etiquette [35]. The unlicensed 2.4 GHz frequency bands, in which both Wireless LAN (e.g. IEEE802.11b/g) and Bluetooth technology operate is a highly successful example of applying the license-exempt model. Currently, there is an increasing pressure on regulators to greatly extend license-exempt spectrum in order to accommodate the ever-increasing growth in wireless devices operating in these bands.

The secondary usage model of licensed spectrum allows licensed but under-utilized frequency bands to be accessed by the secondary unlicensed users, given that the secondary operations do not cause any harmful interference to the licensee (the primary user or incumbent user). There are two essential approaches for the secondary spectrum usage: the “Underlay” approach and the “Overlay” approach.

The underlay sharing approach allows the secondary radio systems to access most of the radio spectrum concurrently with the primary systems, with minimal transmission powers as strictly limited by the regulatory authorities to reduce the potential interference. Such techniques as Ultra-wide band (UWB) that spread the emitted signal over a large band of spectrum and enforce a spectral mask on the transmission signals are used so that the undesired signal power seen by the incumbent radio systems is below the acceptable noise floor of the primary users.

The “overlay” operation allows the secondary devices to identify sections of idle spectrum (the “white spaces”) in the licensed frequency bands, and to transmit over these bands when they are not in use. One application of such secondary approach is the unlicensed reuse of TV broadcast bands by employing the cognitive radio systems, which are being proposed in the emerging IEEE802.22 standard for wireless regional access networks. We focus our work on the overlay spectrum management in this dissertation.

An important consequence of recent reforms to spectrum management is that they open up the possibility to exploit dynamic spectrum access (DSA), an emerging paradigm in wireless communications and networking. The key characteristic of DSA systems is their ability to exploit knowledge of their electromagnetic environment and adapt their operation to access the spectrum without causing harmful interference to the licensed user. The key promise of these systems is that they provide the opportunity to explore highly flexible and efficient management and use of spectrum across the dimensions in frequency, time, location and code [35]. It is not the scarcity of spectrum that causes the problem, rather it is the lack of ability to dynamically access spectrum that prevents the new communications services to be developed.

2.2 Architectures of Dynamic Spectrum Access Networks

In order to enhance the spectrum efficiency and provide flexible access to the available spectrum, unlicensed devices should be adequately managed in the DSA networks. In general, there are three basic types of DSA architectures for managing dynamic spectrum access: the centralized architecture, the distributed architecture, and the autonomous architecture.

2.2.1 Centralized Access Architecture

The centralized access architecture is a management model in which the management of spectrum opportunities is controlled by a single entity or node, which is called the spectrum broker. The spectrum used for dynamic access could be exclusively reserved by regulatory authorities, or identified by the spectrum awareness capabilities of the DSA systems in a distributed manner. The spectrum broker, which centrally manages the spectrum, is responsible for deciding which spectrum opportunities can be used and by which radios in the network. Dedicated frequencies within the spectrum managed by the spectrum broker are in general allocated as spectrum information channels for the purpose of exchanging information among network devices.

2.2.2 Distributed Access Architecture

In the distributed access architecture, the unlicensed devices in the network are collectively responsible for identifying and negotiating use of underutilized spectrum (i.e. the spectrum opportunity). In certain scenarios, the distributed mode of spectrum access management may be between the co-operative radio access networks. The distributed access architecture can be further divided into two sub-models: the centralized model and the de-centralized model.

In the centralized model, such as the one adopted by IEEE 802.22, the dynamic access network cell consists of a base station (or access point) and a number of user terminals. The base station and the user terminals collaboratively perform spectrum sensing in order to ensure detection and protection of the incumbent users in the licensed bands, and to identify the spectrum opportunities for their communications.

In the de-centralized model, as proposed in [18], a group of unlicensed devices form a user group to ordinate their spectrum sensing and communications. The members in the group collectively manage a pool of available spectrum that is verified through spectrum sensing, and coordinate their operations (sensing and communications) using a number of underlay (UWB-like) control channels.

2.2.3 Autonomous Access Architecture

In the autonomous access architecture, each unlicensed devise independently performs spectrum sensing identifying potential licensed incumbent users, and attempts to optimize its signal transmission on the identified spectrum opportunities in response to the transmission characteristics of the licensed incumbent users and other unlicensed devices. The most well known example of dynamic access networks using the autonomous management approach is XG (next generation) project conducted by the Defense Advanced Research Project Agency (DARPA) in the U.S. [19, 20], which are targets military applications.

2.3 Challenges of Dynamic Spectrum Access Networks

There are several challenges for the unlicensed devices in the dynamic spectrum access networks to exploit the spectrum opportunity, which is defined by location, time, frequency, transmission power, and code. We identify and describe a few of the most fundamental challenges, among others, as follows.

The first challenge is how to accurately identify the spectrum opportunities so that the licensed incumbents’ operation can be protected. The second challenge is how to efficiently utilize the spectrum opportunities to support the quality of services of the secondary radio system without cause harmful interference to the licensed incumbents. And the third challenge is the way as of how the distributed cognitive radio systems coordinate with regards to the usage of spectrum opportunities.

2.3.1 Identification of Spectrum Opportunities

In order to reliably protect the licensed incumbent in the licensed spectrum from being harmfully interfered by secondary devices, the spectrum opportunities need to be accurately identified. However, identifying spectrum opportunities is a challenging problem as discussed in [21].

Different types of licensed users have different requirements of sensitivity and rate of sensing for detecting their presence. Generally, the sensitivity of the sensing receivers of the cognitive radios should outperform the licensed receivers by a large margin so as to avoid the “hidden node” problem of opportunistic spectrum access. We refer to the “hidden node" problem here as that an unlicensed radio that is capable of detecting the transmission of the licensed transmitter starts its own transmission, which cause interference to the licensed receivers that are in the close proximity of the cognitive radio transmitter.

FCC in its proposal [1] identifies three possible techniques that might allow unlicensed radio devices to determine whether the white space in TV band is available for secondary use at a given location:

- Detecting the presence of a TV signal through passive sensing ("listen-before-talk");
- Geo-location based method using GPS or other technologies aided by a database to verify what frequencies are occupied by incumbent in the proximity;
- Employing dedicated beacon transmission to signal the unavailable spectrum in the neighborhood.

2.3.2 Coexistence for Spectrum Access

Unlicensed radios operating in the licensed bands shall be designed to share the spectrum with licensed incumbent system designated for exclusive spectrum use, and/or with other unlicensed radio systems. Coexistence capability for spectrum access enables the unlicensed radios to achieve the goal of interference avoidance between the secondary users and the licensed incumbents (and/or the other unlicensed radio systems) that are sharing the spectrum in a distributed communication environment.

In particular, we refer to the interference-avoided sharing of the secondary radio systems in the licensed spectrum with licensed incumbent systems as vertical coexistence. Similarly, the spectrum sharing between the secondary radios in either licensed or unlicensed bands with interference avoid in mind is referred to as horizontal coexistence. Both vertical and horizontal coexistences require the unlicensed radio devices to have the capability of identifying spectrum opportunities (We focus on the scenarios where spectrum opportunities are not exclusively allocated for dynamic access).

Vertical coexistence helps avoid neither a lengthy and expensive licensing process nor a re-allocation of spectrum to the new wireless services. Although unlicensed radios with dynamic spectrum access capabilities (such as spectrum sensing) are able to operate in the sporadically used licensed spectrum without causing harmful interference to the licensed incumbents that are not required for any system modification, the licensed radio systems may assist the unlicensed radios to identify the spectrum opportunities in vertical coexistence scenarios. Some methods of such assistance include:

- Beacon transmission generated from the licensed users to inform the permission or prohibition of the spectrum access, and
- Predictable spectrum usage patterns of the incumbent users, which are accessible by using a spectrum usage database.

In horizontal coexistence scenarios, the DSA-capable unlicensed devices identify opportunities and coordinate their usage with one another, using the spectrum management architectural models as described in the previous section. To achieve sustainable spectrum usage, the unlicensed radio systems in general need to operate in compliance with a set of spectrum etiquette rules or protocols. The goals for designing the spectrum etiquette and coexistence protocols are:

- Mitigation of harmful interference among coexisting unlicensed radio systems;
- Efficient utilization of the spectrum opportunities;
- Fair sharing of the spectrum opportunities among the coexisting unlicensed radio systems.

2.3.3 Quality of Services Assurance

Another key challenge for dynamic spectrum access network to address two apparently conflicting requirements: assuring the QoS satisfaction for the services offered by the DSA network devices, while at the same time providing reliable spectrum sensing for guaranteeing licensed user protection. To perform reliable incumbent detection applying the basic listen-before-talk method on a single frequency, the unlicensed radios have to allocate quiet times for spectrum sensing, which would interrupt data transmission and therefore impair the QoS of DSA networks.

2.4 Cognitive Radio – the Enabling Technology of DSA Networks

To meet the requirements of awareness and adaptation for the secondary operations, cognitive radios have been identified as a key enabling technology for DSA based wireless systems and networks, where the operating parameters (such as frequency, power, modulation, and code) of the unlicensed device can be rapidly reconfigured to the changing communication requirements and spectrum conditions of the transmission environment. Based on software-defined radio (SDR) technology, cognitive radios are able to provide greater flexibility and access to spectrum and improve the spectrum utilization by seeking and opportunistically utilizing radio resources in time, frequency and space domains on a real time basis.

2.4.1 Cognitive Radio Architecture

Figure 2-2 shows the architecture of the cognitive radio at a high-level of abstraction. The cognitive radio identifies and determines the conditions (spectrum and location) in the radio environment through the Awareness function. The radio environment information collected by the awareness function then is fed to the cognitive engine, which is the central decision maker of the cognitive radio. With the capabilities of learning and reasoning, and taking the Regulatory Rules and Incumbent Database into account, the cognitive engine analyzes the radio environment and manages how the cognitive radio reacts to the radio environment through the function of Adaptation, among others, attempting to achieve various communication objectives (such as interference avoidance, Quality of Services, fair spectrum sharing, and etc.). The function of Collaboration, controlled by the cognitive engine, allows the cognitive radio to effectively communicate and collaborate with other radio systems in the environment so as to optimize the network-wise performance.

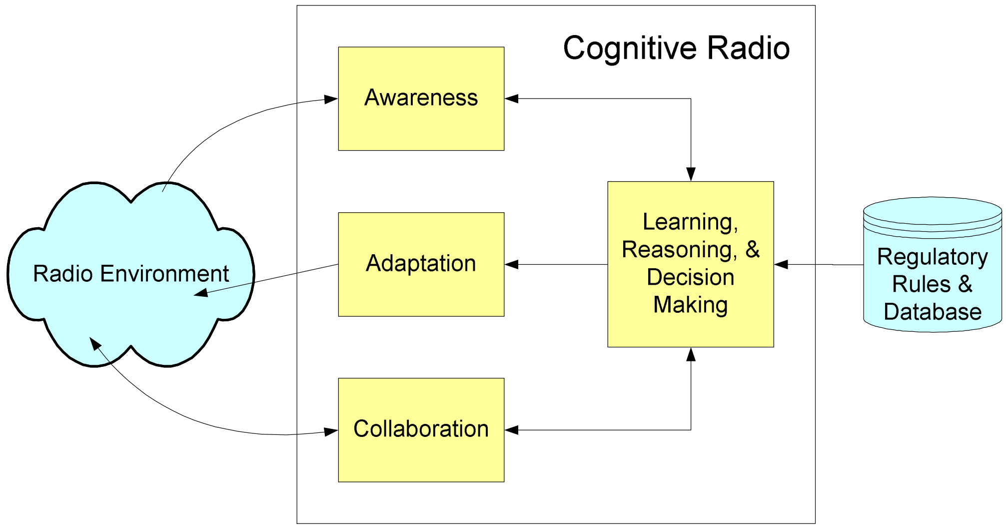

Figure 2-2 Cognitive Radio Architecture

2.4.2 Software Define Radio – the Re-configurable Platform

A software defined radio (SDR), as the re-configurable platform of the cognitive radio, is a software programmable radio system that is able to support multiple air interfaces and network protocols, utilizing wideband antennas, RF conversion, and analog to digital (A/D) and digital to analog (D/A) conversion. Typically, functionalities of a SDR including Intermediate Frequency (IF) processing, Base-band processing, and data transmission processing are implemented in software on digital signal processors (DSPs), general purposed processors (GPPs), or FPGAs. We introduce the basic Hardware architecture and major design challenges of software defined radios in this the sub-section.

2.4.2.1 Basic Hardware Architecture of Software Defined Radio

The basic components of a software defined radio include the following units [5, 36]:

- Antenna unit
- Radio frequency (RF) processing unit
- Wideband analog-to-digital (A/D) and digital-to-analog conversion (D/A) unit
- Intermediate frequency (IF) processing unit
- Base band processing unit
- Bit-stream control unit
- Source interface unit
- End-to-end timing control unit

A. Antenna Unit

In order to provide access to a variety of wireless communication systems, the antenna unit is typically required to be omni-directional, low-loss, and wideband. For an improved performance of the radio system, signal processing techniques based on multiple antenna elements (array antennas) such as space division multiple access (SDMA) and interference cancellation can be employed to allow the software defined radio to select the optimal operation parameters and algorithms adapting to the environment. An antenna with such capabilities is called a smart antenna or software antenna [30, 31, 32]. The multiple access of a smart antenna unit is accomplished by forming beam toward the direction of the targeted user or allocating null points to the direction of undesired users or interferers such that the system capacity and coverage are improved.

B. RF Processing Unit

The RF processing unit in a transmitter up-converts the intermediate frequency (IF) signals to the radio frequency (RF) signals, then amplifies, and transmits the converted signals to the antenna unit. In the receiving path, the received signals from the antenna unit are pre-amplified to a constant level and down-converted to lower frequency band (the intermediate frequency) that is suitable for signal processing such as wideband A/D conversion. Typically, RF conversion and processing are done in the analog domain. While the down-conversion method is the key technical point, it is also important for a wideband software defined radio system to maintain the amplifier linearity and efficiency across the frequency band.

C. A/D/A Conversion Unit

In the A/D/A conversion unit, the amplified analog signals from RF or IF are sampled and converted to digital signal in the receiving path, and the digital signals are converted to analog signals that are to be transmitted by the upper-frequency band unit such as RF or IF unit. The sampling technique is the key in the A/D/A unit. According to the Nyquist criterion for band limited signal f_s, the sample rate of the A/D conversion must be at least two times of the bandwidth of the IF to be digitized, W_a. In practical systems, modest over-sampling is typically performed: $f_s > 2.5\ W_a$.

In a software defined radio, wideband A/D/A conversion unit is typically employed to access a broad segment of spectrum (e.g. 10~50 MHz). As the product of dynamic range and sampling rate is approximately constant for a A/D technology, sampling over several narrower sub-bands in parallel can be considered to increase the useful dynamic range at the cost of increasing system complexity.

D. IF Processing Unit

The key operations in the IF processing unit is to perform frequency conversion and wideband digital filtering. This unit amplifies and converts the transmitted and received signals between the base-band and intermediate frequency. When multiple signals from different services are presented at the receiver, the software defined radio's wideband digital filtering in the IF processing unit select the appropriate service frequency band.

E. Base-band Processing Unit

The base-band processing unit digitally modulates and transfers the data to the A/D/A unit or IF processing unit in the transmitting path. Conversely in the receiving path, the incoming data are recovered through demodulation. In addition to modulation and demodulation, the other key functions in the base-band processing unit include framing, forward error coding, mapping (together with modulation), and transmission filtering in the transmitter, and receiving filtering, code and symbol timing, sampling rate conversion (re-sampling), de-mapping (together with demodulation), decoding, fading compensation, and interference cancellation in the receiver.

The complexity of performing the key functions in the base-band processing unit is determined by the base-band bandwidth W_b, the complexity of the signal waveform and the related signal processing such as coding/decoding. For typically encoded waveforms such as binary phase shift keying (BPSK) and quardrature phase shift keying (QPSK) with a symbol rate of R_b, we have the following relation, assuming such waveforms are generated one sample at a time: $R_b < W_b < 2^* R_b$. Over-sampling will decrease the transmitted power of spectral artifacts and increase the transmit power and processing demand (W_b). On the other hand, digital modulations require in the receiver path timing recovery with extended precision (e.g. up to 96 bit) arithmetic, which may be difficult to implement.

F. Bit-stream Control Unit

The bit-stream control unit, implementing the medium access control (MAC) protocols, digitally multiplexes/de-multiplexes source coded bit stream (service data) from/to multiple users. It provides functionalities of channel bandwidth allocation, delivery of service data and control messages, security management, and OA&M (operations, administration and maintenance). The processing demand of the bit-stream control unit increases linearly with the number of simultaneously active subscribers.

G. Source Interface Unit

The source interface unit of a software radio provides and manages the input/output (I/O) interfaces to the external data sources in flexible manners. In a user terminal, the data sources include the user and the source encoder and decoder. On the other hand, the source interface unit in a base station needs to interface with the PSTN (public service telecommunication networks) or the Internet. Protocol convergence and interoperability with external networks create processing demand in the base station's source interface unit.

H. End-to-end Timing Control Unit

The end-to-end timing control unit controls the transmission delay between the transmitter and the receiver. The end-to-end delay is introduced by the external network, and by each processing stage in the transmit/receive chain of the radio device due to finite processing and I/O resources.

2.4.2.2 Design Challenges of Software Defined Radios

A. High Quality Wideband RF Access

It seems to be very challenging to use a single RF stage for a wideband system due to the difficulty of building antennas and LNAs on a bandwidth ranging from hundreds of megahertz to units or tens of gigahertz. It is more practical to use multiple RF stages depending on the frequency band used for the software radio to achieve wideband RF access.

B. Wideband A/D/A Conversion and Direct A/D/A Conversion at RF

There is a trade-off between the sampling rate and the resolution (i.e. the number of bits representing the signal samples) – the higher the sampling rate, the lower the resolution. Taking into account the high dynamic range of the signals to be sample, low sampling resolution may not be adequate. However, with today's technology, 1 Giga sample per second could only allow a resolution of 6-8 bits to represent the sampled signal. The limited resolution for the sampled signals, frequency jitter, and inter-modulation products are the key challenges for wideband A/D/A conversion. Moreover, Jitter effects make A/D conversion directly at RF very difficult. [33, 34]

C. Computing Capability of the DSP Hardware

In order to execute a large number of complex communication functions in real time employing software, the DSP hardware is required to have sufficient computing capabilities in terms of processing speed and power consumption. The computing demand is further increased when multiple systems are active simultaneously. In addition to a sufficient processing speed, low power consumption is another key design constrain for a software radio based mobile terminal which is powered by a battery.

2.4.3 Cognitive Functions

2.4.3.1 Awareness

The awareness function of the cognitive radio includes spectrum awareness and location awareness as described in the following.

2.4.3.1.1 Spectrum Awareness

Spectrum Awareness (Spectrum Sensing) is the capability that a cognitive radio system uses to determine the spectrum availability through observation and analysis of the radio frequency spectrum. It's required that the unlicensed operations of the cognitive radio system shall not cause any harmful interference to the licensed operations of the primary users. In general, however, there is no obligation for the primary systems to adjust their operation behaviors in order to coexist with the secondary devices. Therefore, the cognitive radio system shall be able to reliably detect the present of the licensed operations in the proximity through spectrum sensing that satisfies a variety of restricted sensitivity requirements. Spectrum sensing is based on the hypothesis model as described below.

Basic hypothesis model for licensed incumbent detection can be defined as follows:

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

where *x(t)* is the signal received by the sensing receiver of the cognitive radio, *s(t)* is the transmitted signal of the incumbent user, *n(t)* is the additive white gaussian noise (AWGN) and h is the amplitude gain of the channel. H_0 is a null hypothesis, which states that there is no licensed user signal in a certain spectrum band. On the other hand, H_1 is an alternative hypothesis, which indicates that there exists some licensed user signal. If the sensing receiver mistakenly determines that H_0 is H_1, the cognitive radio will miss a spectrum opportunity. We call such situation a false alarm. On the other hand, when H_1 is regarded as H_0, it is called a misdetection, which would lead to harmful interference created by the cognitive radio to the incumbent users.

We can evaluate the detection performance of the sensing receivers using the receiver operating characteristic (ROC) curve. The ROC curve, as shown in Figure 2-3, specifies the probability of detection (the true positive rate) as a function of the probability of false alarm (the false positive rate).

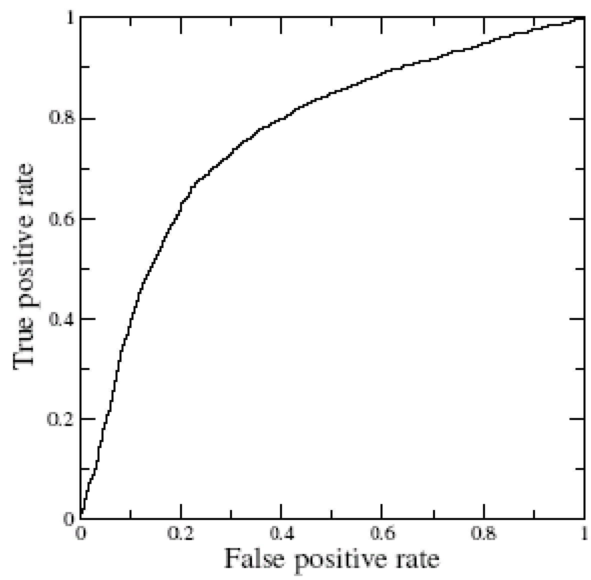

Figure 2-3 Receiver Operating Characteristic Curve

A number of digital signal processing techniques have been proposed to effectively perform spectrum sensing for cognitive radio systems. These techniques are at large categorized into the following three types: match filtering [23], energy detection [24], and Cyclostationary feature detection [25]. If one of these sensing techniques is utilized independently by each cognitive radio device, however, their performance may be degraded significantly resulted from multi-path fading and shadowing. Cooperative spectrum sensing has been considered as a key solution to address such limitation by offering a distributed framework to cooperatively collect signal strengths of licensed incumbents from spectrum sensors in various locations of a cognitive radio network.

2.4.3.1.2 Location Awareness

The location awareness is the capability that a cognitive radio system uses to determine its location and the location of other transmitters in a particular radio environment. With the location information, the cognitive radio can determine whether it is allowed to transmit, and if it is allowed, the appropriate operating parameters such as the power and frequency that can be selected at its location.

The location of a cognitive radio can be determined by using geo-location system such as Global Positioning System (GPS) or Galileo, which additionally provide the cognitive radio the accurate global time information therefore enabling time awareness as well. Another alternative for determining location information for a cognitive radio is to employ method based on angle or time-of-arrival measurements.

The location awareness capability benefits the cognitive radio for reliably protecting the licensed incumbent by inquiring the incumbent database to determine the usable set of channels at its location. Moreover, when two cognitive radios are setting up a communication link with each other, the location information helps make optimal use of the channel for the communications.

2.4.3.2 Adaptation

The adaptation is the capability of the cognitive radio to adjust the operation parameters, which include operating frequency, modulation, coding, and transmission power, adapting to the dynamic radio environment. The basic operations of the parameter adaptation are described as follows.

2.4.3.2.1 Dynamic Frequency Selection

Dynamic frequency selection (DFS) is to allow the cognitive radio to change its operating frequency to avoid harmful interference to the licensed incumbents or optimize the spectrum usage under certain conditions.

2.4.3.2.2 Adaptive Modulation and Coding

Adaptive modulation and coding (AMC) is to enhance the overall system capacity by flexibly matching the modulation and coding schemes to the dynamic channel conditions for each radio device. With AMC, the power of the transmitted signal is held constant over a certain interval, and the modulation and coding format is changed to match the current received signal quality or channel conditions. Radio devices that are close to each other are typically assigned higher order modulation with higher code rates (e.g. 64 QAM with R=3/4 turbo codes), but the modulation-order and/or code rate will decrease as the distance increases.

2.4.3.2.3 Transmit Power Control

Transmit Power Control (TPC) is the ability of the cognitive radio to perform transmission at full power limits when permitted and necessary, but constrain the transmitter power to a lower level to avoid harmful interference to the licensed incumbent or to allow greater sharing of spectrum with other unlicensed devices when higher power operation is not necessary.

2.4.3.3 Collaboration

Collaboration is the capability of the cognitive radio that enables the radio system to share the spectrum with the licensed incumbent under the prearranged policies or agreements, or to sharing the spectrum with other collocated unlicensed cognitive radio devices in order to mitigate performance degradation caused by mutual interference. The goal of the collaborative inter-system spectrum sharing (coexistence) is to maintain efficient and flexible spectrum usage, and provide fairness of spectrum access to all the unlicensed devices.

Notably, the effectiveness of the inter-system spectrum sharing would rely on the availability of an efficient and reliable inter-system communication channel. The other aspect of the collaboration function of the cognitive radios, therefore, is the capability that enables the radio systems to effectively establish communications with both the licensed incumbent systems and other unlicensed radio systems in order to coordinate the spectrum utilization.

2.4.3.4 Learning, Reasoning, and Decision Making

The cognitive radio extends the software defined radio with a cognitive engine that is composed of a knowledge base and performs the functionalities of reasoning, learning, and decision making to control the spectrum awareness, adaptation, and collaboration functions in compliance with the regulatory rules and taking into account the licensed incumbent database. A cognitive radio that does not possess the capability of learning is called a "policy-based" cognitive radio, in which the operations are managed by the reasoning function in the cognitive engine by examining the current radio environment and making decisions on how the system should react. On the other hand, the "learning-based" cognitive radios make decisions based on the information specified in the knowledge base that is extrapolated based on both learning and reasoning. Figure 2-4 illustrates the architectural components inside the cognitive engine.

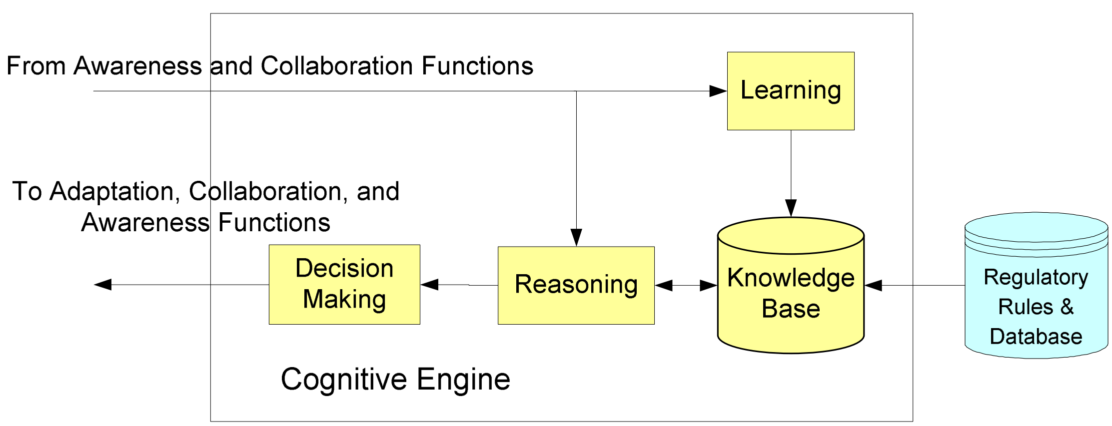

Figure 2-4 Cognitive Engine

The knowledge base in the cognitive engine consists of two data structure: Predicates (in the forms of logic expressions) and Actions. Predicates use the radio parameters to represent the states of the radio environment. On the other hand, actions define the operations that the reasoning function would decide to perform to adapt to the radio environment [26].

The cognitive engine, with the reasoning function, continuously monitors the current state of the system and selects the actions that are most appropriate in that state. To that end, the reasoning function evaluates all the possible actions and search for the optimality determined by an objective function. The decision making function then allocate radio resources for executing the selected optimal actions.

The learning function of the cognitive radio is to manipulate and evolve the knowledge base from the past experience (i.e. the effectiveness of the past decisions under a given set of conditions). The updated information, i.e. the new action list learned from the previous lessons, is stored in the knowledge base for future references used by the reasoning function to make better decisions that are suitable to the dynamically changing radio environment. There are many learning algorithms and tools are being considered for cognitive radios, which include hidden Markov models [27], neural networks [28], and genetic algorithms [29]

3 IEEE 802.22 Standard – an Overview[1]

3.1 Introduction

In December 2002, the Federal Communications Committee (FCC) in the United States released a “Notice of Inquiry” [37] to explore the possibility of allowing access to the TV bands for unlicensed devices on a non-interfering basis. Subsequently, in its Notice of Proposed Rule Making (NPRM) released in May 2004 [1], and its first Report and Order (R&O) and further NPRM released in October 2006 [38], the FCC proposed that TV channel 5 to 13 in the VHF band and 14 to 51 in the UHF band could be used for fixed broadband access systems.

Considering the relatively low levels of industrial noise and ionospheric reflections, reasonable antenna sizes, and good non-line-of-sight (NLOS) propagation characteristics that make the TV channels in the high-VHF and low-UHF bands ideal for providing long range communications in sparsely populated rural environments, such yet to be completed rule-making proceedings of the FCC create a great opportunity to develop systems that are capable of using the TV bands on a non-interfering basis to bring broadband access to rural areas, where there are a large number of vacant TV channels and where the population density is less than 60 person/km^2 , for which cabled media such as Digital Subscriber Line (DSL) and coaxial cable technologies typically make economic sense.

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[1] This chapter is based on the coauthored paper [9].

Other regions of the world will likewise follow the same trend and evaluate the use of this spectrum for broadband access to promote both economic growth and more efficient use of this highly valuable and useful spectral resource. For example, Canada has taken steps in this direction by releasing a subset of TV channels in the UHF band for licensed wireless broadband access in remote rural area [39]. The European Union is also to open the discussion on new use of the TV bands in 2010.

In such context, the development of the emerging IEEE 802.22 standard on Wireless Regional Area Networks (WRAN) is to specify a world-wide applicable cognitive radio-based air interface, including both physical (PHY) and medium access control (MAC) layers, for use by unlicensed devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Services. IEEE 802.22 standard aims to provide wireless broadband access to the hard to reach, low population density areas in a timely and cost efficient manner, while at the same time assuring that the incumbent operations in the TV bands, i.e. digital TV and analog TV broadcasting, and low power licensed devices such as wireless microphones, are adequately protected.

3.2 System Aspect

Figure 3-1 shows the IEEE 802.22 WRAN standard relative to other IEEE 802 wireless data transmission standards in the evolution of wireless communications technologies developed by the IEEE 802 LAN/MAN Standard Committee (LMSC).

IEEE 802.22 WRAN is a fixed point to multi-point network that aims to provide wireless broadband access to the rural area with a typical range of 30 km (up to a maxim of 100 km). A base station (BS), with an omni-directional antenna located at 75 m above the average ground level, provides services to up to 255 fixed Customer Premise Equipments (CPE) that are equipped with outdoor directional antennas located at nominally 10 meters above the ground. The minimum peak capacity at the edge of coverage is targeted to be 1.5 Mbit/s in the downstream and 384 kbit/s in the upstream direction.

The service availability at the edge of coverage of a IEEE 802.22 WRAN is designed to be at least F (50, 99.9). That is, at least 50% of locations (households or businesses) can be reached at the edge of coverage area, and at least 99.9% of the time the services will be available reliably when the service is available in a location.

Due to the extended coverage made possible by the use of the lower frequencies in the TV bands, the PHY parameters are optimized to absorb longer multipath excess delays than what can be accommodated by other IEEE 802 wireless standards. Considering a typical 30km communications range, an excess delay of up to 37 usec can be handled by the OFDM modulation employed by the IEEE 802.22 PHY layer while preserving system spectrum efficiency with a symbol cyclic prefix of 1/8.

For the coverage ranges of more than 30 km that are beyond the absorption capability of the PHY, the MAC layer takes the role to handle the additional propagation delay for the communication distances of up to 100 km through adaptive scheduling mechanisms.

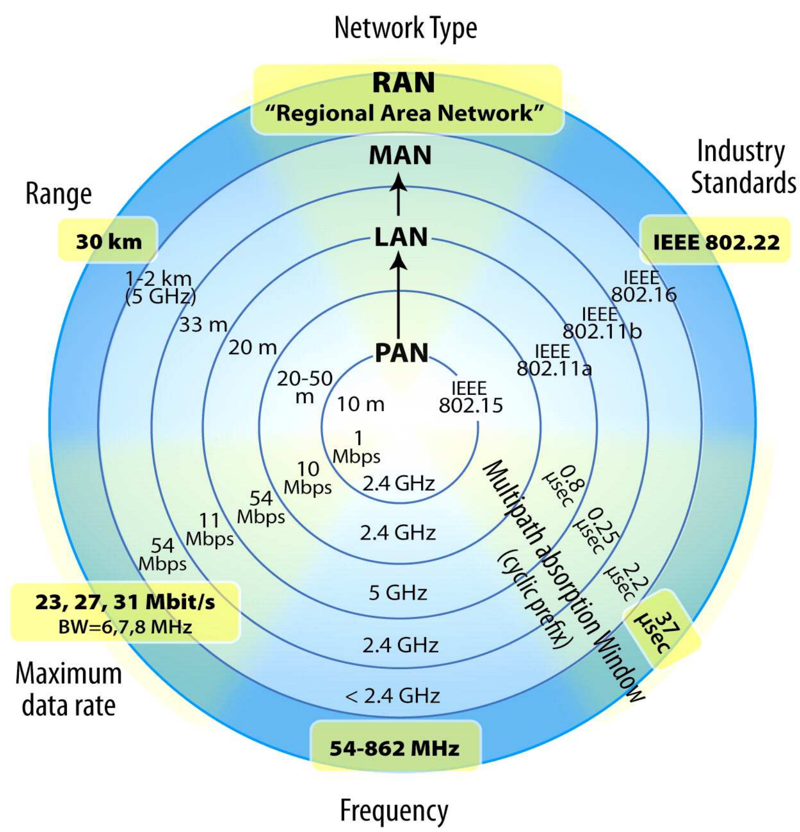

Figure 3-1 IEEE 802.22 Standard Relative to Other IEEE 802 Wireless Communications Standards

3.3 Reference Architecture

As shown in Figure 3-2, the reference architecture for the IEEE 802.22 system specifies the PHY and MAC layers and the interfaces to a Station Management Entity (SME) through PHY and MAC Layer Management Entities (PLME and MLME), as well as to higher layers such as IP, ATM, and IEEE 1394 through an IEEE 802.1d compliant convergence sub-layer.

At the PHY layer there exist three primary functions – the main data communications physical layer (PHY), the Spectrum Sensing Function (SSF), and the Geo-location function. The SSF and Geo-location function provide the spectrum awareness and the location awareness respectively to enable cognitive capabilities of the IEEE 802.22 systems.

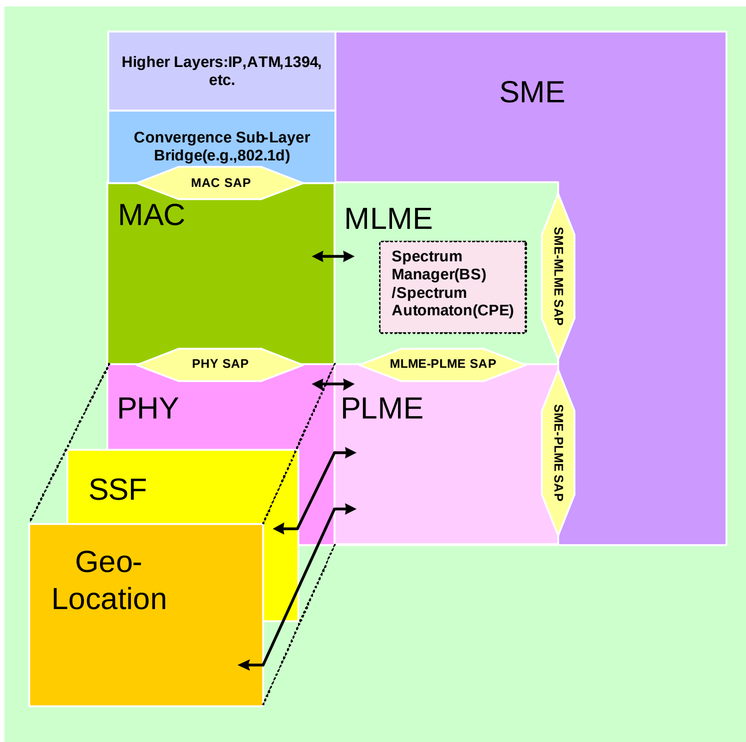

Figure 3-2 IEEE 802.22 WRAN Reference Architecture

As shown, the Cognitive Engine functionality of the IEEE 802.22 system is realized by a functional entity known as the Spectrum Manager (SM) that exists in the MAC Layer Management Entity (MLME) at the BS, or a “lightweight” SM known as a Spectrum Automaton (SA) that exists in the MLME at each CPE. The SM at the BS controls the use of and access to spectral resources for the entire network cell that includes the BS and all the associated CPEs served by the BS. The SA at each CPE controls the autonomous behaviors that are necessary to assure proper operations of the CPE that do not cause any harmful interference to the incumbents in the circumstances of system startup or initialization, channel switching, and temporary loss of communications with the BS.

3.4 Physical Layer

IEEE 802.22 standard adopts the 2048-carrier orthogonal frequency division multiple access (OFDMA) [66] technology to provide a reliable end-to-end link suitable for non-line-of-sight (NLOS) operation with simple equalization.

3.4.1 TDD OFDMA and Parameters

Unlike other systems such as IEEE 802.16, the fractional bandwidth use within each primary channel is not considered in IEEE 802.22 WRAN standard. In other words, the granularity of frequency spectrum for WRAN is one single TV channel. Since it is not always possible to have paired TV channels available, the standard is initially defining a single time domain duplex (TDD) mode, with plans to specify a frequency division duplex (FDD) mode as a future amendment to the standard.

IEEE 802.22 systems will support various TV channel bandwidths (BW) that are in use on a worldwide basis (i.e. 6, 7, and 8 MHz TV channels). For different bandwidths of TV channels, the clock scaling technique is used to maintain the same number of 2048 samples for each Fast Fourier Transform (FFT) duration, and the same number of (1680) useful sub-carriers (which include 1440 data sub-carriers and 240 pilot sub-carriers) and 368 guard sub-carriers (including the DC/0th sub-carrier) for each OFDMA symbol. Moreover, the same frame structure, ratios of cyclic prefix to OFDMA symbol, coding schemes, symbol mapping rules, and interleaving schemes are used for different bandwidths of TV channels. Note that, however, each type of TV channel bandwidth uses a different sampling frequency (i.e. $\Delta f=BW*8/7$). This results in different carrier spacing values (Δf / 2048), FFT periods ($1/\Delta f$), symbol durations, signal bandwidths ($1680*\Delta f$), and data rates for the various BW types.

Since IEEE 802.22 will cover very large areas, four different lengths of cyclic prefix, ¼, 1/8, 1/16, and 1/32 of symbol duration, are defined to allow for different channel delay spreads and to efficiently utilize the available spectrum.

3.4.2 Adaptive Modulation and Coding

The IEEE 802.22 standard defines 12 combinations of 3 modulation schemes (i.e. QPSK, 16QAM, 64QAM) and 4 coding rates (i.e. ½, 2/3, ¾, 5/6), from which a WRAN system can flexibly selected for data communications to achieve various trade-offs of data rate and robustness, depending on channel and interference conditions. **Table 3-1** lists all the transmission modes (combinations of the modulation schemes and coding rates) that are supported in the standard. Among these transmission modes, mode 3 to mode 12 are used for data communications, modes 1 is used for transmission of code division multiple access (CDMA) [65] based ranging, BW request messaging, urgent coexistence situation notification, and finally mode 2 is used for co-existence beacon transmission. The peak data rates and spectrum efficiencies shown in the table are calculated assuming a single TV channel of 6 MHz. For other bandwidths such as 7 MHz or 8 MHz, these numbers will be scaled accordingly.

Convolutional coding is the only mandatory mode of forward error control coding (FEC) defined in the standard. The data burst is encoded using a ½ rate binary convolutional encoder with the constraint length of 7. Different coding rates can be obtained by puncturing the output of the convolutional encoder. In order to improve the capacity and coverage of the system, three optional advanced FEC modes are adopted at the cost of increased decoding latency and complexity: two variants of turbo codes, i.e., duo-binary convolutional turbo code (CTC) and shortened block turbo codes (SBTC), and low density parity check codes (LDPC).

It is worth mentioning that the bit interleaving process following FEC is different from those of other IEEE 802 standards such as 802.16 or 802.11. The block interleaving algorithm is a turbo-based structure using an interleaving unit integrated in an iterative structure. Interleaving parameters are selected to optimize the interleaving spreading between adjacent samples and separated samples in order to achieve better frequency diversity.

PHY Mode	Modulation	Coding Rate	Peak Data Rate in 6 MHz (Mb/s)	Spectral Efficiency (BW = 6 MHz)
1	BPSK	1	4.54	0.76
2	QPSK	½	1.51	0.25
3	QPSK	½	4.54	0.76
4	QPSK	2/3	6.05	1.01
5	QPSK	¾	6.81	1.13
6	QPSK	5/6	7.56	1.26
7	16-QAM	½	9.08	1.51
8	16-QAM	2/3	12.10	2.02
9	16-QAM	¾	13.61	2.27
10	16-QAM	5/6	15.13	2.52
11	64-QAM	½	13.61	2.27
12	64-QAM	2/3	18.15	3.03
13	64-QAM	¾	20.42	3.40
14	64-QAM	5/6	22.69	3.78

Table 3-1 Modulation and Coding Rates for IEEE 802.22

3.4.3 Sub-carrier Allocation and Channelization

In the IEEE 802.22 WRAN environment, channels are typically frequency-selective but change slowly over time. In order to obtain robust channel estimation and good tracking ability for frequency offset and phase noise, one pilot is placed on every 7 useful sub-carriers in the frequency domain and the pilot positions in terms of the sub-carrier number are changed on a OFDMA symbol by OFDMA symbol basis to ensure every sub-carrier has one pilot over a period of 7 OFDMA symbols. The pilot pattern as shown in Figure 3-3 is repeated every 7 sub-carriers in the frequency domain and every 7 OFDMA symbols in the time domain. The pilot pattern is the same for the downstream (from the BS to the CPEs) and the upstream (from the CPEs to the BS) of data communications.

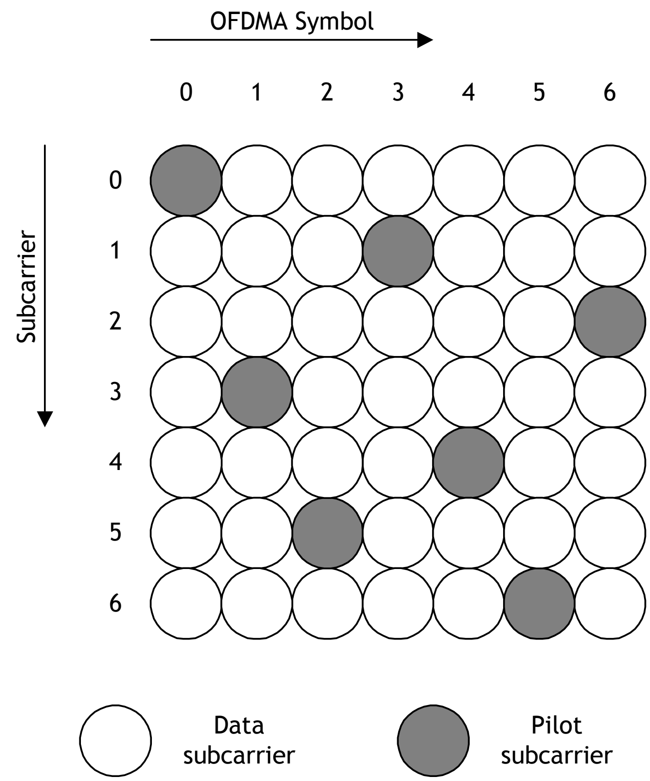

Figure 3-3 Pilot Pattern before Interleaving

The basic unit of resource allocation in IEEE 802.22 standard is a sub-channel, which consists of 28 contiguous sub-carriers including 24 data sub-carriers and 4 pilot sub-carriers. Considering that there are 1680 useful sub-carriers, 60 sub-channels in total are available in each OFDMA symbol.

In the downstream, all the data sub-carriers in the 60 subchannels will be interleaved with a block size of 1440 (24x60) before the transmission in order to explore the frequency diversity (note that the pilot sub-carriers are not interleaved in the downstream). In the upstream, two sub-channels are reserved for ranging, BW requests, and other maintenance purposes. The rest of the sub-channels are interleaved with a block size of 1624 (28x58) for both pilots and data. The frequency interleaving algorithms for upstream and downstream are the same as the bit interleaving algorithm mentioned in last subsection with different parameters though. Note that pilot sub-carries are interleaved in the upstream so as to ensure that every upstream burst arriving at the BS has one pilot on each sub-carrier over the period of 7 OFDMA symbols, which is the minimum size of the upstream burst. On the other hand, pilot sub-carriers are excluded from the interleaving process in downstream so that the fast channel estimation at the receiving CPEs is allowed to accommodate delay sensitive applications.

3.4.4 Preambles

In order to support burst detection, time/frequency synchronization, and channel estimation, IEEE 802.22 standard defines three types of preamble - super-frame preamble, frame preamble, and coexistence beacon preamble. Preambles are constructed in one OFDMA symbol with a cyclic prefix of 1/5.

The super-frame preamble is designed for the frequency and time synchronization among the BS and the associated CPEs of a WRAN cell that has stringent requirements on both center frequency tolerance and symbol clock tolerance, which should be within ±2 ppm. The super-frame preamble is transmitted by the BS and consists of 4 repetitions of a short training sequence (STS) following the cyclic prefix. STS is generated in frequency domain and transformed to time domain using inverse fast Fourier transform (IFFT). The frequency domain sequence, which has non-zero binary (+1, -1) values only on every 4th sub-carriers, is generated in an algorithmic way from m-sequences to ensure low peak-to-average-power-ratio (PAPR). The frequency domain sequence will result in 4 repetitions of a 512-sample sequence in each OFDMA symbol in the time domain.

The frame preamble is used for synchronization, channel estimation, frequency offset estimation, and received power estimation between the BS and the associated CPEs. It consists of 2 repetitions of a long training sequence (LTS). Similar to STS, LTS is also generated in frequency domain but has non-zero binary values on every 2nd sub-carrier. There are in total 114 different low PAPR LTSs available with low cross correlation in order to support a variety of deployment scenarios. The coexistence beacon preamble is used for coexistence beacon detection, synchronization, frequency offset estimation, and channel estimation of beacon transmission. With low cross-correlation, the coexistence beacon preamble has the same structure as the super-frame preamble but uses different STS to be differentiated from the super-frame preamble.

3.4.5 Ranging and Power Control

Ranging is performed to allow the BS and CPEs to synchronize their timing, thus minimizing multi-access interference, which results from multiple CPEs using the shared spectrum. In particular, it is necessary to align the BS received signal from all CPEs within a certain window, to ensure the orthogonality of sub-carrier allocation from different CPEs is maintained. This synchronization window is determined by the length of the cyclic prefix and the multi-path time dispersion exhibited by the channel. This operation is usually carried out during network entry (i.e. the initial ranging); however it is also necessary to regularly update and track variations in timing offset, using periodic ranging, to reflect changes in the network (for example, increased round-trip delay). With frequency selective fading, the multi-path fading characteristics modify the mean correlation output power. The multi-path attenuation and phase shift applied to the correlation output power would cause an irreducible error in timing offset. Moreover, the presence of noise causes a larger spread of timing offset errors.

The transmit power control in IEEE 802.22 is to reduce the transmit power at a CPE to the lowest possible levels while maintaining a reliable communication with the BS. Another purpose of CPE transmit power control is to minimize the dynamic range between carriers received at BS from CPEs at various locations. The maximum and minimum transit power for each sub-channel used for data communications are 4 watt EIRP (Equivalent Isotropically Radiated Power) and -24 dBm EIRP respectively. Each CPE maintains the same transmitted power density across all assigned sub-channels without exceeding the maximum allowed EIRP level.

3.5 Medium Access Control Layer

The 802.22 MAC provides mechanisms for flexible and efficient data transmission and supports cognitive capabilities for both reliable protection of incumbent services in the TV band and self-coexistence among 802.22 systems.

3.5.1 Management of Data Transmission

An IEEE 802.22 system is a point-to-multipoint network in which a central base station (BS) controls the medium access of a number of associated customer premise equipments (CPEs) for broadband wireless access applications. In the downstream direction (from BS to CPE) data are multiplexed in time-division multiplexing (TDM) fashion, while in the upstream direction (from CPE to BS) the radio channel is shared by the CPEs applying the DAMA-TDMA (demand-assigned multiple access – time-division multiple access) scheme on an on-demand basis. The concept of a connection plays a key role in the 802.22 MAC. The mapping of all services to connections, as performed in the convergence sub-layer (CS), facilitates bandwidth allocation, QoS and traffic parameter association, and data delivery between the corresponding CSs. While each 802.22 station has a 48-bit universal MAC address which serves as the station identification, the 12-bit connection identifications (CID) are primarily use for data transmission within an 802.22 system.

3.5.2 Super-frame and Frame Structures

The 802.22 MAC employs a super-frame structure in order to efficiently manage data communication and facilitate a number of cognitive functions for licensed incumbent protection, inter-network synchronization and self-coexistence. As depicted in Figure 3-4, a super-frame transmitted by a BS on its operating channel begins with a special preamble, and contains a super-frame control header (SCH) and 16 MAC frames.

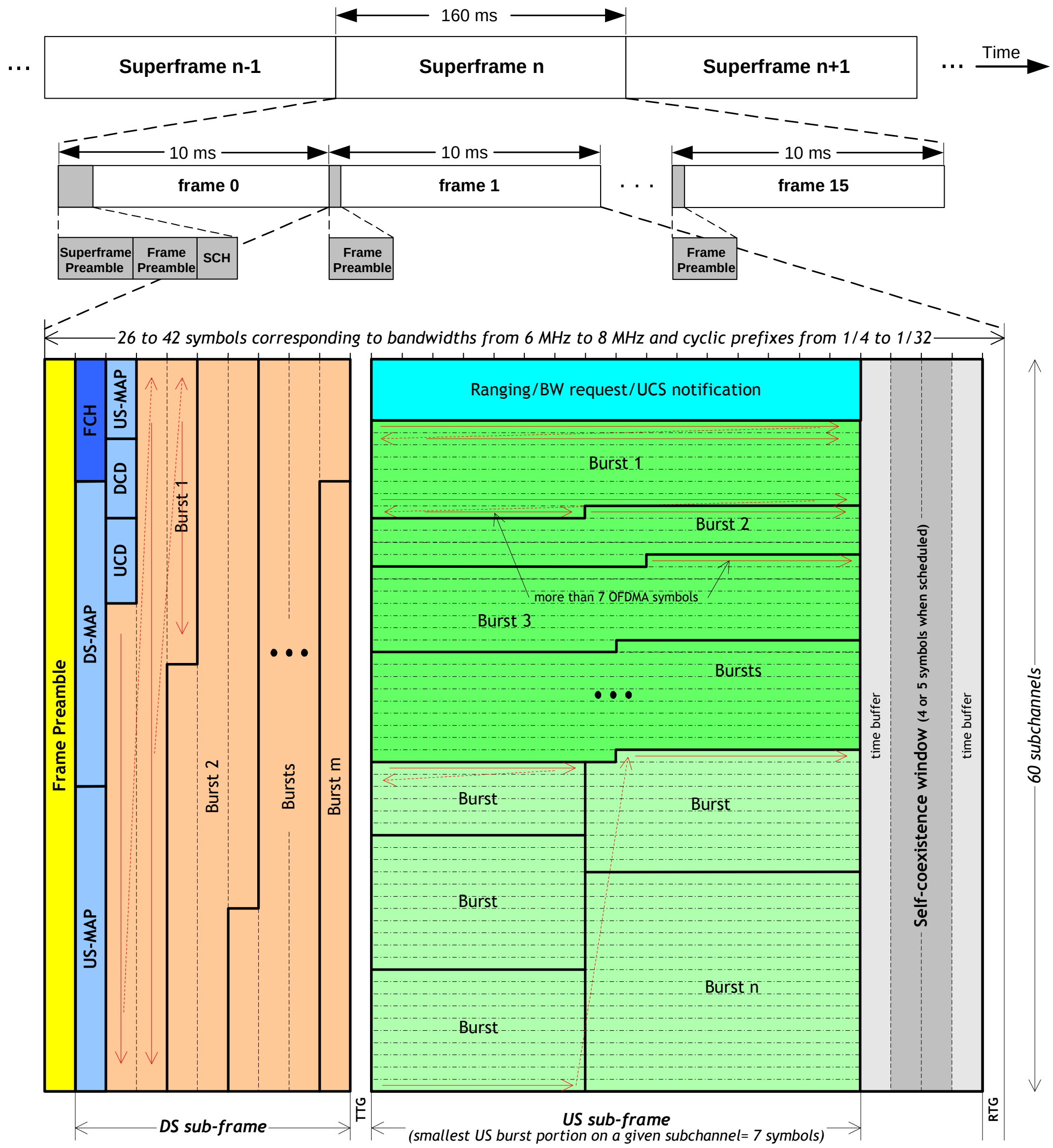

Figure 3-4 Super-frame and Frame Structures in IEEE 802.22

Each MAC frame, with a 10ms frame size, is comprised of a downstream (DS) sub-frame and an upstream (US) sub-frame with an adaptive boundary in between. While the DS sub-frame only contains a single PHY PDU (protocol data unit), the US upstream sub-frame may have a number of PHY PDUs scheduled from different CPEs, and consists of contention intervals for initialization, bandwidth request, Urgent Coexistence Situation notification, and self-coexistence. Begins with the frame preamble, frame control header, DS-MAP and US-MAP (i.e. the payload scheduling information in DS or US), data payload in the DS sub-frame are laid out vertically first in the frequency domain and then horizontally in the time direction. As the DS traffic for the far-end CPEs can be scheduled early in the DS sub-frame, such data layout allows the MAC to absorb the round trip delay for a coverage range of 100km. On the other hand, data in the US sub-frame are first scheduled in time on a logical sub-channel and then proceed to the next logical sub-channel.

3.5.3 Network Entry and Initialization

In contrast to other existing wireless access technologies, the network entry and initialization procedures in the IEEE 802.22 MAC not only define the regular processes such as synchronization, ranging, capacity negotiation, authorization, registration and connection setup, but also explicitly specifies the operations of geo-location, channel database access, initial spectrum sensing, network synchronization and discovery.

The determination of geographic location in the BS is required to use satellite-base technology, which also enable synchronization of the BS with the neighboring networks by sharing a global time source. In the CPE, if satellite-base technology is not available, the BS will instruct the CPE to conduct a terrestrial-based geo-location process. The list of available TV channel is obtained by referring to an up-to-date TV channel usage database augmented by spectrum sensing performed both by initializing BS and CPEs.

3.5.4 Spectrum Sensing and Spectrum Management Supports

To effectively address detection of and avoidance of harmful interference to incumbents, IEEE 802.22 MAC provides a comprehensive set of techniques and management messages for incumbent signal measurement and spectrum management. With the capabilities provided by the MAC, the BS is able to flexibly instruct the CPEs to measure TV channels for a specific period of time, in compliance with certain detection requirements, so that a reliable spectrum occupancy map of the cell can be obtained. Once the BS analyses the reports from its CPEs, operations such as dynamic frequency selection and transmit power control can be performed in a timely and effective manner as to resolve the coexistence situation with incumbents.

3.5.5 Quiet Periods Scheduling for Spectrum Sensing

Incumbent signal measurement can be of two types: in-band (co-channel and directly affected adjacent channels) measurement and out-of band (other alternative channels) measurement, all of which have to be conducted in quiet periods in which no WRAN transmission is allowed on the measured channel. Considering that a worst-case long quiet time, which could last for the duration of multiple frames, would cause negative impact on the quality of services, a two-stage sensing mechanism is defined. In the first stage, Intra-frame Sensing allows measurement to be performed in a period of less than one frame. However, if finer measurement is needed, an 802.22 system will proceed with Inter-frame Sensing stage in which contiguous quiet sensing time of multiple frames is allocated.

3.5.6 Self-Coexistence

In a typical deployment scenario, multiple 802.22 systems, each of which could have a large range of up to 100km, may operate in the same vicinity. Mutual interference among these collocated WRAN systems due to co-channel operations could degrade the system performance significantly. To address this important issue, the 802.22 MAC specifies a self-coexistence mechanism that is based on Coexistence Beaconing Protocol (CBP) and consists of four spectrum sharing schemes that address different coexistence needs in a coherent manner.

The CBP is a communication protocol based on coexistence beacon transmission among the coexisting WRAN cells. A CBP packet, delivered through the beacon transmission in a dedicated self-coexistence window (SCW) in the MAC frame, is comprised of a preamble, a SCH and a CBP MAC PDU, and is able to reliably efficiently conveys all necessary information across TV channels for facilitating network discovery, coordination and spectrum sharing.

During a SCW that is synchronized across all TV channels, a WRAN station (BS or CPE) can either transmit or receive CBP packets. For efficient inter-cell communications, each WRAN system is required to maintain a minimum repeating pattern of SCWs in transmit (or active) mode, even though in general the SCWs can also be scheduled to be in either mode on an on-demand basis.Each WRAN system could reserve its own SCWs on the operating channel for exclusive CBP transmission or share the active SCWs with other co-channel neighbors through contention-base access. By knowing the SCW patterns of the neighbors, a WRAN system can schedule receiving operation at the appropriate moment to capture the CBP packets transmitted from the neighboring systems of interest.

The CBP-based coexistence mechanism is described as follows. When an event for spectrum acquisition is triggered, a WRAN system first tries to resolve the spectrum demand locally through the Spectrum Etiquette procedure that attempts to select and utilize a TV channel that will not cause harmful interference to the neighboring systems. If there is no such spare TV channel available, the WRAN system proceeds with the Interference-free Scheduling method, which allows the WRAN BS to adapt the traffic scheduling for the associated CPEs so as to avoid co-channel interference with the neighbors. The interference-avoidance behavior, however, is passive therefore may not satisfy the resource demand in a timely manner. In such case, two spectrum sharing schemes that provide interactive coordination capabilities are next utilized. One of these schemes is called Dynamic Resource Renting and Offering, in which spectrum resources can be shared by the occupier WRAN system with the requester cell through a two-way renting/offering communication process. If the spectrum demand is still not satisfied (e.g. the occupier may refuse to rent), the demanding WRAN cell finally resorts to the On-demand Spectrum Contention protocol. Employing this dynamic channel contention protocol, the spectrum usage conflict can be resolved in a fair and efficient manner through simple exchange and comparison of contention access priority numbers among the coexisting WRAN systems.

3.6 Cognitive Functions

In order to operate in the TV bands without affecting DTV, analog TV, and licensed wireless microphones operated by TV broadcasters and other eligible licensees, The IEEE 802.22 systems will have to be cognizant of all incumbent operations in their vicinity.

The necessary tools are being included in the standard to fulfill these cognitive functions. First, the location of each base station and CPE will be accurately established. This will be described in detail in the Geo-location section below. The second tool is access to a channel availability database that will provide reliable information on the relevant limitations on channel availability for WRAN use at any given location. The third tool is the sensing capability that is included in the standard to sense the presence and identify the type of incumbent signals in channels of interest.

These capabilities will, by allowing the BS to control the channel usage and the transmission power in a network cell, constitute the set of cognitive functions needed to allow operation of 802.22 systems in the TV broadcast bands on a non-interference basis with the incumbents.

3.6.1 Spectrum Manager

The higher level intelligence at the base station that will use all the inputs of the cognitive functions to decide on the TV channel to be used by the WRAN cell and the transmission power (EIRP) limits imposed to the specific WRAN devices is called the Spectrum Manager. This entity is to be conceptually located at the MAC sub-layer in the base station as illustrated in Figure 3-2, will work closely with the data path MAC to communicate with the CPEs and will interface with the PHY Layer Management Entity to control the local sensing and geo-location functions and with the Station Management Entity for access to the incumbent database and for any local over-ride of the operator.

Various steps need to be taken by the spectrum manager to declare that a channel is may be used for operation. First, spectrum sensing has to be carried out on the actual working channel (N) to make sure that no incumbent service is present. Then, spectrum sensing is performed on the first adjacent channels (N+/-1) on which TV receivers may receive interference due to the presence of WRAN transmission on the adjacent channels. The distance to the protected contour, known as keep-out distance, will need to be verified through access to the TV incumbent database.

If it is confirmed that the WRAN operation on channel N may create interference to an incumbent service operating on a related channel, the spectrum manager will react with have the following four options:

- Reduce the transmission power of the CPEs to eliminate the interference potential in their local area;

- If such decrease in transmission power of CPEs renders the service unsustainable, de-associate these CPEs (i.e., these CPEs would need to seek service on another channel with another BS from the same or a different service provider);
- Reduce the transmission power of the base station to eliminate the potential interference;
- In many cases, a reduction in transmission power of the base station will no longer allow proper WRAN operation offered to the distant CPEs, and the spectrum manager will need to initiate a channel move (to a backup channel) involving the base station and all of its associated CPEs.

The WRAN base station therefore has complete control of the channel selection and of the transmission power level of each associated CPE. The control of the transmission power is made possible through reducing the maximum limit of the transmission power that the base station establishes with each CPE based on the CPE's local environment and the potential interference that can be generated at the nearby incumbents.

Before any of these actions take place, a clear diagnostic of the situation will need to be performed at the base station using the sensing results transmitted to the base station from the CPEs, the sensing results measured by the base station sensor itself, the geo-location of all the devices in the network cells, and the confirmation obtained by querying the on-line centralized incumbent database based on the collected information.

As mentioned in section 3.3, a process equivalent to the spectrum manager, but with much more limited functionality, will take place at the CPE to carry out the initial spectrum sensing functions, identify the available WRAN services in the area and determine initial channel availability before associating with a base station to minimize interference potential. This lightweight intelligent process has been called the CPE Spectrum Automaton. This automaton will also be used to pursue orderly sensing activities during the idle time of the CPE terminal and report its findings to the base station.

It's envisioned that there will always be a manual over-ride at the base station in case an unexpected interference situation occurs. It is assumed that the WRAN operator will have the ultimate responsibility for avoiding interference to incumbents.

3.6.2 Geo-Location and Database

As one of the fundamental requirements in the standard, all devices in the WRAN system are installed in fixed locations and the BS has the knowledge of its location and the locations of all of the associated CPEs. It is further required that the accuracies of the location information known by the WRAN system must be within a 15 meter radius for the BS and, for the CPES, must be within a 100 meter radius for 67% of the cases and within 300 meter radius for 95% of the cases.

In order to meet these location requirements, all devices in the network are equipped with satellite-based geo-location technology (SGT) such as GPS [60] and Galileo [61].

During the initialization procedure of a new CPE that intends to join the network, the SGT in the CPE shall successfully lock to the necessary number of satellites and in doing so the CPE shall accurately determine its location before it is allowed to transmit and attempt to associate with the BS.

Another requirement of the IEEE 802.22 standard is that the BS must have access to an incumbent database service (IDS), which provides accurate and up-to-date information describing the protected incumbent operations in the area.

When a new CPE attempts to associate with a BS during its initialization process, it sends its location coordinates to the BS. The BS then uses the location information for the new CPE to query the incumbent database. Other parameters of the CPE, such as the antenna pattern, the EIRP, and the antenna height, can be provided along with the location coordinates so that the IDS can determine a set of geo-location points that represent the expected area over which the CPE could potentially interfere. A resultant list of available channels is generated by the intersection of each list of available channels corresponding to each geo-location point. The IDS then returns to the BS this resultant list of available channels on which the CPE can operate without potentially causing interference to the protected incumbent services.

3.6.3 Spectrum Sensing

Spectrum sensing involves observing the radio frequency spectrum and processing the observations to determine if a channel is occupied by a licensed transmission.

In IEEE 802.22 standard, both the base station and the CPE sense for three different licensed operations: analog television, digital television and wireless microphones. In addition to these signals the 802.22 working group is developing a standard for a self-organizing network of beacon devices (known as IEEE 802.22.1), which is intended to give additional protection for low-power licensed uses such as wireless microphones, in-ear monitors, and similar devices.

The spectrum sensing requirements are specified in terms of four parameters - the sensing receiver sensitivity, the channel detection time, the probability of detection and the probability of false alarm. Three of these parameters are the same for all the licensed signal types. The channel detection time is 2 seconds, the probability of detection is 90% and the probability of false alarm is 10%. The sensing receiver sensitivity is different for the three licensed transmission. The sensing receiver sensitivity for analog television transmission (e.g. NTSC in North America) is -94 dBm, while the sensing receiver sensitivity for digital television transmission (e.g. ATSC in North America) is -116 dBm. Finally, the sensing receiver sensitivity for a wireless microphone transmission is -107 dBm. If we assume that the sensing receiver has a noise figure of 11 dB then the noise power level is approximately -95 dBm. Therefore, sensing at -116 dBm corresponds to an SNR (signal to noise ratio) of -21 dB.

The 802.22 spectrum sensing framework is defined based on four components: per-channel sensing, quiet periods, standardized messaging, and implementation independence. Each TV channel is sensed independently of all other TV channels, so broadband multi-channel sensing is not required. The standard, however, will not preclude an implementation that senses multiple channels simultaneously. This architecture was selected to allow for a low-cost design that tunes the sensing receiver to one channel at a time. The second component of the sensing framework is the use of quiet periods. The MAC layer supports the scheduling of quiet periods during which the base station and all the CPEs temporarily cease transmission. The MAC layer also allows signaling between nearby base stations that enables these base stations to synchronize their quiet periods. Sensing is performed during these scheduled quiet periods to minimize interference caused by the WRANs to the sensing receiver. The third component of the sensing framework is standardized reporting of spectrum sensing. Sensing is performed in both the base station and the CPE, but the final decision on whether a given channel is available for use by the WRAN is made at the base station. Therefore, the results of the spectrum sensing performed at the CPE must be reported to the base station in a standardized messaging mechanism. Also, the spectrum sensing in the CPEs is controlled by MAC management messages sent by the base station. The fourth and final pillar in the spectrum sensing framework is the spectrum sensing implementation independence. Specific spectrum sensing techniques is not specified in the standard. The designers are free to implement what ever spectrum sensing techniques they choose as long as the chosen techniques meet the specified sensing requirements and allow communications for the sensing control and report to be performed in the standardized messaging method.

4 Dynamic Frequency Hopping for DSA Networks[2]

4.1 Introduction

In this chapter, we address the challenge of Quality of Services (QoS) assurance for Dynamic Spectrum Access (DSA) Networks, using the IEEE 802.22 WRAN as the system model.

As depicted in Figure 4-1, an IEEE 802.22 WRAN (wireless regional area network) cell consists of a Base Station (BS) and the associated Customer Premise Equipments (CPEs) that communicate to the BS via a fixed point-to-multi-point radio air interface. The typical radius of the coverage area is 33 km [6]. Apart from coexisting with Digital TV (DTV, such as ATSC in North America) and analog TV (such as NTSC) services, 802.22 (or WRAN) cells also have to be aware of Part 74 devices (such as licensed wireless microphones) and other licensed devices in the TV bands. It is envisioned that channel (radio frequency spectrum) availability for data transmission of a WRAN cell is determined by referring to an up-to-date incumbent database augmented by distributed spectrum sensing performed continuously both by the BS and the CPEs.

[2] Part of this chapter is based on the joint work [7, 43].

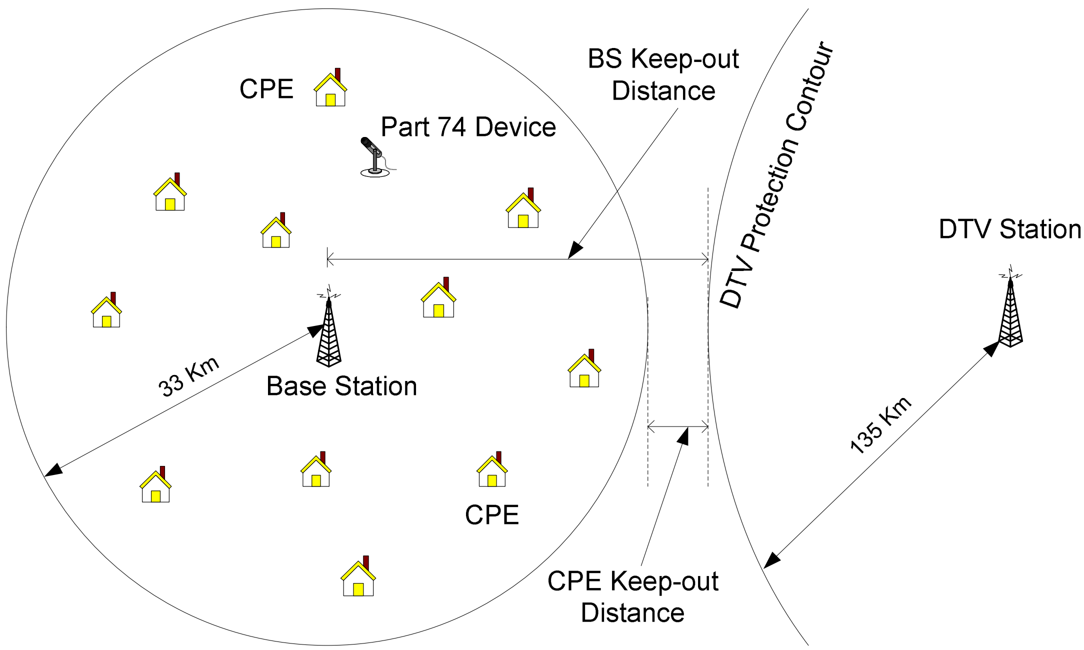

Figure 4-1 A Typical 802.22 WRAN Cell Coexisting with DTV and Part 74 Devices

The IEEE 802.22 WRAN operations need to satisfy two apparently conflicting requirements: assure the Quality of Service satisfaction for WRAN services while providing reliable and timely spectrum sensing for guaranteeing the licensed user protection. In fact IEEE 802.22 standard requires that the maximum transmission delay is 20ms in order to support VoIP and other delay-sensitive services [41]. On the other hand, the sensing reliability required by DTV incumbents is quite high (i.e. WRAN devices shall be able to detect DTV signals above a detection threshold of -116dBm with at least 90% probability of detection and at most 10% probability of false alarm [41]). Analyses of well-known sensing technologies as listed in Table 4-1 show that the sensing task takes up to several tens of milliseconds per channel [8], given the required reliability. For example, the DTV energy detection at 6MHz requires 69.43ms per channel. In fact, because of out-of band interference, a channel can be considered to be free only if its adjacent channels are also free, making it necessary to sense several channels. Hence, a sensing period can range from tens of milliseconds up to more than 100 milliseconds. In addition, it is required that licensed incumbent signals shall be detected by WRAN devices with no more than 2 seconds "delay" (i.e. the Maximum Channel Detection Time), starting from the time the licensed signal exceeds the detection threshold on a TV channel [41]. In other words, a WRAN cell has to perform sensing on a working channel at least every 2 seconds.

Sensing Technology	**Sensing Time**
DTV energy detection (6 MHz)	69.43 ms
DTV pilot tone energy detection (10 kHz)	268.10 ms
DTV pilot tone correlated detection	10.29 ms
DTV horizontal sync correlated detection	23.97 ms
DTV PN511 correlated detection	72.64 ms
FCC Part 74 Device Beacon Capture	100 ms

Table 4-1 Spectrum Sensing Time for Various Sensing Technologies

A channel that is to be sensed cannot be used for data transmission. Thus, a WRAN cell operating consistently on a single channel has to interrupt data transmission every 2 seconds for sensing and continue to transmit on that channel only if no incumbent was detected. This so called "listen before talk" or non-hopping mode, as depicted in Figure 4-2, is the basic mode of the 802.22 systems. Such periodic interruptions of data transmission, however, decrease the system throughput and can significantly impair the

QoS of the 802.22 systems (e.g. interruption of more than 20ms is usually considered to be harmful for voice transmission and other delay-sensitive applications).

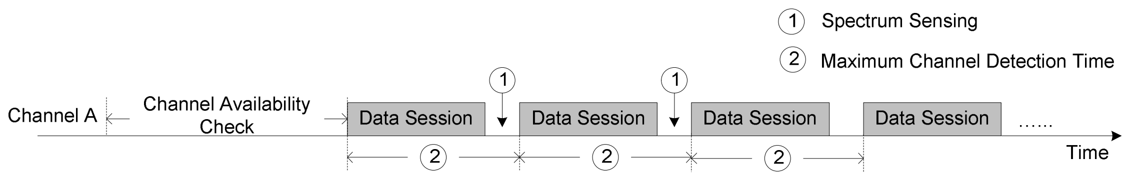

Figure 4-2 The Basic Listen-before-talk Operation in IEEE 802.22

In order to mitigate this phenomenon, an alternative operation mode known as Dynamic Frequency Hopping (DFH) has been proposed [40, 8] in IEEE 802.22. In the DFH mode a WRAN cell hops among a set of channels. During the operation on a working channel, sensing is performed in parallel on the intended next working channels. After 2 seconds (the maximum channel detection time), a channel switching takes place: one of the intended next working channels becomes the new working channel; the channel previously used is vacated. Hence, no interruption is required any longer for sensing. Obviously, efficient frequency usage and mutual interference-free spectrum sensing can only be achieved if multiple neighboring WRAN cells operating in the DFH mode coordinate their hopping behavior.

Motivated by this requirement we further propose in this chapter the concept of DFH Communities (DFHC) [43] and assess its advantages. The key idea of DFHC is that neighboring WRAN cells form cooperating communities, which choose their hopping channels and perform DFH operation in a coordinated manner. The further major contribution of this chapter is to develop concepts of fundamental mechanisms for managing such cooperative communities.

The reminder of this chapter is organized as follows. In Section 4.2 we describe the principle of DFH. Section 4.3 presents and discusses the concept of DFHC in detail. Section 4.4 introduces mechanisms and protocols for initiating and maintaining a DFHC and Section 4.5 proposes mechanisms for the coexistence of multiple DFH communities. A performance analysis is given in Section 4.6. Section 4.7 concludes the chapter.

4.2 Principle of Dynamic Frequency Hopping

In this section, we will describe the principle of the Dynamic Frequency Hopping operations.

4.2.1 Simultaneous Sensing and Data Transmission

A WRAN cell in the DFH mode uses the working (in-band) channel for data transmission and performs spectrum sensing on out-of-band channels simultaneously as shown in Figure 4-3. We refer to this operation as Simultaneous Sensing and Data Transmission (SSDT), or "Listen-while-Talking (LWT)". Guard bands between the in-band and out-of-band channels are allocated to mitigate adjacent interference caused by data transmission to the out-of-band sensing. An out-of-band channel sensed to be vacant is considered to be validated.

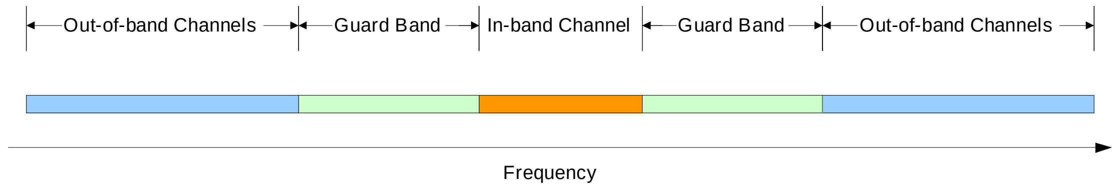

Figure 4-3 Simultaneous Sensing and Data Transmission (Listen while Talking)

4.2.2 Dynamic Frequency Hopping Operations

As previously mentioned a WRAN cell can use a working channel for up to two seconds before it has to perform spectrum sensing in order to re-validate the channel.

The DFH mode works as follows: The time axis is divided into consecutive operation periods, in each of which a WRAN is operating on a validated channel, while simultaneously sensing – and validating – out-of-band channels as explained above (SSDT). A WRAN cell in the DFH mode thus, as shown in Figure 4-4, dynamically selects one of the channels validated in a previous operation period for data transmission in the next operation period. This channel can be used for data transmission for up to two seconds (the maximum channel detection time) after the time it was validated.

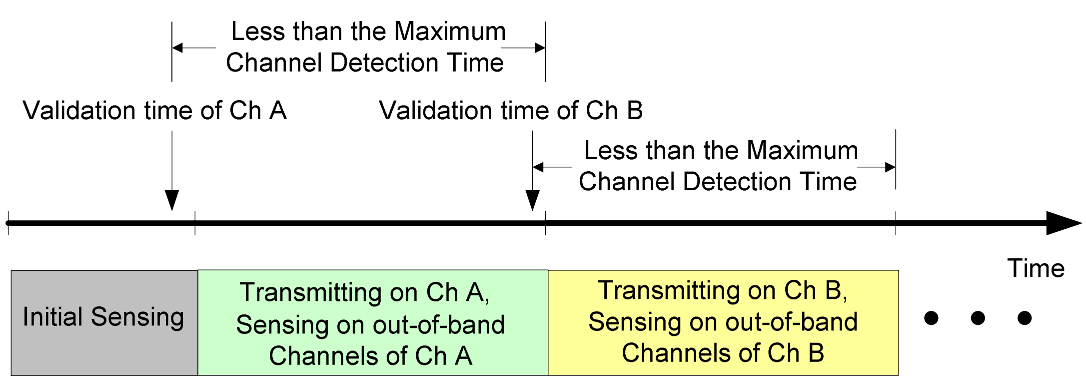

Figure 4-4 Dynamic Frequency Hopping Operation

4.2.3 Fast Channel Switching

DFH is justified only, if the channel switching can be executed quickly enough. Recognizing that hardware channel switching delays are negligible in today's evolving technologies – e.g. in the range of tens of microseconds in current 802.11 wireless cards [44] – a novel fast channel switching technique has been proposed [40]. Applying the proposed mechanism, a WRAN cell performs periodic channel maintenance on a set of hopping channels that are initially setup, such that switching delays for channel setup and channel availability check are eliminated and the protocol overhead is curtailed

The fast channel switching procedure is described as follows.

1) Select and maintain a cluster of channels that have passed the Channel Availability Check. We refer to this channel cluster as Cluster A.
2) Perform initial channel setup for new channels in Cluster A. Channels in Cluster A for which channel setup has been performed successfully are classified as channels in Cluster B. Note that a channel that is not effectively maintained through regular channel maintenance is considered as a new channel.
3) Perform Dynamic Frequency Hopping using channels in Cluster B.
4) Perform regular (periodic) channel maintenance for a channel on which the WRAN system is currently operating.
5) The 802.22 WRAN System schedules Dynamic Frequency Hopping operation such that the maximum interval of regular (periodic) channel-maintenance for all CPEs on every channel in Cluster B is not exceeded, so as to guarantee the

effectiveness of transmission parameters obtained from the previous channel maintenance. We determine that a channel is well maintained if the above condition (maintenance interval less than the maximum allowed interval) is satisfied.

6) If a channel is not well maintained, the 802.22 WRAN System eliminates this channel from Cluster B.

7) Channel Move information is embedded in the MAC management messages that are regularly transmitted from the base station to CPEs. So the overhead for channel move messaging is negligible.

Figure 4-5 provides an example of fast channel switching for dynamic frequency hopping.

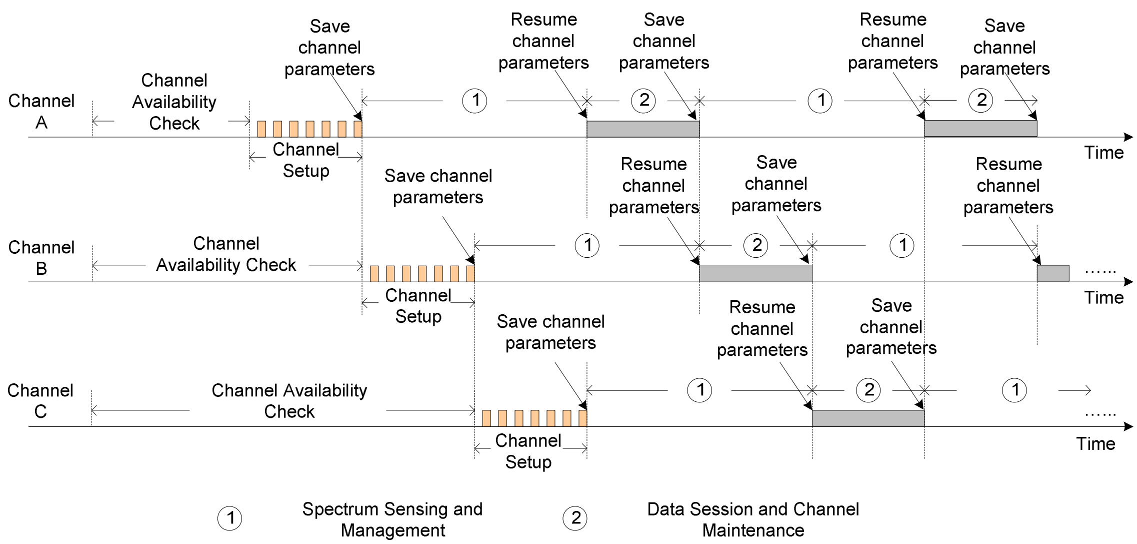

Figure 4-5 Fast Channel Switching for Dynamic Frequency Hopping

4.2.4 Frequency Requirements for DFH

In order to perform reliable sensing in the DFH mode, the channel being sensed cannot be used for data transmission by the WRAN cell. This implies that a single WRAN cell operating in the DFH mode needs at least two channels in order to perform data transmission and reliable sensing in parallel (in further considerations we will, for the sake of simplicity, assume that there is no out of band interference of the WRAN cells). By simple extension of this scheme, 2N free channels would be needed to support N totally uncoordinated, mutually interfering cells without collisions in channel usage among them.

If, however, spatially overlapping cells decide to cooperate, the channel usage can be significantly reduced. In the following we prove by construction that only N+1 vacant channels (i.e., channels free of both incumbents and other WRANs) are enough.

Figure 4-6 illustrates the Phase-shifting DFH operation [4] of N=3 overlapping WRAN cells over (N+1)=4 vacant channels. Each WRAN cell shifts its DFH operation phase by one Quiet Time (QT) against the operation phase of the previous WRAN cell as shown in Figure 4-6. For instance, WRAN2 shifts its operation by one QT against the operation of WRAN1, and WRAN3 shifts by one QT against that of WRAN2. During a QT, channel sensing is performed. This implies that a QT has to be at least equal to the minimum time required for reliable channel sensing.

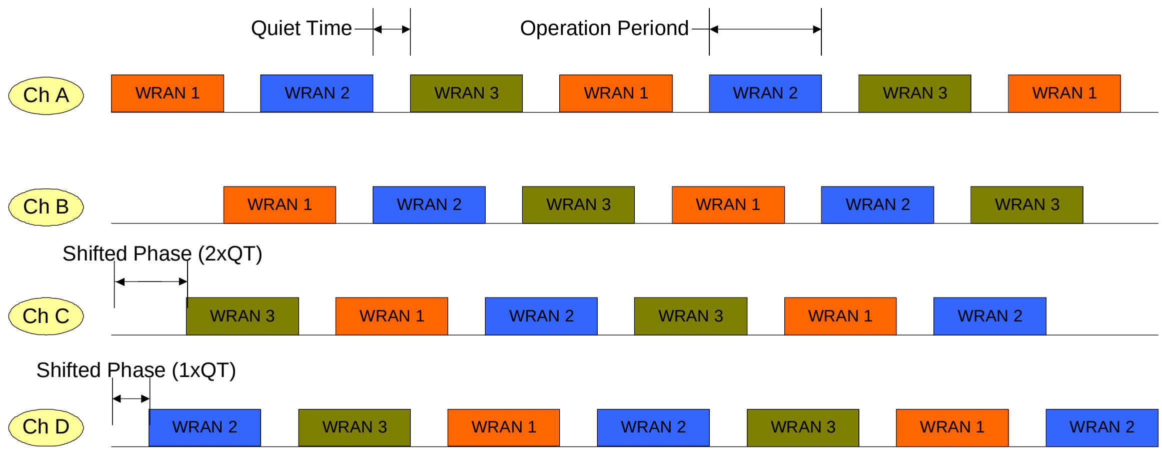

Figure 4-6 Phase-shifting DFH Operation

We have demonstrated that a set of N overlapping cells can operate continuously using (N+1) channels as long as the length of a single transmission is larger than the product N*QT. We will further refer to this observation as the "N+1" rule [40]. Imposing the above explained hopping pattern of time shifted jumps is, however, possible in case of strict coordination, which motivates the concept of DFH Community (DFHC) as described in Section 4.3.

4.3 Dynamic Frequency Hopping Communities

Dynamic Frequency Hopping Community (DFHC) is a non-empty set of neighboring WRAN cells following a common protocol that supports a coordinated DFH operation in order to ensure mutual interference-free channel sensing and to minimize the channel usage, applying the DFH phase-shifting explained above.

Figure 4-7 shows a scenario where the WRAN cells in their close proximities form communities for coordinated DFH operations.

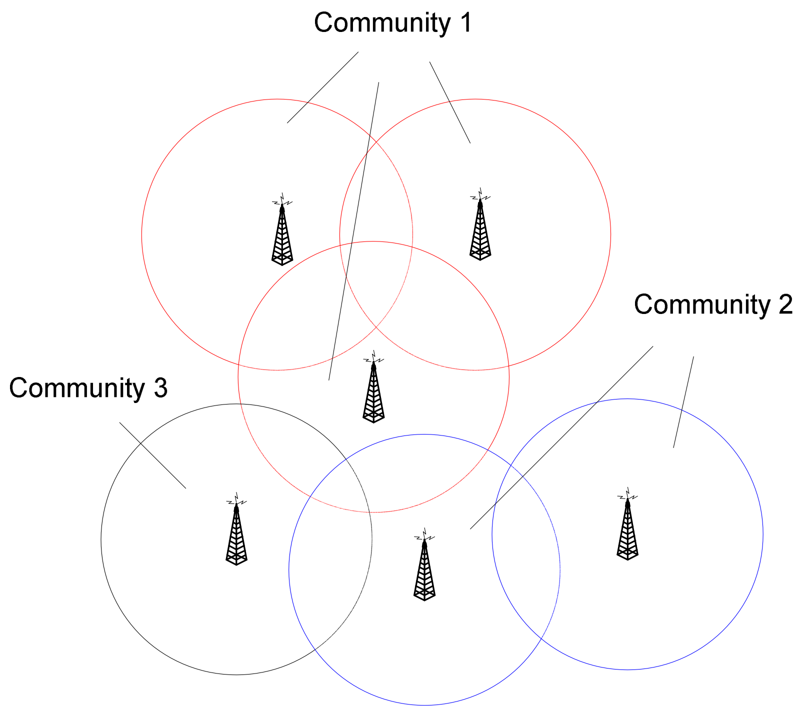

Figure 4-7 DFH Communities

A DFHC has one leader and, possibly, some community members. The DFHC leader is responsible for decisions about community membership, calculating the hopping patterns (phase-shifting sequences) for all members and distributing this information within the community. Members provide the leader with their neighborhood and channel availability information, i.e. information about their sensing results and observed channel usage of the neighboring WRAN cells.

For a group of WRAN cells to create a DFHC, the following requirements should be satisfied:

- Community members are able to communicate with the community leader.
- Each community member is able to perform the SSDT operation as described in Section 4.2.1.
- Community members have reasonably synchronized clocks. (Up to a given accuracy)
- The community members share a joint notion of a Quiet Time of a channel X – a time period during which no community member is allowed to transmit on that channel.

In the 802.22 draft, a best effort method called Coexistence Beacon Protocol (CBP) is proposed for over-the-air inter-cell communications. The basic mechanism of CBP works as follows. BSs of neighboring cells schedule a coexistence window at the end of every MAC frame (synchronized among BSs). During a coexistence window, neighboring BSs communicate using coexistence beacons. Note that CBP has been developed for constant channel assignments while in DFH mode the channel assigned for transmission to individual cells does strongly vary in time. Therefore we introduce for the support of the inter-cell communications within a community an abstraction of the Inter-Network Communication Channel (or Communication Management Channel, simply CMC) on which the CBP is executed. The detailed discussion of this issue will be discussed in chapter 6.

4.4 Dynamic Frequency Hopping Communities Management

DFHC initialization and maintenance are supported by numerous activities which will be referred to as community management. We begin its discussion with a set of operational principles:

- A WRAN cell is represented by its BS, which has a unique IEEE 802 MAC address and a priority.
- WRAN cells attempt to create or join communities whenever possible. Nevertheless a single cell that has lost the association with a community will always temporarily falls back to the non-hopping mode.
- The association with a community is based on a soft state principle, subject to renewal within a life-time period determined by a TIMER value. Lack of renewal will lead to fallback into the non-hopping mode on the last used channel.

In the following we present an outline of the mechanisms for DFHC management.

4.4.1 Neighborhood Discovery

Each BS periodically broadcasts announcement messages (BSANN) on the CMC. Two cells are called one-hop neighbors if the control messages (e.g. BSANN) of one cell can be received by the other cell. A BS-ANN message contains the state of the BS (Non-hopping, DFHC leader or DFHC member), a list of actually known neighbors, a hopping channel list, and the priority of the community leader (if belonging to a community).

4.4.2 DFH Community Creation

To create a DFHC, a community leader is selected first. The community leader of a DFHC is defined as a BS with the highest priority value (and smallest MAC address within equal priorities). Each BS believing to fulfill this condition within its neighborhood declares itself a DFHC leader. The declared leader selects a set of hopping channels and broadcasts its leadership using leader announcement (LDRA) messages on the CMC. An LDRA message contains a list of community members (at the beginning just the leader itself) and the selected hopping channels with the hopping pattern of the community.

A WRAN cell in the non-hopping mode might decide to create a community if no LDRA message is heard. Upon receiving LDRA messages from (possibly multiple) leaders, a BS, however, can decide to join one of the advertised communities. These decisions are based on policies not discussed in this chapter.

To join a community, a BS transmits a membership request message (MBRA) on the community's CMC. An MBRA message contains the targeted community leader's identification, and the neighborhood and channel availability information of the requesting BS. Upon receiving the MBRA, the leader decides whether to accept or reject the joining request and sends an acknowledgement containing the decision. This might have to be preceded by a proper maintenance of the existing community to assure that the joining station fits into the hopping behavior.

4.4.3 DFH Community Maintenance

Each channel hopping pattern calculated and distributed by the community leader has a lifetime. A community member can use the hopping pattern only during this lifetime. The leader periodically renews the hopping pattern by broadcasting an LDRA containing the renewed hopping pattern for the community. The start time for using the new hopping pattern is set to the expiration time of the previous hopping pattern. The reception of a new hopping pattern is acknowledged by all members. If some member did not receive a new hopping pattern from the leader before the old pattern's lifetime is expired, it cannot stay in the DFH mode and has to return to the non-hopping mode.

The neighborhood and channel availability information of a community are updated by all members of the community. For this purpose, each community member performs spectrum sensing, tracks BSANN messages from neighboring cells, and reports to the leader if needed, by sending MBRA messages.

The leader recalculates the channel hopping pattern for the community based on the received MBRA messages. The new hopping pattern can be distributed in two possible ways: either by renewing the hopping pattern at the end of the old hopping pattern's lifetime or by sequential switching of all members to the new hopping pattern.

The first option ensures a collision free switching between the two hopping patterns. Even if some community member does not receive the new hopping information it cannot use the old one any more since it is expired. This approach, however, lacks the flexibility of distributing new hopping pattern in the middle of the old hopping pattern's lifetime without causing pattern conflicts, in case some members fail to receive the new hopping pattern and continue to use the old one.

This hopping pattern confliction issue can be avoided by sequential switching. In this approach the leader switches each member individually to the new hopping pattern (which is selected to be collision-free with the patterns of members not switched yet) and verifies whether the recommended switching really took place by sensing newly assigned channel. Thus we introduce an “implicit confirmation by acting” for adopting of the new pattern. Sequential switching is performed such that even if some member does not switch to the new hopping pattern as ordered, all members already switched can use the new hopping pattern without collisions.

Sequential switching for adding a new member is demonstrated in Figure 4-8. The old assignment is shown in the background. First, all members are switched to the new hopping pattern which means shifting their hopping pattern by one Quiet Time on channel 4. Additionally, the operation periods on channel 1 are shortened by one Quiet Time during the switching procedure. After all members have switched, there is enough space to add the new member (last slot in channel 4). This approach thus ensures no collision between the old and the new hopping patterns.

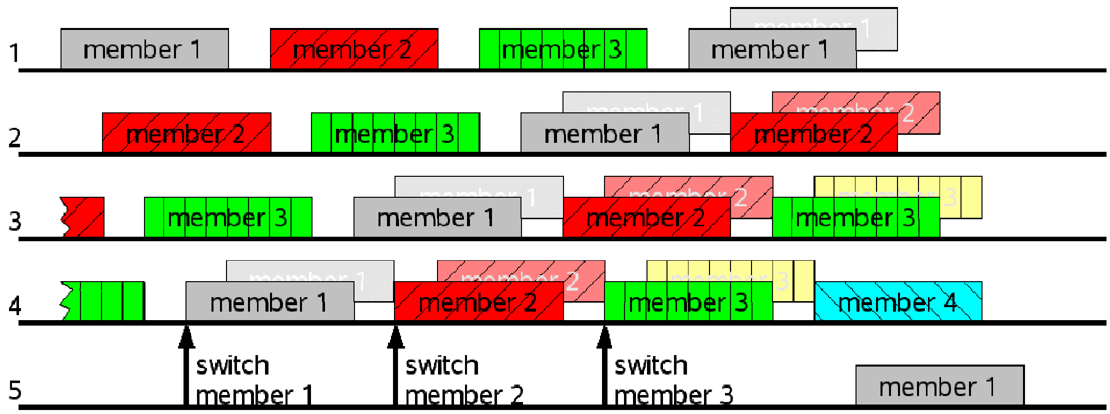

Figure 4-8 Sequential Switching for New Member Insertion

Whenever a community member detects an incumbent on a channel, it cannot utilize that channel for the next hops. The member should inform the leader by sending an MBRA message containing the new channel information. Until the leader calculated and distributed a new hopping pattern, the cell should use some backup channel for the time period it is scheduled to use the interfering channel.

4.5 Coexistence of DFH Communities

The mechanisms introduced so far support the management of one DFH community. In a large network of WRAN cells, however, multiple such communities might exist, which have to coexist. As creation of communities as described above is a distributed process following appearing/disappearing of cells as well as changes of their connectivity, it is easy to see that rearrangements of established communities might occasionally be useful. In particular it might help in:

- Reducing total number of channels used;

- Resolving channel usage conflicts among communities;
- Reducing communication overhead for community management.

This section introduces mechanisms to shift cells between communities, and to split and merge communities. Whether and when to rearrange communities depends on polices that are beyond the scope of this dissertation. In addition we will discuss how to avoid and resolve collisions between communities.

4.5.1 Rearrangement of DFH Communities

We propose three operations for rearrangement: cell shifting, community splitting and community merging.

A cell shifts from one community to a new one by first requesting to join the new community. If the leader of the new community accepts the joining request, the cell may explicitly leave the old community. The cell then starts to use the hopping pattern received from the new community.

In contrast to shifting of a cell, multiple cells are involved in splitting and merging of communities leading to consistency problems discussed in Section IV.C. These potential collisions of different hopping patterns can be avoided by always performing the splitting and merging at the end of the lifetime of a channel hopping pattern as described below.

If a leader decides to split its community, it divides the community into two and selects two new leaders (where it may become one of the new leaders). The leader first announces the intention to split the community. This intention contains the member lists of the new communities and the new leaders. The designated new leaders and all members of the community shall acknowledge this announcement (where some acknowledgements may get lost). Upon reception of (at least some of) these acknowledgements the old leader may – if it wants to continue the split – schedule the new leaders to announce the new communities starting operation upon expiration of the lifetime of the old community. Note that if some members are lost, they might request later to join one of the new communities.

A WRAN cell can initiate a merger of two communities with itself being the leader of the new community. Note that the initiating cell might be one of the two old leaders or a normal member. When deciding to merge two communities, a cell assures that all members of the old communities can still be a member of the new community and there are sufficient available channels for the new community. The cell then announces the intention of community merging to leaders of communities to be merged. If both leaders agree, the expiration times of their hopping patterns have to be synchronized, i.e. the leader with the earlier expiration time renews its hopping pattern after the hopping pattern of the other community expires. The dedicated new leader then announces the new community on CMCs of both to-be-merged communities by setting the new community's start time to the synchronized expiration time of the old communities. Once the new community has been announced, all members acknowledge the announcement on the CMC of the new community, which then starts to operate using the hopping pattern calculated by the new leader.

4.5.2 Collision Avoidance and Resolution

BSANN messages are used to announce channel availability and neighborhood information. Channels being included in a BSANN from another community or a non-hopping BS are labeled occupied by the receiving BS. It might nonetheless occur that two neighbor communities select an overlapping channel set as working channels. In this case priority values (transmitted via BSANN messages) of community leaders or non-hopping BSs are used to resolve this conflict. A BS, which detects such collision and has a lower community (or non-hopping BS) priority, releases the overlapping working channels.

4.6 Performance Analyses

In this section we study the DFHC performance regarding the achievable system throughput and the channel usage. For the throughput analysis we compare the non-hopping mode to the DFH mode. For the channel usage analysis we compare the number of channels used in the DFHC mode with the global minimum (computed by an optimization tool).

4.6.1 Throughput Analysis

The main advantage of the DFH mode compared to the non-hopping mode is the non-interrupted data transmission. Equation (1) shows the throughput T as function of the sensing time X and the used bit rate b (ignoring the channel switching overhead).

$$T(x) = b * 2\ s / (2\ s + X\ s) \qquad (1)$$

In the DFH mode the throughput does not depend on the sensing time (X=0) and is always equal to b, since sensing is performed in parallel to data transmission. Therefore the DFH mode can achieve a higher throughput than the non-hopping mode (X>0).

4.6.2 Channel Usage Analysis for a group of Communities

In Section 4.2.4 we have derived the upper bound of 2N and the lower bound of N+1 channels for a set of N mutually interfering cells following the phase-shifted DFH principle as a single community.

It can, however, be expected, that if numerous cells cover a larger area not ALL of them will mutually interfere (not all cells will be one-hop neighbors). In fact, grouping those cells into several communities with limited interference among those communities, and utilizing the possibility of spatial frequency reuse provide a potential for reducing the total number of required frequencies.

Let us assume that M cells are randomly distributed in a square normalized to the size 1 by 1 with a normalized interference distance d<1 (i.e. cells being in distance larger than d do not interfere). This assumption leads to a random interference graph.

These cells are split into communities in such a way that all cells belonging to a single community are one-hop neighbors. Obviously, there exist numerous alternative groupings of cells into communities. We use two different approaches to generate communities, one where we minimize the total number of communities and another one where the total number of connections between communities is minimized.

The optimal number of channels required is based on the assumption that all cells follow a global hopping pattern generated by a central controller. This number can be computed by solving a standard graph coloring problem, so called “chromatic number” +1 channels being the minimum. We use a standard Integer Programming solver (CPLEX [45]) for computing this chromatic number.

Figure 4-9 shows the analysis results for M=10 (shown in the top sub-figure) and M=20 (shown in the bottom sub-figure) cells. These results are an average over 40 independently generated graph instances per M.

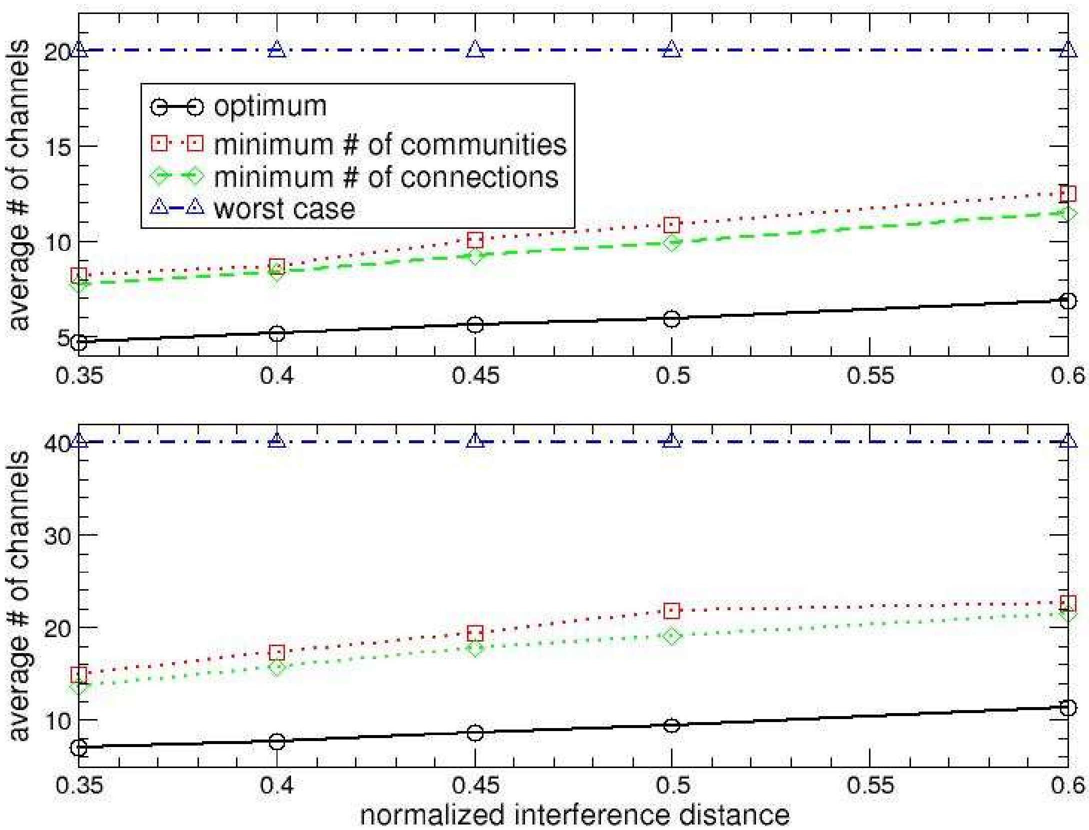

Figure 4-9 Channel Usage Analysis for a Group of Communities

As expected, splitting into numerous communities is advantageous, and the number of required channels is lower than 2N. Moreover, our intuition about not aiming for the minimal number of communities but minimal connectivity among communities has been confirmed (admittedly, we do NOT consider the overhead for community management). In fact, the total number of channels could be further reduced by relaxing the community definition such that all members are only required to be one-hop neighbors of the leader instead of being mutually one-hop neighbors. This would allow for further channel reuse within a community and offer greater flexibility in the community creation.

4.7 Conclusion

The emerging IEEE 802.22 standard is defining one of the first cognitive radio based wireless systems to become reality. When operating on a single channel, the QoS of WRAN cells degrades due to sensing interruptions. This can be mitigated by Dynamic Frequency Hopping, where data transmission is performed without interruptions in parallel with spectrum sensing. However, in a bigger cluster of cells, frequency hopping could lead to significant problems if no coordination scheme is employed. Dynamic Frequency Hopping Community is a concept introducing coordination among cells. As shown, it leads to a better QoS and throughput behavior, while requiring a modest amount of channels for hopping. It enables coexistence of multiple communities. In fact DFHC could also be used to coordinate channel usage of cells operating in the non-hopping mode. In this chapter we have presented principles of mechanisms for dynamic rearrangement adapting to changes of cluster topology. As future work we will focus on detailed specification and analysis of protocols supporting these mechanisms as well as various aspects related to policies driving evolution of such communities.

5 Distributed Frequency Assignment for DFH[3]

5.1 Introduction

Frequency planning is an important method to control co-channel interference in multi-cell communication systems. It is based on solving the frequency assignment problem (FAP). The FAP consists of a set of cells, where neighboring cells have certain (static) interference relationships and hence, should not be assigned the same frequencies (also referred to as channels in the following) for operation. The goal of the FAP is the assignment of a pre-specified number of frequencies to each network cell while minimizing the total amount of frequencies needed. Mathematically, the FAP can be expressed as a graph coloring problem, by assigning each node one (or multiple) color(s) such that no two connected nodes have the same colors while trying to minimize the total number of colors used. A graph where the nodes represent the set of cells and the edges between the nodes represent their interference relationships is being used for this purpose.

This graph coloring problem is difficult; mathematically speaking, this problem belongs to the class of NP-hard problems. Finding the system optimum for practically relevant systems requires prohibitively long computation times even with modern computational equipment. Therefore two approaches are usually used:

[3] This chapter is based on the coauthored paper [46].

- Sub-optimal algorithms that have a significantly reduced computational complexity while handling the full interference graph.
- Decentralized approaches, in which each node selects its frequency based only on partial knowledge of the interference graph. This allows for parallelization of the computation and leads to the most significant reduction of the computational time.

In the usually investigated wireless cellular networks with static frequency assignment both these approaches achieve remarkably good results in the sense of minimizing the number of frequencies necessary for assuring a given level of traffic, as compared to the real optimum. However, in the last decade an increased interest is observed in systems that are not "frequency-static" but change their operational frequency. Such systems do provide better immunity both against fading and interference. Such an approach is referred to as frequency hopping. It is intuitively clear that if each cell applies frequency hopping the FAP approaches a new level of complexity. Thus, the issue of reducing the computational complexity becomes critical – and thus the promising decentralized approach described above is especially attractive. In this chapter we consider a special instant of such frequency hopping systems – the emerging IEEE 802.22 [40] standard for wireless regional area networking. Its goal is to allow communications in temporarily unused TV bands (called secondary communications) but vacate the band if the owner of the band (called the primary user – PU) returns. In order to ensure unimpaired operation of the PU, a used channel has to be sensed periodically by the 802.22 system. 802.22 draft standard features a Dynamic

Frequency Hopping mode [7, 8, 40, 43] where a cell can hop over a set of channels. In this mode the channel to hop to is always sensed in parallel to the data payload transmission on the current channel, enabling non-disruptive communications. Although the hopping frequency is rather slow (in the order of seconds), there are evidently tough requirements on the computational complexity of the frequency assignment algorithms. On the other hand we believe that such optimization is feasible – in contrary to systems with much faster hopping.

The remaining chapter is structured as follows. In Section 5.2 we discuss related work regarding approaches for frequency hopping. In Section 5.3 we present our system model and formulate the problem statement. In Section 5.4 we present a precise centralized optimization approach to be used as reference for comparison, and introduce a candidate decentralized approach. Then, in Section 5.5 we investigate the performance of the distributed approach. Finally, we conclude the chapter in Section 5.6 by discussion of options for improvement of the distributed approach.

5.2 Related Work

The issue of “static” graph coloring for channel assignment is well documented in literature and it has been frequently applied to cellular network planning. Standard references for this can be found in [54, 50]; for more in-depth studies, an excellent web page on the topic is maintained by Eisenbl atter and Koster [49].

Frequency hopping has drawn significant research attention in the context of GSM cellular systems, Bluetooth and WLAN (among others). In GSM, frequency hopping is an optional mode to mitigate fast fading and co-channel interference. Once every TDMA frame (which has a duration of 4.17 milliseconds the transmit frequency for each terminal is changed according to a pre-specified hopping sequence. The impact of this hopping sequence (also referred to as Mobile Allocation List – MAL) design in studied in [47]. The authors propose a scheme which generates frequency lists assuming the knowledge about the frequency lists of neighboring, i.e. interfering, base stations such that interference between the neighboring (hopping) cells is within some specified constraint. Further work on the assignment of frequency lists in GSM systems can be found in [53]. In contrast, [51] investigates dynamic frequency hopping in GSM and compares it to random hopping. The frequency hopping pattern of a mobile is adapted based on measurements made at the base station and the mobile. The recalculation is done after every TDMA frame. The chapter studies several degrees of dynamic adaptations if the currently used frequency list is not satisfactory. However, the chapter does not consider a jointly performed frequency list assignment over several cells.

Frequency hopping is also applied in Bluetooth systems for similar reasons (i.e. mitigating interference and fading). Hopping is performed about every 0.5 millisecond and Bluetooth cells choose from several pre-specified hopping sequences. However, the Bluetooth Special Interest Group (SIG) worked out an Adaptive Frequency Hopping (AFH) method for second generation Bluetooth devices to improve the interoperability between Bluetooth and other systems like WLAN [55]. AFH allows Bluetooth to adapt to the environment by identifying fixed sources of interference and excluding them from the frequency hopping list. This process of re-mapping also involves reducing the number of channels to be used by Bluetooth. The Bluetooth specification requires a minimum set of at least twenty channels.

5.3 System under Study and Problem Statement

5.3.1 Single Cell (Hopping) Operation

A secondary cell operates on one (at a time) arbitrary channel out of N available ones. The maximum time period a secondary cell can interfere with a primary user is given by $T_{\max}$; consequently, the operating channel must be vacated at least after each *Tmax* period (in order to be sensed and re-validated). Note that there are additional delays to be considered here, like the time needed for sensing the new candidate operating channel (T_{sense}), and the time needed for switching the operating channel of the cell (T_{switch}). We assume $T_{\max}$ to be a multiple integer of T_{sense} + T_{switch} and since $T_{sense} >> T_{switch}$ we do not consider switching times in our investigations ($T_{switch} = 0$).

The BS can select from two basic modes of operation. The non-hopping ("listen before talk") mode uses static channel assignment where the data communication is periodically interrupted (every $T_{\max}$) in order to perform sensing on that channel. The FAP in this case can be solved by applying e.g. one of the several existing graph coloring algorithms based on either global or local knowledge (hence, following either a centralized or decentralized approach).

In the hopping mode [7, 8, 40] the BS switches the cell to a new channel with periodicity of $T_{\max}$ seconds, even if its current channel is not used by a PU. The potential new working channel is previously sensed in parallel to the data communications on the current channel. Hence, in the hopping mode the data communication is interrupted only by a time span of T_{switch}, which we assume to be marginal. If no new channel is found to be available (due to PU or CR system activity), the base station switches to the non-hopping mode and immediately schedules a sensing period in order to check the current working channel for PU activity.

5.3.2 Cellular Operation

We consider a (large) area where a set of *V* distinct CR cells are located. Depending on the distance between CPEs and BSs of several cells, it is possible that cells interfere with each other when operating on the same channel. We model this in form of an interference topology graph *G = (V, E)* where $V = \{v_1, ..., v_n\}$ represents the set of CR cells and $(i, j) \in E$ *(i, j)* if v_i and v_j are within each other's interference range (thus, the CR cells v_i and v_j cannot operate on the same channel at the same time). We assume that cells have means to discover the interference relationships within their neighborhood through the exchange of control messages.

The presence of primary users is assumed to be static as well as the structure of the interference graph. Furthermore, we assume that if a PU appears, it affects all CR cells in the network.[4] Dynamically appearing and disappearing PUs as well as only locally visible PUs are subject to future work.

5.3.3 Problem Statement

Clearly, the hopping approach has the potential to support (almost) continuous service provision and thus the QoS needed for real-time applications. Additionally, the achievable throughput is much higher in the hopping mode (5% in 802.22 with $T_{\max} = 2$ s and $T_{sense} = 0.1$s). However, a network operating in hopping mode requires a larger amount of channels compared to the case where each cell operates in non-hopping mode. The channel usage is an important metric due to two reasons. The smaller the number of channels a CR network requires, the lower is the probability that a CR cell is operating on a channel which is reclaimed by a PU.

In addition, the smaller the number of required channels, the more CR cells can operate on the same set of channels. Therefore, in this chapter, we investigate the difference in terms of channel usage between non-hopping and hopping modes, i.e. the consequences of frequency hopping for the frequency assignment problem.

In particular, we compare two different approaches, one with central and one distributed channel assignment. In the central approach a single node in the network has global knowledge and can compute the optimal frequency hopping assignments for all

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[4] In 802.22 the main class of PUs is TV broadcasters which have a much larger interference range compared to 802.22 cells. Additionally, they have a rather static behavior which does not change frequently over time.

cells. In the distributed approach each cell decides on its own about the next frequency to be used only depending on the currently used frequencies of its neighbors.

5.4 Generation of Hopping Sequences

5.4.1 Centralized Approach

In the hopping mode, the central entity needs to generate a channel assignment sequence per cell consisting of a set of channels and a schedule when to switch and to which channel. In case of global knowledge, we suggest the following generation of hopping sequences. Initially, the central node computes the chromatic number χ_G [5] and the corresponding channel assignments of the network (of the graph *G*) solving the LP in Equations (1-4)[6]:

$$\min \sum_{\forall c \in C} y_c \qquad (1)$$

$$\text{s.t.} \sum_{\forall c \in C} x_{c,v} = 1 \qquad \forall v \in V \qquad (2)$$

$$x_{c,v} + x_{c,w} \leq 1 \qquad \forall c \in C \wedge \forall (v,w) \in E \qquad (3)$$

$$y_c \geq x_{c,v} \qquad \forall (c,v) \in C \times V \qquad (4)$$

[5] The chromatic number of a graph *G* is the minimum number of colors required to completely assign each node a color while ensuring non-interference of neighboring nodes.
[6] Note that the problem can also be approximated by heuristics. However, for our investigations we always used the system optimum.

where $x_{c,v}$ is a binary assignment variable of color *c* and node *v*, constraint (2) assures that each node is assigned a color, and constraint (3) assures that neighboring nodes do not get the same color. Note that y_c is an indication variable denoting the usage of color *c* in the network at all (constraint 4). The network is represented by its interference graph *G = (V, E)* as introduced in Section 5.3.2. *C* is the set of colors (channels) available.

Next, the central entity generates a fixed hopping sequence for each cell. The hopping sequence is generated based on the initial channel indices:

Firstly, all cells with channel index one switch to χ_G + 1 simultaneously. After $T_{sense} + T_{switch}$, the cells with channel index two then switch to channel index one etc., resulting in periodic channel hopping sequences for all cells. Note that there should be enough time for the cells to perform data communications, sensing, and channel switching, i.e., the following condition should hold:

$$T_{\max} / (T_{sense} + T_{switch}) \geq \chi_G \quad , \qquad (5)$$

otherwise multiple cells need to hop at the same time which would require additional channels (as well as a more careful coordination scheme)[7].

The total number of channels required to operate the network is exactly χ_G + 1 [7] due to the fact that hopping times are shifted – such that no two neighboring cells hop at the same time. This is a lower bound of a hopping network regarding its frequency requirement. However, notice that it is based on strong assumptions. The central entity

[7] In this work, we consider only graph instances where this condition holds.

has to collect the information regarding the complete interference graph, then it has to solve the above frequency assignment problem and afterwards it has to reliably distribute the hopping assignments to all cells. We consider this approach mainly for comparison reasons in the following rather than proposing it for practical usage.

5.4.2 Decentralized Approach

Because of scalability reasons, the above centralized approach is probably not applicable to larger network sizes. Therefore, we are interested in generating the hopping sequences in a distributed way based on local information only and quantifying the performance of this scheme.

As a basis, we took the Distributed Largest-First algorithm (DLF) [52] originally designed to solve static FAPs. This approach is known to perform near to optimal for static FAPs in practical problem instances. We modified DLF to handle the problem of generating the hopping sequences with the expectation to also perform well for this case.

The basic idea of DLF is the following. After discovering their cell neighbors, each node of the graph (i.e. each cell) collects information about the node degree (number of neighboring nodes) of its neighbors. The cells then choose their working channels in descending order of that node degree, i.e. the cell with the highest node degree selects its channel first. For equal node degrees a random number is used for tie breaking. A cell always chooses the lowest channel available and distributes its choice within the neighborhood. This method ensures that no two neighboring cells can get the same channel (as only one channel is chosen in a time). A crucial assumption for this approach is obviously that cells can communicate with each other.

Now consider the case of frequency hopping. We modify the DLF approach, referring to it as decentralized hopping approach – DHA. Each cell performs the following steps:

First, it initializes its neighbor list as described for the DLF. Then, all cells perform the priority selection procedure of DLF; the cells with the highest priority within their neighborhood choose a working channel (the lowest channel index available), communicate their choice to their neighbors, and start using the channel. After this initial choice all cells with the second highest priority are allowed to choose their operating channel and so on. Up to this point, the channel allocation is identical to that of the DLF algorithm. Note, however, that there is always a time shift of $T_{sense} + T_{switch}$ between the channel selections of two neighboring cells.

After using a channel for $T_{\max}$ seconds, a cell vacates the currently used channel and hops to the next available one with the lowest channel index. Note that the initial hopping order between the cells remains unchanged. This is due to the fact that all cells use their channel for the same amount of time ($T_{\max}$) and due to the property of DLF that no two neighboring cells select their channels at the same time.

Although the order of the channel selection is periodic among the cells, it might happen that – depending on the choice of all other cells – the selection of the channels themselves results in a non-periodic channel hopping sequence. This effect is due to the “dynamic” choice of the next operating channel while system operation, and is a major difference to the centralized approach.

5.5 Performance Evaluation

In this section we compare the number of channels used in case of the non-hopping and the hopping mode. For both cases we compare two approaches a central and a distributed one, as introduced above. As previously mentioned, the central approach should be regarded as a comparison case rather than as a practical approach.

5.5.1 Methodology

We randomly generated interference topology graph instances using Culbersohn’s graph generator [48] on a 1 by 1 unit plane, with the number of nodes varying between N = 10 and 40. The nodes are connected (i.e. the cells are interfering) if their euclidian distance is smaller than or equal to d, where we vary this distance between d = 0.35 and 0.5.

We have generated 60 random graph topologies for each of those (N, d) pairs. In accordance to 802.22 we chose $T_{\max} = 2$ s and $T_{sense} = 0.1$s. In case of the centralized approach, we transform the graphs into linear programs and compute the chromatic number using CPLEX [45].

In case of the DHA we have implemented a simulation to perform the channel selections for each cell. The simulation time is set to 150 s. We observe the total number of channels each graph instances requires over time. The maximum number of channels required over time is taken as performance metric for each graph. Afterwards, we average that number for both the central and distributed approach over the (N, d)-graphs, for each (N, d) pair.

5.5.2 Results

First, we present the results for frequency requirement for the non-hopping mode, i.e., the traditional frequency assignment problem. Afterwards, we study the same metric for the hopping mode, comparing the LP solution to the DHA algorithm, and show that the performance difference between the centralized and DHA approach increases significantly. In Figure 5-1 we present results for two different interference distances (d = 0.35 and d = 0.5). The key issue to observe from Figure 5-1 is that for the non-hopping mode, i.e. for traditional graph coloring, the performance difference between the centralized and decentralized approach (DLF) rather small. This is in accordance with previous publications and holds for a wide set of graphs. Hence, for the non-hopping mode the decentralized approach is much more preferable due to its easy and operation without overhead.

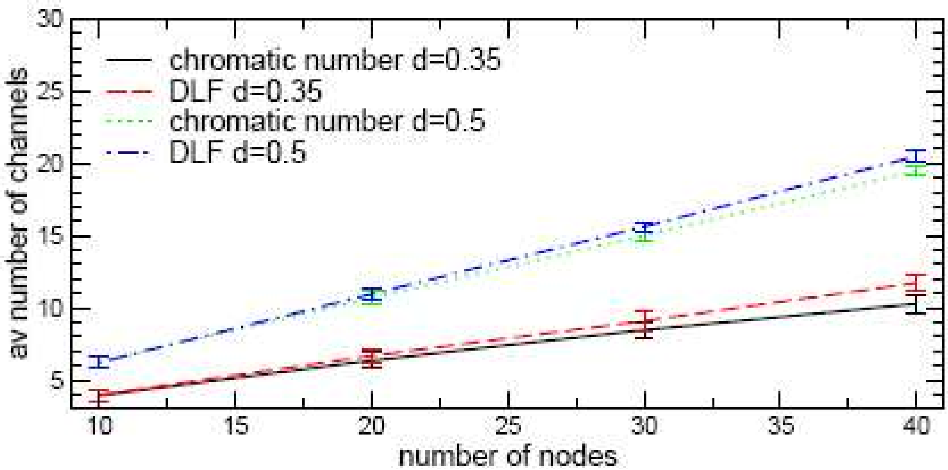


Figure 5-1 Average number of channels required for interference-free assignment for the non-hopping mode (We show the average results for the centralized and decentralized approach for a varying number of nodes per graph for two different interference ranges d = 0.35 and d = 0.5.)

In Figure 5-2 we show the number of channels required for operating the hopping network in the central or distributed fashion described above. Comparing Figure 5-1 and Figure 5-2 we observe that for both – centralized and decentralized – algorithms, the hopping mode requires more channels. Whereas the difference between the central hopping and non-hopping approach is rather small (χ_G +1 compared to χ_G), the difference between the DHA and DLF is much larger (in other words, the cost of operating the network by the decentralized approach is much higher for the hopping mode). The DHA uses a lot more channels than the central (optimal) hopping approach and also has a very high variance. This is rather surprising seeing the good results achieved by the DLF for the non-hopping mode.

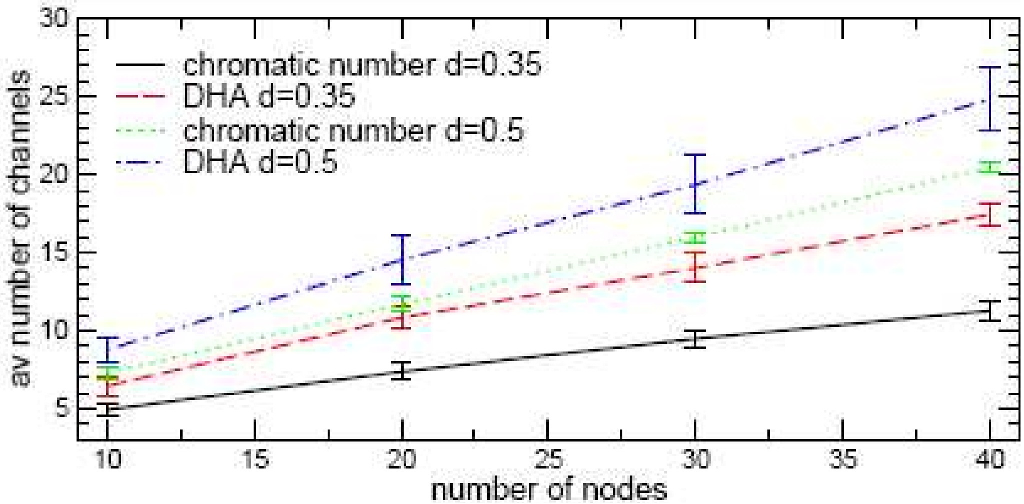
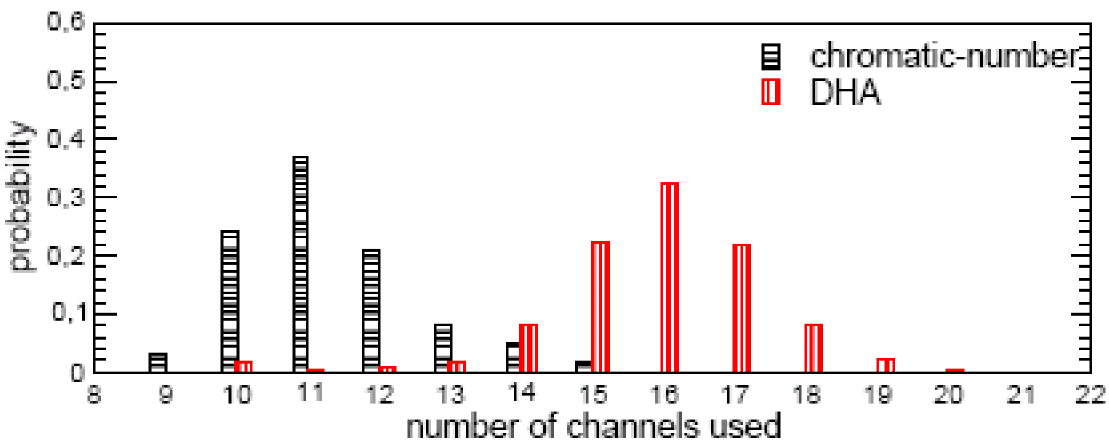


Figure 5-2 Average number of channels required for interference-free assignment in case of the hopping mode (We show the average results for the centralized and decentralized approach for a varying number of nodes per graph for two different interference ranges d = 0.35 and d = 0.5.)

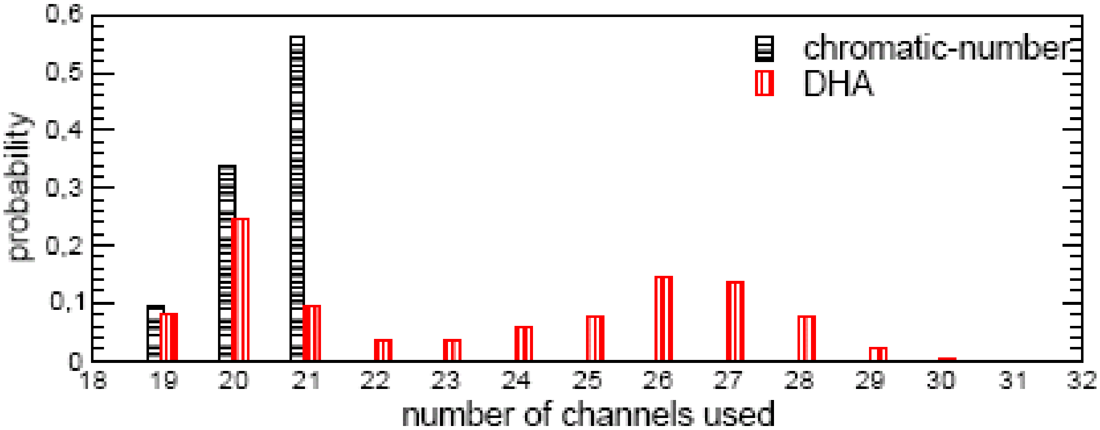
This performance difference is further investigated in Figure 5-3. Here we present the probability density function (PDF) of the number of required channels to operate a network with |V | = 40 cells in hopping mode for the centralized hopping and the DHA. The graphs show the probability that the network occupies a certain number of channels for many different graph instances. We can see that in both figures, i.e. for low and for high cell densities, the variance of the number of channels used is much smaller in the centralized approach (chromatic number). Figure 5-3 (a) shows that for d = 0.35 the PDFs do not have strong overlaps and show a clear value for the expected number of required channels for the DHA. In contrast, Figure 5-3 (b) shows that for a high cell density the DHA has no single center of mass but is subject to two “centers of mass” – one close to the average of the centralized approach and one with a much larger number of channels.

We noticed that this behavior occurs also for smaller cell numbers, i.e. |V | = 20, 30 with high cell density.

To investigate this behavior further, we show the channel usage over time of the DHA for 4 different (selected) graph instances in Figure 5-4. It can be seen that some have a constant channel usage, which does not change over time while others have a strongly varying channel usage for the observed time span. We notice that the constant channel usage corresponds usually to an optimal one, i.e. for these instances the DHA can achieve the optimal channel usage ((χ_G +1). These instances are responsible for the first "center of mass" overlapping with the centralized approach in Figure 5-3 (a) and Figure 5-3 (b).



(a) $|V| = 40,\ d = 0.35$ (low cell density)



(b) $|V| = 40$, $d = 0.5$ (high cell density)

Figure 5-3 PDF of the channel requirement for the centralized (chromatic number) and decentralized (DHA) approaches in the hopping mode

Why are there more such "favorable" (i.e. optimal with respect to channel usage) instances for a high cell density (i.e. in Figure 5-3 (b)) than for low cell densities (i.e. in Figure 5-3 (a))? The reason for this is related to the amount of neighborhood information available at each node. In a complete graph (a graph where each node is connected with every other one), the DHA would always perform optimal since all nodes have "global" knowledge of the graph. Likewise, in a graph where each node has no connection at all, the DHA also performs optimal. For graphs in between these two extreme cases, the performance of the DHA varies; with a tendency to perform better the more nodes are connected with each other (i.e. the more knowledge the nodes have). In order to support this claim we calculated the normalized average node degree for each graph, which is the average node degree of a graph divided by the number of nodes present in the graph. This can be seen as a metric for the connectivity, i.e. the amount of nodes of the graph that are directly connected. All graph instances are then sorted and aggregated into bins based on the normalized average node degree.

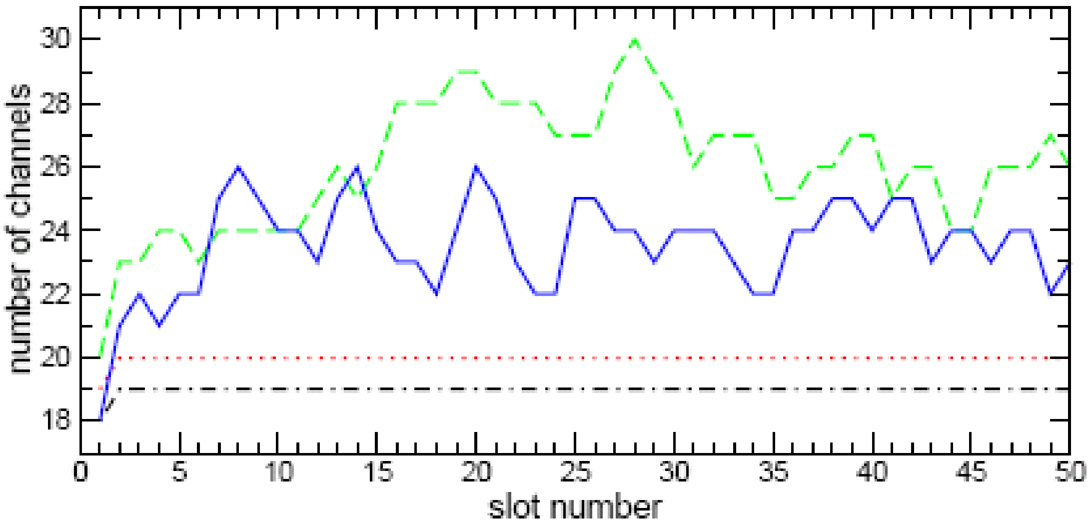


Figure 5-4 Number of channels required over time for 4 different graph instances with |V | = 40 and d = 0.5.

Next, we calculate the normalized difference to the optimum of each graph, which is the number of channels needed by DHA minus the optimum number of channels normalized to the optimum. We average this normalized difference to the optimum for all graphs within each bins of the normalized average node degree and plot the result in Figure 5-5. The figure also shows the percentage of “favorable” graph instances among each bin. We observe that the average difference to the optimum first increases (for the first three bins 0.25, 0.35, 0.45) and decreases thereafter. From bin 0.45 on the average difference to the optimum decreases.

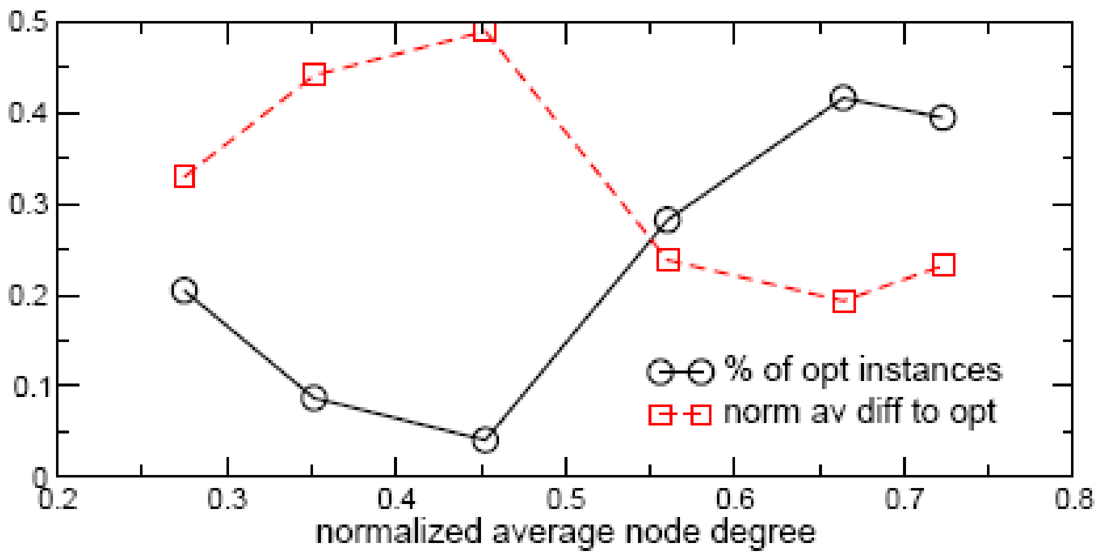


Figure 5-5 Percentage of Optimal Graph Instances and Average Difference to the Optimum over the Normalized Average Node Degree

An opposite behavior is observed for the percentage of "favorable" graphs within the bins. Now consider the knowledge among the graphs in each bin in comparison to the global one. Starting from a light density and increasing it, the knowledge first becomes more and more different (leading to a less amount of favorable graphs among the bins).

However, after the minimum at 0.45 more and more graph instances become favorable again indicating that local knowledge increasingly equals global one again. Finally, we admit that there might also be structural reasons within the graphs determining a favorable or non-favorable graph instance.

5.6 Conclusions

We have discussed the impact of frequency hopping on the required number of channels for cellular networks motivated by the current activities in the 802.22 working group. We have introduced the decentralized hopping approach (DHA), which supports frequency hopping for 802.22-like cellular networks. It has been shown that, unlike in non-hopping mode, this decentralized hopping approach performs much worse than the centralized one in terms of the number of required channels. This is important as the total number of required channels determines the potential impact of cognitive radio (i.e. secondary) interference on primary users. The centralized hopping algorithm, however, needs only a moderate increase of required channels compared to the non-hopping centralized one. We have shown that the performance of the DHA depends on the connectivity of a graph. The higher the connectivity (normalized average node degree) the better is the performance of the DHA in comparison the optimum (on average). Nevertheless, there are favorable graph instances for which the DHA performs particular well.

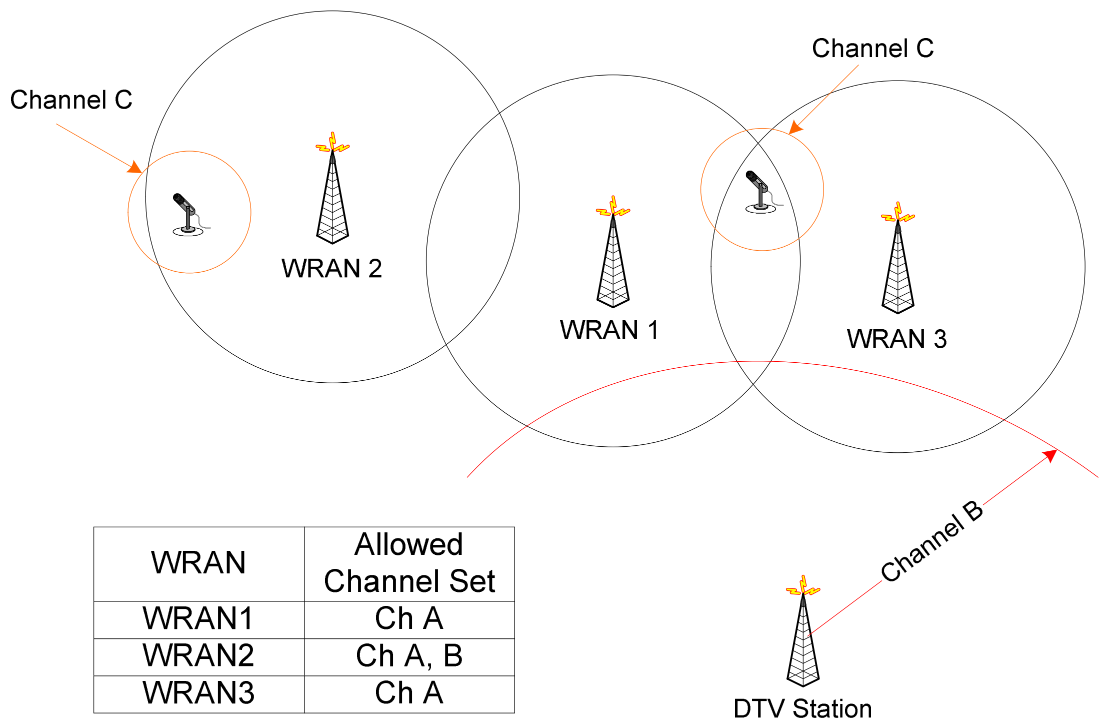
We suggest three issues for future work. For one it remains to investigate the favorable structure of the graphs leading to a low frequency usage by the DHA. In particular, the question arises if practical instances have this characteristic or not. Second, we are interested in investigating the impact of primary user dynamics on the performance results of the centralized and decentralized approach. Finally, our preliminary results motivate the introduction of cooperation between hopping cells (forming for example communities): We will study the performance impact when each such community has regional information about its vicinity and the corresponding overhead required to keep this information up to date.

6 Inter-Network Spectrum Sharing and Communications

6.1 Introduction

In this chapter, we address the design challenges of Inter-Network Spectrum Sharing and Inter-Network Communications for Dynamic Spectrum Access Networks, using the IEEE 802.22 WRAN as the system model.

In a typical deployment scenario, multiple WRAN cells, each of which consists of a base station (BS) and the associated customer premise equipments (CPE) and could have a large communication range of up to 100km, may operate in the same vicinity while coexisting with DTV and Part 74 devices. In order to effectively avoid harmful interference to these licensed incumbents, the set of channels that are allowed for a WRAN cell to operate could be quite limited. For example in Figure 6-1, residing within the protection contours of DTV and wireless microphones, both WRAN1 and WRAN3 are only allowed to operate on channel A, while WRAN2 may occupy either channel A or B, assuming that in total only 3 channels (channel A, B and C) are available. If WRAN1 and WRAN3 (or WRAN1 and WRAN2) attempt to perform data transmission on channel A simultaneously, mutual interference between these collocated WRAN cells could degrade the system performance significantly. Although avoiding harmful interference to licensed incumbents is the prime concern in the system design, another key design challenge to cognitive radio based WRAN systems, with the scenario illustrated above in mind, is how to dynamically share the scare spectrum among the collocated WRAN cells so that performance degradation, due to mutual co-channel interference, is effectively mitigated. Moreover, it’s important that the inter-network spectrum sharing scheme should be developed to maintain efficient spectrum usage, accommodate a large scale of networks with various coexistence scenarios, and provide fairness in spectrum access among the coexisting WRAN cells.



WRAN	Allowed Channel Set
WRAN1	Ch A
WRAN2	Ch A, B
WRAN3	Ch A

Figure 6-1 A Typical Deployment Scenario Where Multiple WRAN Cells are Coexisting with Digital TV and Wireless Microphone Services

To that end, we describe in this chapter a distributed, cooperative, and real-time spectrum sharing protocol called On-Demand Spectrum Contention (ODSC) [8, 11] that has been proposed to IEEE 802.22. The basic mechanism of ODSC is as follows: on an on-demand basis, base stations of the coexisting WRAN cells contend for the shared spectrum by exchanging and comparing randomly generated spectrum access priority numbers via MAC layer messaging on an independently accessible inter-network communication channel. The contention decisions are made by the coexisting network cells in a distributed way. Only the winner cell, which possesses a higher spectrum access priority compared to those of the other contending cells (the losers), can occupy the shared spectrum.

Apparently, the effectiveness of the ODSC protocol relies on the availability of an efficient and reliable inter-network communication Channel for the interactive MAC message exchanges among network cells. In fact, in addition to supporting cooperative spectrum sharing protocols such as ODSC, reliable inter-network communication channel is also indispensable to other inter-network coordinated functions for 802.22 WRAN and, in general, other types of cognitive radio based networks (e.g. inter-network synchronization of quiet periods for spectrum sensing, and coordinated frequency hopping [7, 8, 40]). As the second contribution in this chapter, we introduce a beacon-based inter-network communication protocol called Beacon Period Framing (BPF) Protocol that realizes a reliable, efficient, and scalable inter-network communication channel reusing the RF channels occupied by the network cells.

The remainder of the chapter is organized as follows. In Section 6.2 we describe the details of the ODSC protocol. Section 6.3 presents the concepts of BPF Protocol. Performance analyses and discussion are given in Section 6.4. Section 6.5 proposes future work and concludes the chapter.

6.2 On Demand Spectrum Contention Protocol

6.2.1 Overview

ODSC is a coexistence protocol that employs interactive MAC messaging on the inter-network communication channel to provide efficient, scalable, and fair inter-network spectrum sharing among the coexisting WRAN cells. To achieve these design goals, ODSC allows the coexisting WRAN cells to compete for the shared spectrum by exchanging and comparing randomly generated contention access priority numbers carried in the MAC messages. Such spectrum contention process is iteratively driven by spectrum contention demands (i.e. intra-cell demands for additional spectrum resources to support data services, and inter-cell demands requesting for spectrum acquisitions). The contention decisions are made by the coexisting network cells in a distributed way, which allows an arbitrary number of cells to contend for the shared spectrum in their proximities without relying on a central arbiter. Instead of behaving selfishly, the competing cells cooperated with one another to achieve the goals of fair spectrum sharing and efficient spectrum utilization.

6.2.2 ODSC Procedure

Before initiating MAC layer messaging of the ODSC protocol, a WRAN cell that is demanding additional spectrum resource first evaluates and selects a channel on which no incumbent is detected. The cell then verifies if the selected channel can be shared, employing the transmit power control (TPC) technique, with all other co-channel communication systems without causing any mutually harmful interference. If it is feasible, the WRAN cell schedules its data transmission on the selected channels with appropriate TPC settings. Otherwise, ODSC messaging takes place allowing cooperative spectrum contention among WRAN cells to share the target channel in a time-sharing manner.

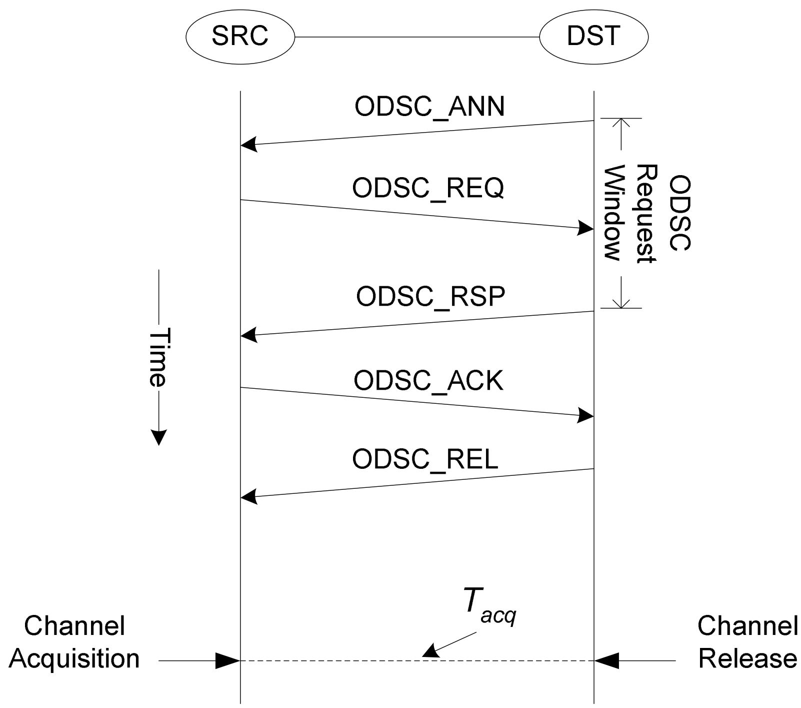


Figure 6-2 Basic ODSC Message Flow

Figure 6-2 depicts the basic MAC messaging flow of the ODSC protocol between two WRAN cells that are within interference range of each other (i.e. within “one-hop”). We assume that the MAC messages are delivered by robustly designed coexistence beacons such that the MAC messages can be received by all coexisting cell within the one-hop distance.

Firstly, a spectrum-demanding WRAN cell, referred to as ODSC source (SRC) captures the ODSC announcement messages (ODSC_ANN) regularly broadcasted by a spectrum occupier WRAN cell, referred to as the ODSC destination (DST).

If SRC receives ODSC_ANN messages from multiple DSTs, it randomly selects one of them. SRC then sends an ODSC request message (ODSC_REQ), including a spectrum access priority number (SAPN), which is a fixed-point number uniformly selected from [0, 2^{32}-1], to the selected DST.

Each DST maintains an ODSC request window so as to allow multiple SRCs to submit ODSC_REQ messages at different time instances without losing the fair chance to participate in the contention process.

At the end of an ODSC request window, if any ODSC_REQ is received, DST randomly generates its own SAPN and compares it with the smallest SAPN carried in the received ODSC_REQ messages.

If the DST's SAPN is smaller (i.e. possesses higher priority), DST sends each SRC an ODSC_RSP message indicating a contention failure. Otherwise, the SRC with the smallest SAPN will receive an ODSC_RSP message with an indication of contention success, and all the other SRC will be informed a contention failure.

Upon receiving a success notice, the winner SRC broadcasts an ODSC_ACK message indicating the time, T_{acq}, at which it intends acquire the channel from the selected DST.

All DSTs that are on the same channel as the one being contended for and are within a one-hop distance of the winner SRC respond to ODSC_ACK message by scheduling a channel release to occur at T_{acq} and broadcasts an ODSC_REL message to the neighborhood. The ODSC_REL message contains information about the channel to release, the channel release time (set to T_{acq}), and the ID of the winner SRC that will acquire the channel.

If ODSC_ACK messages are received from multiple SRCs before the channel is released, a DST selects the earliest T_{acq} specified in the received ODSC_ACK message as the channel release time. This avoids collisions between the neighboring DST and SRC when their channel switching times do not agree.

All SRCs that capture the ODSC_REL message will also schedule channel acquisitions at T_{acq} as long as it is determined from the ODSC_REL message that the 1-hop DST is releasing the channel to either itself or to a winner SRC that is multiple hops away. On the other hand, if multiple ODSC_REL with different T_{acq} are received before the channel switching, the earliest T_{acq} is taken for channel acquisition.

In a large scale network, it is likely that multiple DSTs and multiple SRCs coexist. As the contention processes are fully random and independent, different SRCs could select their own DSTs to contend for the same spectrum resource and the contentions outcomes (i.e. winners of the contention and channel acquisition/release times) could be in conflict. The ODSC message flow described above is designed to coordinate the discrepancies between the conflicting contention decisions in order to ensure the stability of the coexistence behaviors and avoid loss of spectrum efficiency across the networks.

6.3 Beacon Period Framing Protocol

In this section we introduce the Beacon Period Framing (BPF) Protocol that enables reliable, efficient and scalable inter-network communications in support of inter-network coordination functions, such as the ODSC protocol and coordinated DFH.

6.3.1 Super-frame and Frame Structure

As depicted in Figure 6-3, the BPF Protocol adopts the super-frame and frame structure proposed in IEEE 802.22 without loss of generality. All channels are partitioned in time into synchronized super-frames, each of which consists of 16 frames with fixed frame size. Each frame is further divided into a Data Transmission Period and an optional fixed size Beacon Period (BP), which allows coexisting WRAN cells to exchange coexistence beacons for inter-network communications. In line with 802.22, we assume that each BP allows one beacon to be transmitted, and that a network cell is only allowed to transmit coexistence beacons in BPs on its operating channel.

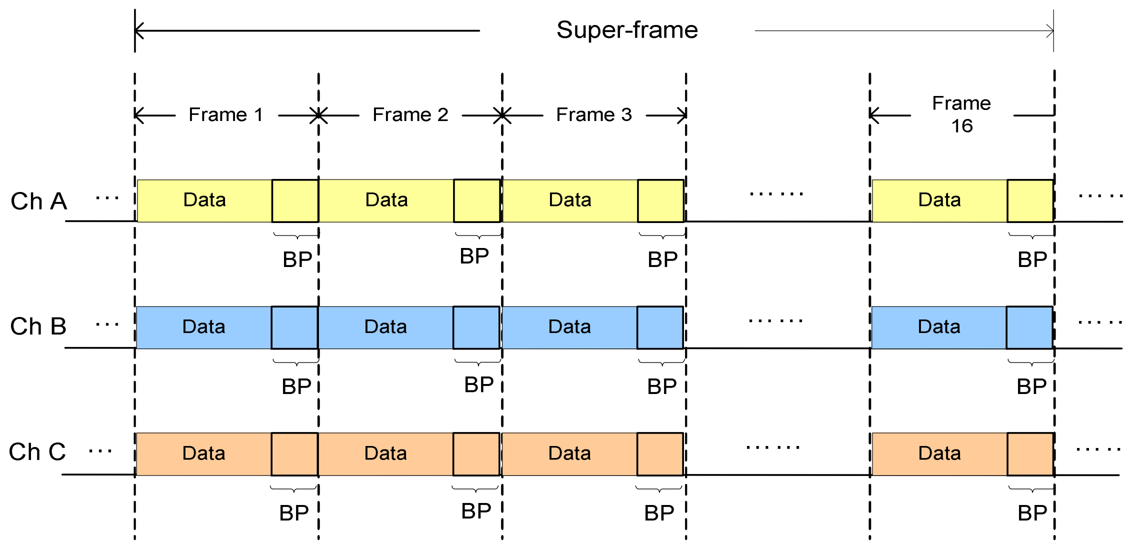


Figure 6-3 Super-frame and Frame Structures on Multiple Channels

Although BPs can be accessed using contention based mechanisms such as Carrier Sense Multiple Access (CSMA) [63, 64] or ALOHA [62], these mechanisms cause coexistence beacons to be transmitted in non-deterministic instances that are unknown to the other coexisting cells. This non-deterministic characteristic renders unpredictable (potentially long) delay and very low bandwidth efficiency for inter-network communications. For example, the allocated bandwidth is wasted if no inter-cell communication can be successfully conducted during a BP.

To order to mitigate the non-deterministic issue of contention-based beacon transmission, each network cell can periodically reserve on the operating channel a BP for exclusive beacon transmission. Although this reservation-based approach improves the system performance and bandwidth efficiency in static coexistence environments, it still suffers from performance limitations when the coexistence scenarios are dynamically changed, due to its lack of flexibility and scalability. The BPF Protocol, as introduced in the following, provides an efficient, flexible, and scalable method for reliable inter-network communication utilizing the beacon periods.

6.3.2 Beacon Period Frame Structure

As shown in Figure 6-4, a BP Frame is a group of 16 BPs in consecutive data frames. The BP frame begins with an Announcement BP (A-BP) and ends with a BP preceding the A-BP of the next BP Frame. The location of the A-BP is designed to be unique across a large number of continuous channels. To achieve that, we specify that an A-BP for a particular channel always resides in a MAC frame with the frame index (within a super-frame) equal to the channel number of the residual channel modulo 16.

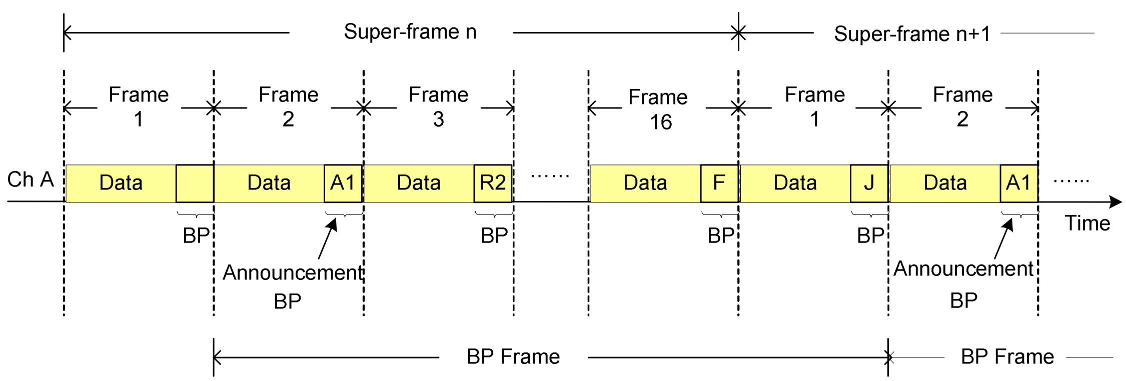


Figure 6-4 Beacon Period Frame Structure

Similar to a regular data frame in a TDMA system, a BP Frame consists of a MAP (the payloads' scheduling information) and the payloads, which are the 16 BPs in the BP Frame. The MAP of a BP Frame is carried by the announcement beacon transmitted in the A-BP. As an example, Figure 6-4 shows the BP Frame structure for a coexistence scenario where cell 1 and cell 2 reside on channel A. The A-BP, which is reserved by cell 1 and labeled as “A1”, is the first BP in the BP Frame. As specified in the MAP, the second BP is reserved for cell2 (labeled as “R2”). The other unassigned BPs are set to be Free-to-use (labeled as “F”) except for the last BP is reserved for “Joining” (allowing a new cell to participate in transmission on the channel).

6.3.3 Types of BP Assignment

1) Announcement BP (A-BP)

The A-BP is always at the beginning of a BP Frame and is reserved by a network cell, behaving as the channel coordinator, for the transmission of the announcement beacon.

2) Reservation BP (R-BP)

An R-BP is reserved for a network cell, say cell x, that resides on the operating channel to perform contention-free beacon transmission. Other network cells that intend to receive a beacon packet from cell x can tune to the operating channel of cell x during x’s R-BP by referring to the MAP.

3) Free-to-use BP (F-BP)

An F-BP can be used in many ways by all network cells reside on the operating channel: either for data transmission, or for beacon transmission (using contention based method) or receptions, or for any other system maintenance purposes.

4) Joining BP (J-BP)

The J-BP is used for an off-channel or new network cell to join the BP Frame so as to participate in communication on the operating channel.

6.3.4 Inter-Network Communications using BP Framing

For two network cells, cell A and cell B that are operating on channel Ch(A) and Ch(B) respectively, the inter-cell communication can be performed as follows:

1) Cell A to receive beacon packets from cell B

- Tune to the operating channel of Cell B – Ch(B), during the A-BP of Ch(B);
- Receive and decode the BP Frame's MAP of Ch(B)
- Identify the R-BP of Cell B – R-BP(B);
- If R-BP(B) exists, receive beacon packets from Cell B at R-BP(B);
- Else, try to receive beacon packets from Cell B during the F-BP on Ch(B);

2) Cell A to transmit beacon packets to cell B

- If a R-BP is required for the beacon transmission, reserve one – R-BP(A);
- Transmit the MAP of the BP frame of Ch(A), during the A-BP of Ch(A);

- If R-BP(A) is available, transmit the beacon packet during R-BP(A);
- Else, transmit the beacon packet during a F-BP on Ch(A).

6.3.5 Channel Coordinator and Channel Members

To order to facilitate efficient, flexible and scalable management of inter-network communications, one of the network cells communicating on the operating channel behaves as the channel coordinator and is responsible for a number of coordination tasks, which include transmitting announcement beacons, managing channel membership (joining of new members and leaving of old members), and scheduling of beacon periods for all channel members by generating the MAP. By default, the network cell that occupies the channel first becomes the channel coordinator. All the other co-channel network cells behave as the channel members after successfully registered with the channel coordinator through the Joining process. A channel member can request for BP reservation and shall follow the schedule in the MAP transmitted by the coordinator.

6.3.6 Flexible and Scalable Scheduling of Beacon Periods

As there are 16 BPs available in a BP Frame, up to 16 co-channel network cells can be simultaneously accommodated for deterministic inter-network communications through BP reservations and, when some of the BPs are shared using contention based access, more than 16 cells can be allowed to communicate on a channel. The assignment of BPs and scheduling of network cells to communicate on BPs are flexibly managed by the channel coordinator. Note that the coexistence scenario could be dynamically changed over time due to, for example, channel switching or mobility of the network cells. BPF Protocol allows the scheduling of BPs to be adapted to the current coexistence scenario optimizing scalability, performance, and bandwidth efficiency for inter-network communications. For example, when the number of co-channel network cells is small, each cell can be allocated more R-BPs so that it can have more control to manage the inter-network communications. On the other hand, when the number of co-channel network cells increases, each cell is allocated less R-BPs so as to accommodate more channel members.

6.4 Performance Evaluation and Discussion

To evaluate the performance of ODSC and BPF Protocols, an NS2 [56] model has been developed for IEEE 802.22 implementing these two protocols for inter-network spectrum sharing and communications.

In our simulations, multiple WRAN cells, synchronized to a common time source, coexist in the same vicinity sharing a SINGLE channel. We configure each superframe to contain 16 frames. The sizes of the frame and the BP are 10ms and 2ms respectively. Each round of simulation runs for 10,000 seconds.

In order to verify the feasibility of these protocols, we conduct simulations for three basic types of coexistence scenarios modeled by contention graphs (in which vertices denote the WRAN cells and edges connecting vertices represent the mutual interference between the cells):

a. Complete Graph scenario - every pair of vertices is connected by an edge;

b. Cycle Graph scenario - vertices are connected in a closed chain;

c. Wheel Graph scenario - a center vertex is connected to all other vertices that form a cycle.

For each type of scenarios, as shown in Figure 6-5, we vary the number of coexisting cells (up to 7 cells) to evaluate the performance scalability of the proposed protocols.

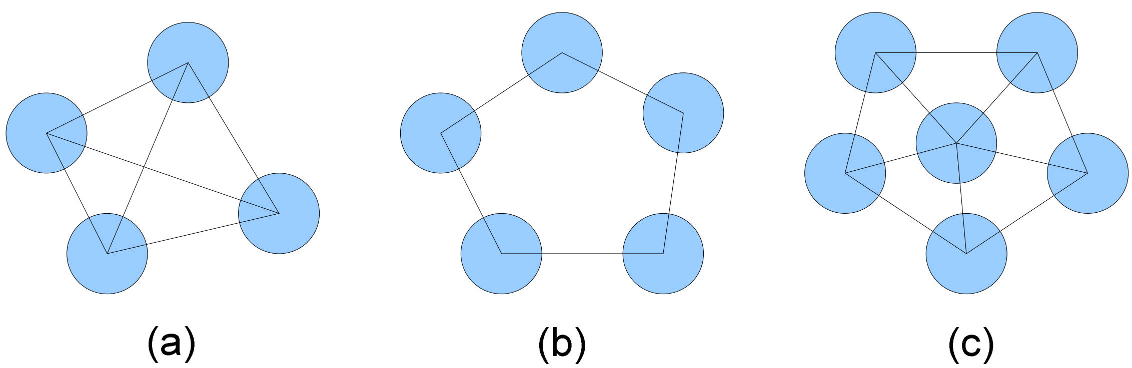


Figure 6-5 Types of Coexistence Scenarios

Table 6-1 shows the simulation results that measure the channel occupancy (i.e. ratio of channel occupation time to the total operation time) of each coexisting WRAN cell applying the ODSC protocol in three types of scenarios. The optimal occupancy as shown in the table is obtained by applying the Max-min fairness scheduling criterion [57] for each scenario.

No. of Cells	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Optimal
2	0.500884	0.494989				1/2
3	0.331630	0.329914	0.335365			1/3
4	0.248409	0.251128	0.251106	0.246233		1/4
5	0.202269	0.193133	0.203893	0.198870	0.198137	1/5

(a) Complete Graph Scenarios

No. of Cells	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Optimal
3	0.331630	0.329914	0.335365					1/3
4	0.501248	0.495934	0.495934	0.500581				1/2
5	0.420031	0.284119	0.419748	0.416048	0.4197			2/5
6	0.497953	0.498706	0.497822	0.498873	0.497619	0.4989		1/2
7	0.430724	0.448526	0.428689	0.436894	0.439151	0.432226	0.348478	3/7

(b) Cycle Graph Scenarios

No. of Cells	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Optimal
4	0.248409	0.251128	0.251106	0.246233				1/4
5	0.334881	0.333089	0.32877	0.334587	0.327745			1/3
6	0.283983	0.277948	0.305698	0.278366	0.283266	0.278926		2/7
7	0.324517	0.335407	0.336619	0.330762	0.330051	0.329977	0.331971	1/3

(c) Wheel Graph Scenarios

Table 6-1 Channel Occupancies of Coexisting WRAN Cells in Three Types of Coexistence Scenarios

Based on the data collected in Table 6-1, we plot the global (Jain’s) fairness index [58] of the coexisting WRAN cells as depicted in Figure 6-6. It shows that the ODSC protocol effectively enable WRAN cells to achieve a closed-to-optimal global fairness performance in all three types of coexisting scenarios without sacrificing bandwidth utilization. Moreover, the fairness performance scales very well with an increasing number of coexisting cells for a variety of scenarios.

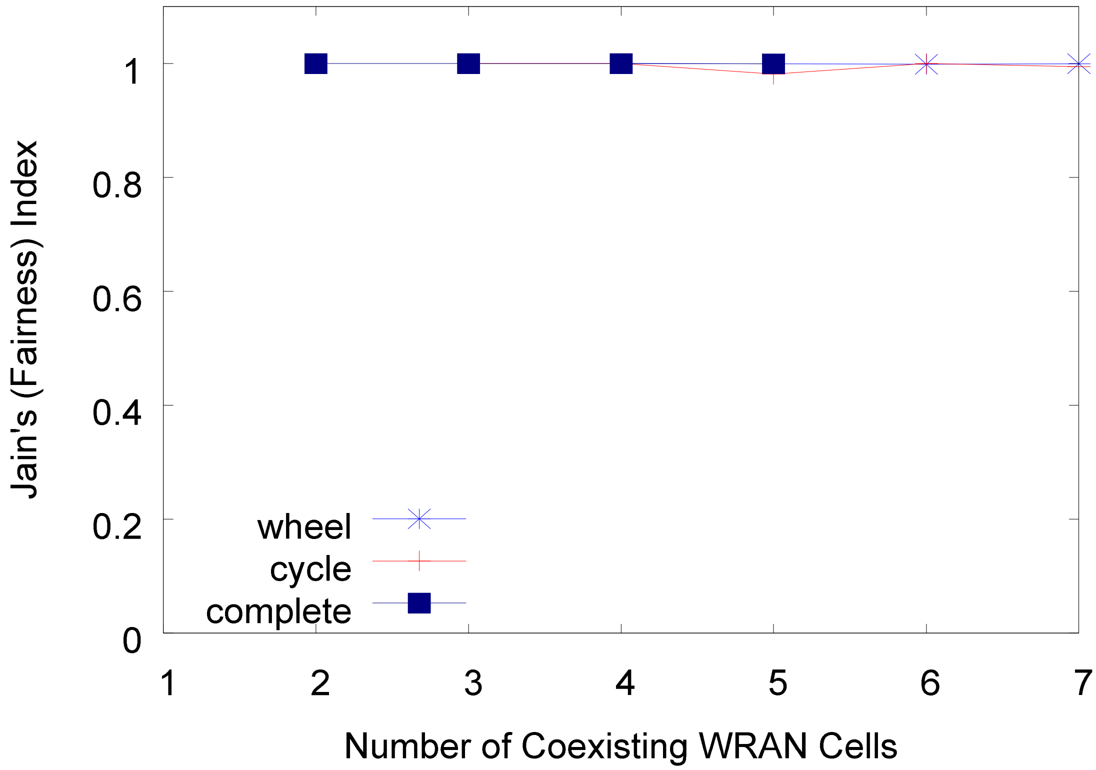


Figure 6-6 Fairness of ODSC in Differenct Coexistence Scenarios

Another import performance metric to evaluate an inter-network spectrum sharing mechanism is the time that the coexisting networks take to converge to the equilibrium of spectrum sharing activities. Figure 6-7 illustrates the convergence time of all the coexistence scenarios employing the ODSC protocol utilizing the inter-network communication channel enabled by the BPF protocol. It can be observed from Figure 6-7 that the complexity of the contention graph of a coexistence scenario determines the convergence time of spectrum sharing. Although increased number of coexisting cells would in general increase the network convergence time, the type of contention graph of a scenario impacts the convergence performance significantly. As an example, the wheel graph scenario with 6 cells, which has an imperfect contention graph, requires almost 2000s to reach the equilibrium, while the wheel graph scenario with 7 cells takes about 1100s to converge. This is due to the imperfect topology of the contention graph that requires longer convergence delay to resolve more intensive inter-network contention conflicts.

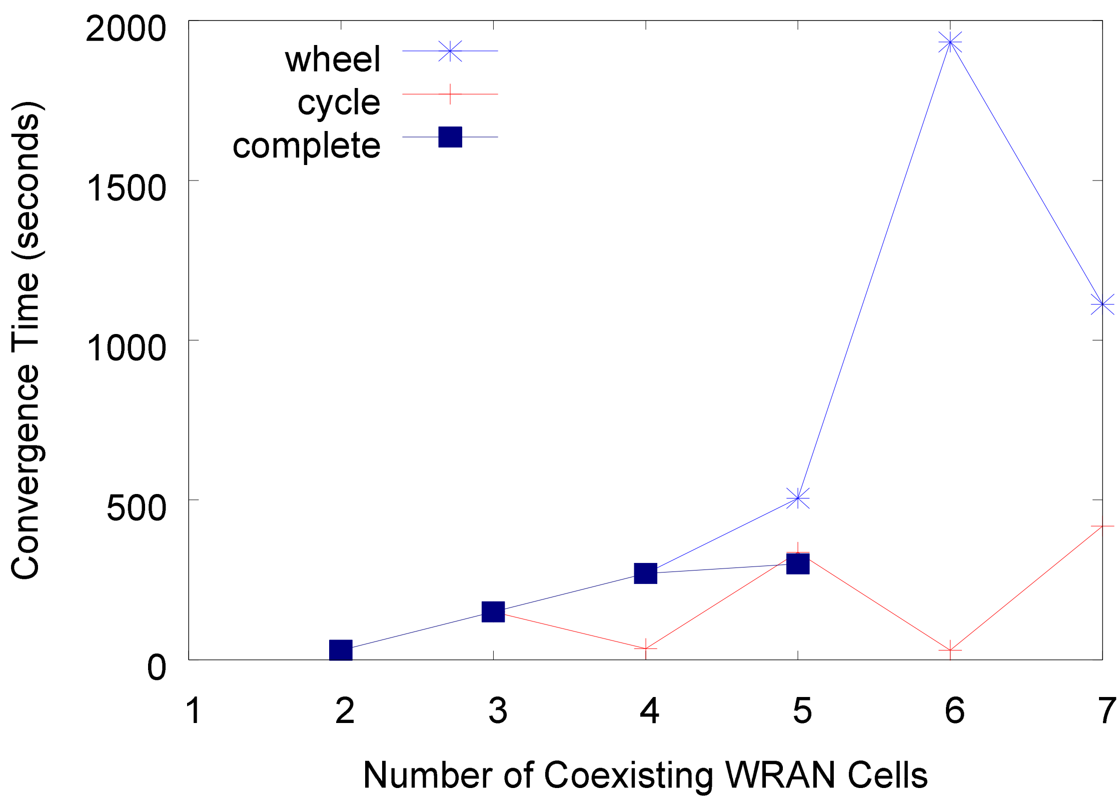


Figure 6-7 Convergence Time of ODSC in Different Coexistence Scenarios

6.5 Conclusion

In this chapter, the design challenges of inter-network spectrum sharing and communications for the emerging cognitive radio based IEEE 802.22 networks are addressed. We present the On Demand Spectrum Contention protocol that enable the coexisting network cells to compete for the scarce spectrum by exchanging and comparing randomly generated contention access priority numbers in an on-demand, distributed, and cooperative manner. In order to support inter-network coordination functions such as ODSC in 802.22 and other cognitive radio systems, we describe in detail the Beacon Period Framing protocol that realizes a reliable, efficient, and scalable over-the-air inter-network communication channel among coexiting cells reusing their occupied RF channels. Extensive simulations conducted on a varity of coexistence scenarios show that the ODSC protocol, enabled by the BPF protocol, provides closed-to-optimal fariness, scalalibility, and spectrum efficiency for inter-network spectrum sharing.

7 Conclusion, Discussion, and Future Work

7.1 Conclusion

With the knowledge that a large amount of licensed spectrum is underutilized in both time and frequency, the concept of dynamic spectrum access (DSA) has been proposed as a promising solution to the potential spectrum scarcity problem, where unlicensed devices (the secondary uses) temporarily "borrow" frequency bands from spectrum licensees (the primary users) while at the same time respecting the rights of the incumbent license holders.

To meet the requirements of awareness and adaptation for the secondary operations, cognitive radios have been identified as a key enabling technology for DSA based wireless networks, where the operating parameters (such as frequency, power, and modulation) of the unlicensed device can be rapidly reconfigured to the changing communication requirements and spectrum conditions of the transmission environment. Based on software-defined radio (SDR) technology, cognitive radios are able to provide greater flexibility and access to spectrum and improve the spectrum utilization by seeking and opportunistically utilizing radio resources in time, frequency and space domains on a real time basis.

Based on cognitive radio technology, IEEE802.22, following the FCC Notice of Proposed Rulemaking (NPRM) [1] in 2004, is an emerging standard based on the concept of Dynamic Spectrum Access for Wireless Regional Area Networks (WRANs) operating on license-exempt and non-interference basis in the TV bands (between 47-910 MHz). It aims at providing alternative broadband wireless Internet access in rural areas without creating harmful interference to licensed TV broadcasting.

In this dissertation, we give comprehensive overviews on Dynamic Spectrum Access Networks, Cognitive Radio Technologies, and the state-of-the-art of emerging IEEE 802.22 standard. In particular, we provide three contributions addressing the following key technical challenges in the design of Medium Access Control protocols for DSA and IEEE 802.22 networks:

- Assuring the QoS satisfaction for DSA (IEEE 802.22) network services, while providing reliable spectrum sensing for guaranteeing licensed user protection.
- Inter-network coexistence of the DSA (IEEE 802.22) networks for efficient, fair and scalable spectrum sharing among the collocated DSA (IEEE 802.22) networks.
- Reliable, efficient, and scalable over-the-air Inter-Network Communication Channel for effective coordinated functions performed among the coexisting DSA (IEEE 802.22) networks.

When operating on a single channel in the basic “listen before talk” mode, the QoS of DSA network cells might degrade due to sensing interruptions. This can be mitigated by Dynamic Frequency Hopping, where data transmission is performed without interruptions in parallel with spectrum sensing. However, in a bigger cluster of cells, frequency hopping could lead to significant problems if no coordination scheme is employed. Coordinated Dynamic Frequency Hopping is a concept introducing coordination among cells. As shown, it leads to a better QoS and throughput behavior, while requiring a modest amount of channels for hopping.

To address the challenge of inter-network spectrum sharing and communications, we present the On Demand Spectrum Contention protocol that enable the coexisting network cells to compete for the scarce spectrum by exchanging and comparing randomly generated contention access priority numbers in an on-demand, distributed, and cooperative manner. In order to support inter-network coordination functions such as ODSC and coordinated DFH in IEEE 802.22 and other cognitive radio based DSA systems, we describe in detail the Beacon Period Framing protocol that realizes a reliable, efficient, and scalable over-the-air inter-network communication channel among coexisting cells reusing their occupied RF channels. Extensive simulations conducted on a variety of coexistence scenarios show that the ODSC protocol, enabled by the BPF protocol, provides close-to-optimal fairness, scalalibility, and spectrum efficiency for inter-network spectrum sharing.

7.2 Discussions

There are a number of interesting questions that are worth discussing as follows.

A. Centralized vs. Distributed Spectrum Sharing

As described in chapter 2, the spectrum sharing among the DSA networks can be managed in three different architectures: centralized, distributed, and autonomous.

The DARPA XG network [1] is a representative example of the autonomous architecture that allows opportunistic spectrum access for peer-to-peer ad-hoc communications.

On the other hand, as proposed in [2], the centralized DSA networks are controlled and coordinated by a central entity, called Spectrum Broker, for accessing the spectrum. The service provider or users of these networks obtain time bound rights from the spectrum broker to part of the spectrum and use it to offer the network services. The management architecture proposed in [2], called DIMSUMnet, assumes that a contiguous chunk of spectrum, called coordinated access band (CAB), is reserved by the regulatory authorities such as FCC for the centralized dynamic spectrum access. For a geographical region, the allocation of various parts of CAB to individual network operators or users is managed by the spectrum broker, who is considered permanently owns the CAB. The network operators or users submit spectrum lease bids to the spectrum broker and grain access to the spectrum by paying a price. Within the CAB, certain fixed frequencies are reserved as so called Spectrum Information Channels, which are used to deliver control information for the spectrum access. Within this centralized architecture, multiple spectrum brokering servers must be redundantly deploy per region and maintain consistent information among them in order to ensure reliable allocation of the spectrum resources. If one of the servers fails, one of the remaining servers will continue to satisfy the spectrum lease and information request in the region. The development of a scalable mechanism in order to minimize the overhead of frequent and deterministic dissemination of spectrum information has been considered a key technical issue.

Moreover, the overhead of the spectrum brokering increases as the number of network cells in a region increase. It's unrealistic to expect the base stations in the network cells to acquire spectrum lease from a spectrum brokering server located remotely, or if the base stations decide to do so, the communication delay and overhead across multiple hops of a wireless link could be quite significant. In order to utilize the Spectrum Information Channels for exchanging the control information for spectrum access, both the base stations and the client devices have to be equipped with dedicated RF interfaces for accessing these spectrum information channels. In certain cases, however, it may not be practical where the base stations and client devices are designed to be inexpensive and simple devices that they may not support the spectrum information channels.

The spectrum sharing mechanism proposed in this dissertation is based on the distributed management architecture that is assumed by most DSA networks employing the method of opportunistic spectrum access. In particular, the system aspects of the IEEE 802.22 WRAN, as shown in the following, are fundamentally different from what the centralized architecture usually assumes:

- There is no dedicated spectrum reserved by FCC (or other regulatory authorities) for dynamic spectrum access in the TV bands.
- The spectrum brokering systems are not available.
- The access to the TV spectrum is opportunistic and license-exempt, and is not based on spectrum trading.

B. Backhaul-based vs. Over-the-air Inter-Network Communications

Although the over-the-air solutions are proposed in this dissertation, the Inter-Network Communications can also be realized using the IP-based Backhaul approach. The major reason that the over-the-air approach is proposed in this work is that we focus our attention on the MAC layer design. The IP-based backhaul solution involves the operations in the higher layers, therefore is out of scope of this work. Another reason that we propose the over-the-air solution as an inter-network communications alternative is due to the following considerations on the backhaul-based approach.

The first consideration is the quality of communications offered by the backhaul solution. The latency and jitter are the major concerns in this aspect. In order to connect to the IP backbone, a base station may have to route the control messages through multiple "backhaul relay radios" over the air until reaching the wired point of presence (POP) connecting to a wired backbone that is optimized to reduce latency and jitter using such technologies as multi-protocol labeling system (MPLS) [67]. The communication latency and jitter, which occurs in both the wireless link and the inside the relay radios, accumulate when each backhaul relay is passed through. Assuming a 10 ms delay introduced by each hop of the wireless relay link and by the IP network, and 5 hops are required to reach the IP backbone from both sides of the communicating base stations, a 110 ms delay is required for the inter-network communications. The connection to the IP backbone could be also realized through non-terrestrial communications, such as satellite services. In such case, however, a permanent latency in the range of 500 ms to 1000 ms is incurred.

The second consideration is the availability of the backhaul network. Although the backhaul network is usually accessible for the DSA networks when they target for providing wireless broadband access services, the backhaul network may not be available in the emergent public safety situations where the network infrastructures are down. Moreover, when the DSA networks are deployed for ad hoc based (infrastructure-less) communications, the connection to the backhaul network may not be practically assumed.

C. Dedicated Radio Frequency vs. In-band Radio Frequency for Inter-Network Communications

Another question arises for over-the-air Inter-Network communications is that, instead of using the in-band radio frequency (the same frequency as for the system's data service communications) for realizing the inter-network communications channel, whether we can utilize a dedicated radio frequency (or a number of dedicated frequencies) for facilitating communications among the coordinating DSA networks.

Unlike in the centralized spectrum sharing architecture as described previously where dedicated frequencies for exchanging spectrum sharing information are reserved by the spectrum owner, it would be infeasible, or at least very difficult, to maintain such dedicated radio frequencies for inter-network communications in the opportunistic spectrum access environment. As the secondary users, the DSA network systems will have to vacate the operating frequencies, including the ones allocated for inter-network communications, whenever the licensed incumbents reclaim the spectrum. In such dynamically changing radio environment, it is not guaranteed that a common frequency can be identified to be accessible to all DSA network systems in a region, and the complexity and overhead for maintaining such frequencies, if ones are identified, would be prohibitively high.

7.3 Future Work

The techniques proposed in this dissertation provide fundamental solutions to a number of key design challenges in the cognitive radio based dynamic spectrum access networks. These fundamental techniques would serve as a foundation encouraging future research in the following aspects:

- Intelligent algorithm developments for frequency-agile DFH operations (coordinated or non-coordinated) optimizing for the objectives of licensed user protection, spectrum utilization, and QoS supports.
- Convergence and fairness analyses, using tools such Game Theory [59], for complex coexistence scenarios in which ODSC is applied.
- Extensions of the current work in support of mobile networks.
- Coexistence of heterogeneous DSA networks.

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