Cognitive PHY and MAC Layers for Dynamic Spectrum Access and Sharing of TV Bands

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ABSTRACT

Research in the physical (PHY) and medium access control (MAC) layers for dynamic spectrum access (DSA) and dynamic spectrum sharing (DSS) is still at its infancy. Aspects such as spectrum sensing, coexistence, measurement and spectrum management, network reliability and QoS support in face of the need to avoid causing harmful interference into incumbents, to name a few, are key to the success of future cognitive radio (CR) systems and have received little attention so far. In addition, it is critical to understand the interplay of these various cognitive radio concepts and how they impact the overall network performance. In this paper we address these questions by presenting the design and performance evaluation of a CR-based PHY and MAC for DSA and DSS of vacant television (TV) channels. This air interface described here forms the baseline of the current IEEE 802.22 draft standard, and features a number of key PHY and MAC CR-based components for use by license-exempt devices in the spectrum that is currently allocated primarily to TV services. Through simulations and prototyping, we analyze the performance of this first CR-based wireless network with respect to spectrum sensing, system capacity, QoS support, coexistence, and network reliability.

Categories and Subject Descriptors

C.2.5 [**Network Architecture and Design**]: Wireless Communication.

General Terms

Algorithms, Performance, Design, and Standardization.

Keywords

Spectrum agile radios, cognitive radios, spectrum sensing, dynamic spectrum access, dynamic spectrum sharing, IEEE 802.22.

1. INTRODUCTION

Cognitive Radios (CRs) [1][2][3] are seen as the solution to the current low usage of the radio spectrum. It is the key technology that will enable flexible, efficient and reliable spectrum use by adapting the radio's operating characteristics to the real-time conditions of the environment. CRs have the potential to utilize the large amount of unused spectrum in an intelligent way while not interfering with other incumbent devices in frequency bands already licensed for specific uses. CRs challenge the current notion of spectrum scarcity, and frame the problem as that of spectrum access and sharing.

In practice, however, for a CR network to be deployed a number of new technologies have to be developed, from the antenna design and potentially going all the way up to the transport layer. Of particular interest in this paper are the PHY and MAC layers [4], which together are at the heart of a true CR. Within these layers, a plethora of new mechanisms such as spectrum sensing, coexistence (with incumbents and self-coexistence), measurement and spectrum management, network reliability and QoS support in face of DSA and DSS[1,2], and so on, have to be designed for harmless access to and sharing of spectrum. In addition, as these new mechanisms may likely have an impact on network performance (e.g., spectrum sensing may take away some time that could otherwise be used for data communication, and hence may compromise QoS), it is critical to analyze their interplay and how to best optimize them for different situations.

In spite of that, little has been done so far on the study of the impact of CR-based techniques on the overall network performance. It is not known whether a CR network can offer satisfactory performance despite the injection of many new incumbent handling mechanisms, and what are the implications in terms of QoS.

In this paper we aim at responding these questions within the context of the work being done at the IEEE 802.22 working group (or simply, 802.22) [5][6], which has been formed back in November/2004 with the goal of developing an air interface[3] based on CRs for unlicensed operation in the TV broadcast bands. As of this writing, 802.22 has produced its first draft standard [7], and the air interface presented here forms the baseline of this draft.

Therefore, the focus of this paper is to study those PHY and MAC layer aspects that allow DSA and DSS of TV bands. More specifically, we investigate the following aspects related to the current 802.22 draft standard: i) spectrum sensing and its impact on the network performance; ii) coexistence (with incumbents and self-coexistence); iii) measurement and spectrum management; and, finally, iv) network reliability and QoS support in face of DSA and DSS. Here, we provide a detailed overview of these mechanisms, investigate how they work together, and study their performance.

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[1] DSA and DSS are distinguished by the fact that the former is defined with respect to the incumbent user, while the latter refers to sharing amongst secondary users.

[2] Another axis called Dynamic Spectrum Multi-channel (DSM) operation also exists [9], but this is not the focus of this paper.

[3] In this work, the term air interface is used to refer to the PHY and MAC layers of the ISO/OSI protocol reference model [4].

The rest of this paper is organized as follows. In Section 2 we provide an overview of 802.22 including system wide aspects such as topology, entities, and coverage, as well as discuss the critical timing requirements which drive the design of various other DSA and DSS techniques discussed in the next sections. In Section 3 we delve into the specific CR-based PHY and MAC technologies enabling DSA and DSS, and which are included in the current 802.22 draft standard. An extensive performance evaluation of these schemes is then given in Section 4. The related work is described in Section 5. Finally, Section 6 concludes this paper.

2. OVERVIEW OF IEEE 802.22

The 802.22 frequency band of operation ranges from 54-862 MHz, while there is an ongoing debate to extend the operational range to 41-910 MHz as to meet additional international regulatory requirements. Also, since there is no worldwide uniformity in channelization for TV services, the current draft standard accommodates the various international TV channel bandwidths of 6, 7, and 8 MHz.

2.1 Incumbents to Protect

Within 802.22, the sensing mechanism is designed to offer protection to two types of incumbents, namely, the TV service and wireless microphones. In particular, wireless microphones are licensed secondary users of the spectrum, and are allowed by FCC to operate on vacant TV channels on a non-interfering basis (please refer to Part 74 of the FCC rules)[4]. Contrary to detection of TV transmission, detection of wireless microphone operation is much harder as they transmit at a much lower power (typically 50 mW for a 100 m coverage range) and occupy much smaller bandwidths (200 KHz).

2.2 Topology, Entities and Relationships

The 802.22 system specifies a fixed Point-to-MultiPoint (P-MP) wireless air interface whereby a Base Station (BS) manages its own cell[5] and all associated Consumer Premise Equipments (CPEs). The BS (a professionally installed entity) controls the medium access in its cell and transmits in the downstream (DS) direction to the various CPEs (which can be user-installable), which respond back to the BS in the upstream (US) direction. In order to ensure the protection of incumbent services, the 802.22 system follows a strict master/slave relationship, wherein the BS performs the role of the master and the CPEs are the slaves. No CPE is allowed to transmit before receiving proper authorization from a BS, which also controls all the RF characteristics (e.g., modulation, coding, and frequencies of operation) used by the CPEs. In addition to its traditional role of regulating data transmission in a cell, an 802.22 BS manages a unique feature of *distributed sensing*. This is needed to ensure proper incumbent protection and is managed by the BS, which instructs the various CPEs to perform distributed measurement activities. Based on the feedback received, the BS decides which steps, if any, are to be taken (see Section 3).

2.3 Service Coverage

A distinctive feature of an 802.22 wireless regional area network (WRAN) as compared to existing IEEE 802 standards is the BS coverage range, which can go up to 100 Km if power is not an issue (current specified coverage range is 33 Km at 4 Watts CPE EIRP). WRANs have a much larger coverage range than today's networks, which is primarily due to its higher power and the favorable propagation characteristics of TV frequency bands. This enhanced coverage range offers unique technical challenges as well as opportunities [5].

2.4 DFS Timing Requirements

The Dynamic Frequency Selection (DFS) timing parameters define the requirements that the 802.22 standard must adhere to in order to effectively protect the incumbents. These parameters serve as basis for the design of the coexistence solutions, and are important in understanding the mechanisms presented in Section 3.

Table 1 illustrates only key DFS parameters defined within 802.22, and which are based on the DFS model ordered by the FCC for the 5 GHz band [8]. Two key parameters are the Channel Detection Time (CDT) and the Incumbent Detection Threshold (IDT). The CDT defines the time during which an incumbent operation can withstand interference before the 802.22 system detects it. It dictates how quickly an 802.22 system must be able to detect an incumbent signal exceeding the IDT. Once the incumbent signal is detected higher than IDT, two other new parameters have to be considered, namely, Channel Move Time (CMT) and Channel Closing Transmission Time (CCTT). The CCTT is the aggregate duration of transmissions by 802.22 devices during the CMT.

As it will be shown later, these parameters are critical not only to the design of efficient PHY and MAC layer mechanisms for the sake of incumbent protection, but also to the design of schemes that cause minimal impact on the operation of the secondary network (e.g., QoS support).

Table 1 – Selected DFS parameters

Parameter	Value for Wireless Microphones	Value for TV Broadcasting
Channel Detection Time	≤ 2 sec	≤ 2 sec
Channel Move Time	2 sec	2 sec
Channel Closing Transmission Time (Aggregate transmission time)	100 msec	100 msec
Incumbent Detection Threshold	-107 dBm (over 200KHz)	-116 dBm (over 6MHz)

3. COGNITIVE PHY AND MAC LAYERS

The distinctive and most critical requirement for the 802.22 air interface is flexibility and adaptability. This stems from the fact that 802.22 operates in a spectrum where incumbents (mostly wireless microphones) may appear and disappear arbitrarily and where the collocated operation of multiple networks will be commonplace, as 802.22 operates under license exempt regulatory model. This requirement has a direct impact on the various DSA and DSS

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[4] Throughout this paper, the terms incumbent and primary services are used interchangeably to refer to the TV broadcast service and wireless microphones (even though, strictly speaking, wireless microphones are secondary, but licensed, users). Accordingly, 802.22 devices are seen as unlicensed secondary users of the band and hence are broadly called secondary services.

[5] Here, we define a 802.22 cell (or simply, a cell) as formed by a single 802.22 BS and zero or more 802.22 CPEs associated with and under control by this 802.22 BS, whose coverage area extends up to the point where the transmitted signal from the BS can be received by associated CPEs with a given minimum SNR quality.

mechanisms present at the PHY and MAC layers, which are discussed in detail in this section.

3.1 The Cognitive PHY

The current 802.22 draft standard uses OFDMA modulation for DS and US traffic. Since delay spread in the order of 25μs up to 50μs are expected, the use of a cyclic prefix of about 40μs is needed. Therefore, in order to reduce the impact of the overhead due to cyclic prefix, a 2K FFT size per TV channel has been selected as the normative mode.

The 802.22 PHY also provides high flexibility in terms of modulation and coding. The BS is capable of dynamically adjusting the bandwidth, modulation and coding on, at least, a per CPE basis. Indeed, OFDMA is a perfect fit to meet these targets as it allows efficient allocation of sub-carriers to match the requirements of the CPEs. Modulation schemes are QPSK, 16-QAM, 64QAM with convolution coding schemes of rate 1/2, 3/4, and 2/3. This results in data rates starting from a few Kbps per sub-channel up to 19 Mbps per TV channel, providing sufficient flexibility.

One of the key features supported by the PHY layer is dynamic channel bonding [9], which allows the 802.22 network to take advantage of multiple vacant TV channels based on availability. Channel bonding offers a number of advantages such as higher capacity, longer ranges, and interference resistance. As TV channels are bonded, the FFT size is increased from 2K (one channel) to 4K (bonding of two channels), and to 6K (bonding of three channels). This way, inter-carrier spacing is fixed and implementation is facilitated.

3.1.1 Spectrum Sensing

In keeping with the general rule of IEEE 802, the 802.22 draft standard cannot specify receiver algorithms. However, 802.22 is a special case in that spectrum sensing is a very important feature of the standard even though its actual implementation will be in receivers. Hence, the objective of the 802.22 group is to define requirements for sensing that have to be met by all manufacturers. This specification of sensing requirements is ongoing [10]. The principal metrics for characterizing a sensing algorithm are “Probability of Detection (PD)” and “Probability of False Alarm (PFA)”, where both these quantities are functions of the received SNR and threshold. Ideally, one would like to have PD = 1.0 and PFA = 0.0. However, in a practical situation these will be hard to achieve and it might be more reasonable to allow a relaxed PFA value of 0.01 – 0.1 and a PD of 0.9 – 0.95. From the incumbent protection point of view, a higher PFA is more tolerable than a lower PD.

There are two main approaches to spectrum sensing: energy detection and feature detection. Energy detection is used to determine presence of signal energy in the band of interest, and is followed by feature detection to determine if indeed the signal energy is due to the presence of an incumbent. Since 802.22 will be implemented in the TV bands, the digital incumbent signals could be either ATSC (North America), DVB-T (Europe), or ISDB (Japan). In this paper we consider only the ATSC.

The ATSC signal has a number of features that could be exploited for feature detection algorithms:

(a) PN 511 sequence: The ATSC signal has a 511-symbol long PN sequence that is inserted in the data stream every 24.2 ms. Since this is quite infrequent, averaging over more than one field would be necessary for detection, leading to longer detection times.

(b) Pilot: The ATSC signal uses a 8-VSB modulation with signal levels (-7,-5,-3,-1,1,3,5,7). A DC offset of 1.25 is added to this at baseband to effectively create a small pilot signal to enable carrier recovery at the receiver. A feature detector that looks for this signal could be built. However, such a detector would be quite susceptible to frequency-selective multipath.

(c) Segment-synch: the ATSC data is sent in segments of 828 symbols. At the beginning of each segment a 4-symbol sequence (5, -5, -5, 5) is sent. Detection of this sequence can be used in a feature detector.

(d) Cyclostationarity: Since the ATSC signal is a digital signal with a symbol rate of 10.76 MHz, cyclostationary detectors may be used as a feature detector.

The main problem with any feature-detection method for ATSC is the requirement of detection at a very low signal level (-116 dbm – see IDT in Table 1). Most of the synchronization schemes designed for ATSC receivers fail at these low signal levels, and the detector may require large number of samples to average over for a reliable detection. In Section 4.1.1.1 we present results of real measurements of two schemes: energy and field-sync detection.

3.2 The Cognitive MAC

The 802.22 MAC is very flexible, and can provide an adequate service to secondary users while enforcing the necessary incumbent protection mechanisms. To make an effective use of the radio spectrum, the MAC regulates DS medium access by Time Division Multiplexing, while the US is managed by using a Demand Assigned TDMA scheme.

3.2.1 Superframe and Frame Structures

The superframe structure is depicted in Figure 1. At the beginning of every superframe, the BS sends a special preamble and superframe control header (SCH) through each and every TV channel (up to 3 contiguous) that is used for communication and that is guaranteed to meet the incumbent protection requirements. The SCH contains information such as the multiple channels being used, future quite period schedules, support for adaptive antenna system, multiple bandwidth CPEs, and so on. CPEs tuned to any of these channels and who synchronize and receive the SCH, are able to obtain all the information needed to associate with the BS. During the lifetime of a superframe, multiple MAC frames are transmitted which may span multiple channels and hence can provide better system capacity, range, multipath diversity, and data rate. Note, however, that for flexibility purposes the MAC supports CPEs which are capable of operating on single or multiple channels.

The MAC frame structure is shown in Figure 2. During each MAC frame the BS has the responsibility to manage the US and DS directions, which may include ordinary data communication, measurement activities, coexistence procedures, and so on. A MAC frame is comprised of two parts: a DS subframe and an US subframe. The boundary between these two segments is adaptive, and so the control of the DS and US capacity can be easily done. The DS subframe consists of only one DS PHY PDU. An US subframe consists of contention intervals scheduled for initialization (e.g., initial ranging), bandwidth request, UCS (Urgent Coexistence Situation) notification, and coexistence purposes (see next subsection), and one or multiple US PHY PDUs, each transmitted from different CPEs.

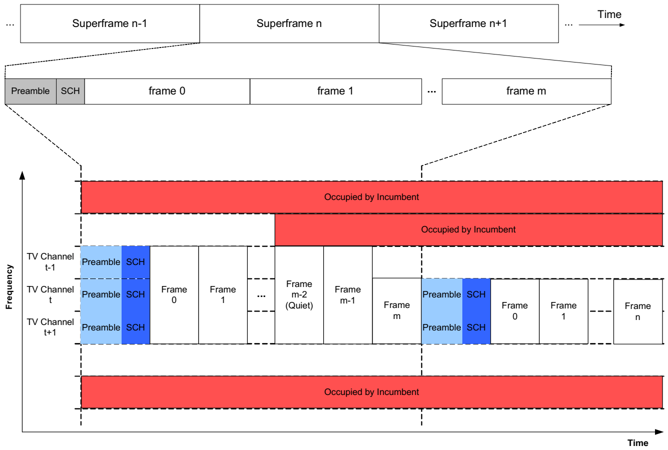

Figure 1 – General superframe structure

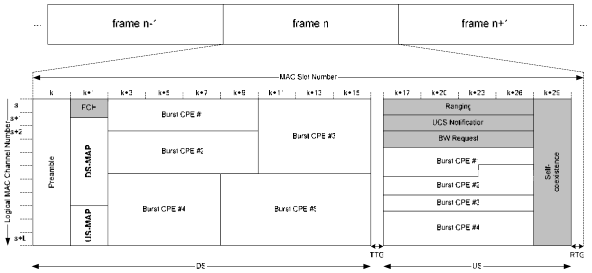

Figure 2 – The MAC frame structure with key zones

3.2.2 Coexistence

Effective coexistence is one of the key responsibilities of a CR. Within the context of 802.22, coexistence has two facets: i) coexistence with incumbents; and ii) self-coexistence. As the name suggests, coexistence with incumbents deals with DSA mechanisms for a reliable, efficient, and timely detection of primary services (alternatively, detection of white spaces), followed by a network recovery procedure once these incumbents are detected. In contrast, self-coexistence addresses DSS amongst collocated 802.22 cells. Self-coexistence in 802.22 is a critical issue given its unlicensed operation and its very large coverage range.

3.2.2.1 Measurement and Spectrum Management

Regardless of which coexistence method is in use, a solid and flexible measurement and spectrum management component is of paramount importance. This involves mechanisms by which nodes cooperate in performing channel measurements, measurement reports are generated and communicated (e.g., to the BS in case of 802.22), decisions are made as to which channels to use, when, and for how long (hereby referred to as spectrum management).

The 802.22 draft standard includes a comprehensive measurement and spectrum management ingredient that provides the necessary flexibility and efficiency. Here, the BS instructs associated CPEs to perform periodic measurement activities, which may be either in-band or out-of-band. In-band measurement relates to the channel(s) used by the BS to communicate with the CPEs, while out-of-band correspond to all other channels.

For in-band measurements the BS quiets the channel so that incumbent sensing can be carried out, which is not the case for out-of-band measurements. Therefore, in-band sensing requires tight control at the MAC (see Section 3.2.2.2), while out-of-band sensing is less critical. In order to ascertain the presence of incumbents, 802.22 devices need to detect signals at very low SNR levels (see Section 3.1.1) and with certain accuracy, which is dynamically controlled by the BS.

Depending on the incumbent detection algorithms available at the various CPEs, measurements can take different amount of time. The BS can also indicate which CPEs must measure which channels, for how long, and with what probability of detection and false alarm. In addition, for best operation the BS does not need to require every CPE to conduct the same measurement activities. Rather, clustering techniques are incorporated which can distribute the measurement load across CPEs, and the measurement outcome is used to obtain a spectrum occupancy map for the entire cell. Once measurement reports are returned to the BS, the BS analyzes them and takes actions, if appropriate.

The current draft standard also incorporates a vast set of functions allowing efficient spectrum management. Operations such as switch/add/remove channels and suspend/resume channel operation, are among the many actions the MAC may undertake in order to guarantee incumbent protection and effective coexistence.

3.2.2.2 Coexistence with Incumbents

Coexistence with incumbents is a multi-stage process and involves detection, notification and recovery. Detection is bounded by CDT, while notification and recovery are limited by CCTT and CMT.

3.2.2.2.1 Incumbent Detection

For in-band channels, the current 802.22 draft MAC employs the two-stage sensing (TSS) mechanism as shown in Figure 3. This mechanism works hand in hand with the spectrum sensing algorithms described in Section 3.1.1. As the name suggests, it is comprised of two stages which have different time scales and goals: fast sensing and fine sensing.

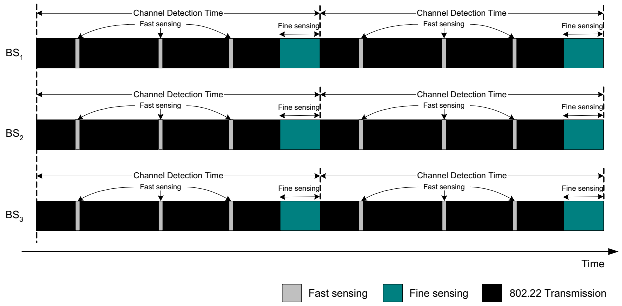

Figure 3 – TSS mechanism

Fast Sensing: The fast sensing stage is comprised of one or more fast sensing periods per CDT, as depicted in Figure 3. During this stage, a fast sensing algorithm is employed (e.g., simple energy detection – see Section 3.1.1). Typically, this is done very fast (under 1ms/channel) and so can be made to be highly efficient. The outcome of the measurements done by all CPEs and the BS during this stage are consolidated in the BS, which then decides on the need for the following fine sensing stage. For example, if during the fast sensing stage it is concluded that energy in the affected channel is always below IDT, the BS may decide to cancel the next scheduled fine sensing period.

Fine Sensing: The existence of this stage is dynamically determined by the BS periodically at each CDT, and is based on the outcome of the previous fast sensing stage. During this stage, more detailed sensing (e.g., feature detection – see Section 3.1.1) is performed on the target channels in order to decrease the false alarm rate. Typically, algorithms executed during this stage can take in the order of milliseconds (e.g., 24.2ms in the case of field-sync detection for ATSC) for each frequency channel, since they look for particular signatures of the primary user transmitted signal.

One of the major benefits to the TSS mechanism is allowing the CR network to meet the stringent QoS requirements of real time applications such as voice over IP. Considering the fact that incumbents in TV bands do not come on the air frequently, only the fast sensing stage will be used most of the times, and so QoS is not compromised. The fine sensing stage steps in only when required.

Obviously, there is a possibility for having multiple overlapping 802.22 BSs in operation in the same geographical region, and if that would be the case it could undermine the TSS approach (i.e., fine sensing could always be needed). To overcome this problem, the 802.22 draft standard incorporates a very efficient algorithm that is able to dynamically synchronize multiple overlapping cells (see Section 3.2.2.4). Based on this, quiet periods of overlapping BSs are also synchronized resulting in the arrangement depicted in Figure 3. So, sensing can be made with high reliability.

3.2.2.2.2 Incumbent Notification

Once an incumbent is detected, this event must be notified in a timely fashion to the BS. A number of mechanisms are described in the 802.22 draft standard to deal with these situations. For example, a CPE may notify the BS by using the UCS slots available within the MAC frame (see Figure 2). Since the allocation of the UCS window is known to all CPEs, it can be used even when CPEs are under interference. As far as access goes, both contention-based and CDMA can be used. Alternatively, the BS can use polling of CPEs as a way to obtain feedback. In this case, two situations are possible. The CPE can send a notification back to the BS provided it was able to receive the poll, or else if no response is received from CPEs, the BS can take further actions to assess the situation.

3.2.2.2.3 Incumbent Detection Recovery

Once the BS determines that an incumbent has appeared on an in-band channel, it enters the recovery mode of operation. During this mode, the BS executes the Incumbent Detection Recovery Protocol (IDRP) which allows the network to restore its normal operation in a timely fashion with minimal performance degradation. IDRP offers the system a way to maintain the QoS at an acceptable level while protecting incumbent services.

One of the key concepts in IDRP is the use of backup channels, which allow the MAC to quickly re-establish communication in the event of an incumbent appearance. Backup channels are kept in a priority list and are used by a CPE whenever looking for the BS, and in particular during the recovery procedure. This way, the recovery procedure can be made very efficient, as both the BS and CPE would know in advance in which channel to restore the service should an incumbent appear in their channel of operation. Finally, to make the process of recovery smooth, this can be scheduled by the BS within the bounds of CMT or CCTT. Thus, service does not have to be abruptly discontinued.

3.2.2.3 Self-Coexistence

The current 802.22 draft standard addresses self-coexistence in two ways: through the Coexistence Beacon Protocol (CBP) and through inter-BS communication. Inter-BS communication is a passive method in the sense that it cannot be deliberately initiated, but depends on the periodic SCH packets transmitted by the BSs in the beginning of each superframe. CBP, however, behaves in both receive and transmit modes (discussed next).

3.2.2.3.1 The CBP Protocol

The CBP protocol allows CPEs and BSs to transmit coexistence beacons which carry enough information to achieve adequate coexistence and DSS amongst overlapping 802.22 cells6. CBP beacons are intended for inter-cell communication and carry specific information about the cell as well as the sender's DS/US bandwidth allocations. Stations receiving CBP beacons can use this information and schedule their own transmissions during periods of time that do not intersect with their neighbors' allocations. Therefore, DSS can be done not only in frequency but also in time domain.

CBP beacons are scheduled by the BS through the Self-Coexistence windows shown in Figure 2 (which can be in either transmit or receive mode). The Self-Coexistence window defines a period of time where channel access is contention based, as to maximize spectrum usage. In other words, during this time CPEs shall use the contention access mechanism to gain access to the medium and transmit the CBP packet.

In order to maximize the probability that coexistence beacons are received from other collocated 802.22 cells, a CPE is not locked to its BS at all times during a frame. A CPE is only locked to the BS whenever it is scheduled to receive/send data from/to the BS. At all other times during the frame, the CPE is listening to the medium and searching for a CBP beacon through preamble correlation.

A mechanism that can be used by the BS to look out for CBP beacons from other overlapping cells is to either use short quite periods or schedule the Self-Coexistence windows in receive mode. In the latter case, CPEs do not perform any transmission for the duration of the window but simply listen to the medium on the look out for CBP packets and, possibly, BS SCH beacons.

CBP beacons carry important and varied information that is used in many ways. For example, once a CPE receives a CBP beacon from another collocated CPE belonging to a different cell, the first thing this CPE can do is to convey the received information to its BS. The BS, in turn, can implement an interference-free scheduling algorithm, which schedules the various US/DS traffic from/to CPEs in such a way that these allocations do not intersect with the allocations of interfering CPEs. Another use of this information is for bandwidth request purposes. In this case, the CPE may include bandwidth allocation constraint elements when requesting US bandwidth allocation to the BS, thus providing the information the BS would need as to avoid allocating time for this CPE which interferes with other collocated CPEs. Yet another alternative is for the CPE not to send anything to the BS. Here, the BS would have to specifically send a request message to the CPE soliciting any constraints it might have regarding bandwidth allocation. Other uses are also possible.

3.2.2.3.2 Inter-BS Communication

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[6] CBP can operate either through a backbone or over-the-air, but here we focus on the over-the-air implementation.

Inter-BS communication is enabled by allowing the BSs and CPEs to detect and receive both SCH and CBP packets from neighboring cells. Similar to the CBP protocol described earlier, the BSs can allocate Self-Coexistence windows for the purpose of inter-BS communication. During these windows, the BSs can have a higher priority than CPEs to channel access, hence allowing them to exchange information.

3.2.2.4 Synchronization of Overlapping Cells

A key ingredient to coexistence in 802.22 is a method for the synchronization of the superframes of overlapping cells in a totally distributed fashion. By aligning superframes, overlapping cells can establish a logical channel for communication amongst them through the Self-Coexistence windows (see Figure 4). Through this logical channel, overlapping cells can exchange CBP packets as well as synchronize their quiet periods for effective DSS. Hence, both coexistence with incumbents and self-coexistence mechanisms can benefit from the synchronization mechanism.

Synchronization is done by BSs and/or CPEs through the CBP protocol. Among others, CBP packets carry time stamp information. CPEs and the BS within a network, when not communicating, look for coexistence beacons from a neighboring network. Mathematically speaking, when BSi, responsible for cell i, receives a coexistence beacon (either directly or from one of its CPEs) from cell j, controlled by BSj, it shall only adjust the start time of its superframe if, and only if, the following convergence rule [7] is satisfied:

$$\left| \begin{array}{l} (Frame\_Number_j - Frame\_Number_i) \times FDC + \\ Transmission\_Offset - \mathrm{Re}ception\_Offset \end{array} \right| \le \frac{FS \times FDC + GuardBand \times SymbolSize}{2}$$

Where Frame_Number is the frame number within the superframe, FDC is the frame duration code (currently, 10ms), FS is the number of frames per superframe (currently, 16), GuardBand is a few OFDM symbols long, SymbolSize is the size of an OFDM symbol, and Reception_Offset and Transmission_Offset are the index of the symbol number within the frame where the beacon was received/transmitted, respectively. This simple convergence rule has been proved [11] to guarantee real-time, fully distributed, and quick synchronization of overlapping networks.

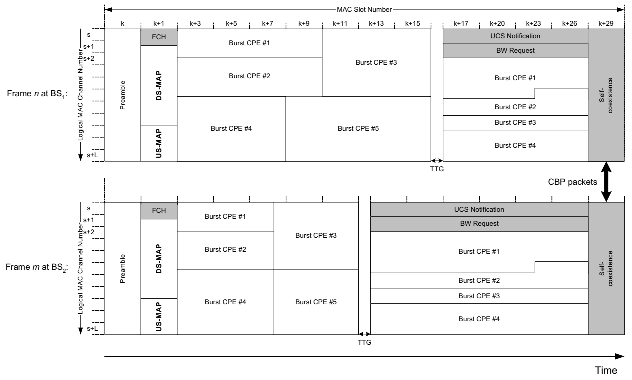


Figure 4 – Communication between two synchronized overlapping cells

4. PERFORMANCE EVALUATION

Except for the spectrum sensing algorithms, we have implemented all of the 802.22 draft standard features described above in the OPNET network simulator. For sensing, we have a simulation platform as well as have built a real-time prototypical sensor that can detect digital TV signals at a low signal level of –116dBm, as per required (see Table 1). For the MAC simulations, all the key functionalities have been implemented and the results shown take their joint behavior and interplay into consideration. For all the MAC simulations, the OFDM symbol size is fixed at 310µsec, each symbol has 1536 data carriers, and the modulation/coding used is 64-QAM rate 2/3, providing a capacity of about 19.8Mbps per 6MHz TV channel. The MAC frame size is 10ms, the superframe contains 16 MAC frames, and the packet size is 1Kbyte.

4.1 Coexistence

4.1.1 Coexistence with Incumbents

The spectrum sensing algorithms work hand-in-hand with the TSS mechanism. In this section we analyze their individual as well as joint performance.

4.1.1.1 Spectrum Sensing

In this section we present some measurement results for DTV sensing. These measurements have been made with a prototype that consists of a commercial grade DTV tuner and RF-front end followed by an A/D converter. The signal is digitized at low-IF and then processed by MATLAB. Figure 5 shows the receiver-operating-characteristic (ROC) of two algorithms: energy detection and PN511 detection. The input signal level was set at -116dbm as required by 802.22 (see Table 1). The energy detector looked at 10-segments of data which is about 770µs whereas the PN511 detector operated either over 1 or 5 fields, which is 24ms or 120ms respectively. The ROC was obtained by varying the threshold for each of these detectors. The noise-only performance of the sensor is first calibrated by disconnecting the signal from the input and measuring the energy and PN511 correlation values. These are then used to set the thresholds. The energy detector threshold varied from 0.34 (Pd = 1, PFA = .3215) to 0.37 (Pd = 0; PFA = 0). The PN511 detector threshold varied from 600 (Pd = .9783, PFA = .3247) to 900 (Pd = .7130; PFA =0) when the number of fields was 5, and from 1600 (Pd = 1, PFA = 0.98) to 2300 (Pd = 0.2771, PFA = 0.06) when 1 field was used for sensing. It is clear that the PN511 detector needs a much longer sensing time than the energy detector due to the infrequent occurrence of the PN511 sequence in the signal. Note that these sensors did not attempt to recover fine carrier or timing lock prior to sensing. It may be possible to improve the detector performance if front-end synchronization is performed prior to correlation with the known PN511 sequence.

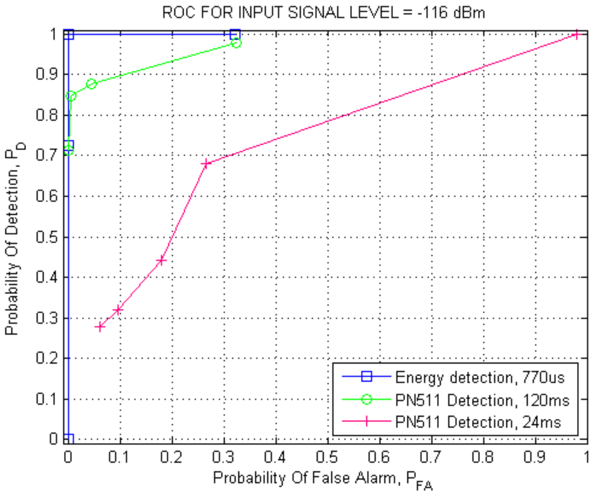


Figure 5 – ROC for energy and PN511 detection

4.1.1.2 TSS Mechanism

To evaluate the TSS scheme, we consider 1 BS and a total of 127 CPEs. We fix the duration of each fast sensing to 1ms, and program the BS to allocate a fast sensing window every 4 MAC frames. Considering that CDT is 2sec and the MAC frame size is 10ms, this would result in approximately 200 frames per CDT. In turn, this results in about 50 MAC frames carrying a fast sensing window per CDT, or around 50ms of fast sensing per CDT.

4.1.1.2.1 Throughput Performance

Figure 6 show the impact of the TSS scheme on the MAC layer throughput. For these simulations we have considered a constant bit rate traffic source, and fixed the US aggregate traffic to 3Mbps while the DS traffic is varied from 2Mbps to 22Mbps. As we can see, for low to medium loads the TSS has nearly no impact on performance. As expected, only at high loads will the quiet periods used by TSS impact performance. Even so, the overall impact on throughput is minimal.

4.1.1.2.2 Delay Performance

The delay performance is as important as the throughput performance, since it has a direct impact on the support of real-time applications such as VoIP. For these simulations we have considered a fixed US aggregate traffic of 3Mbps, while the DS traffic is increased from 3Mbps to 15Mbps. Out of the 127 CPEs in the network, 4 generate real-time traffic (referred to here simply as QoS Traffic) at a constant rate of 32Kbps.

In Figure 7 and Figure 8 we compare, respectively, the DS and US delay performance for both the overall (all traffic types) and QoS traffic, with and without TSS. As we can see, the impact of the inclusion of the TSS scheme is negligible in both the DS and US directions as the BS scheduler can better manage the allocation. The US direction delay is slightly more impacted than the DS due to the very simple scheduling algorithm implemented. We have observed that if more elaborate scheduling techniques are incorporated, the impact of the TSS can be fully absorbed and the US/DS delay remain unaffected. Overall, what is important to note is that even delay requirements as low as 20ms (e.g., full quality telephony) can be met when TSS is employed. Therefore, even with the additional requirement of incumbent protection under stringent DFS parameters (see Table 1), a CR employing the TSS scheme can fully support the most demanding QoS applications.

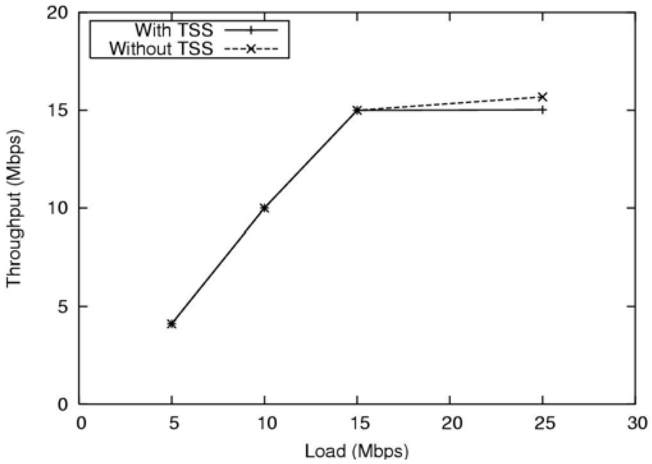


Figure 6 – Throughput performance with TSS

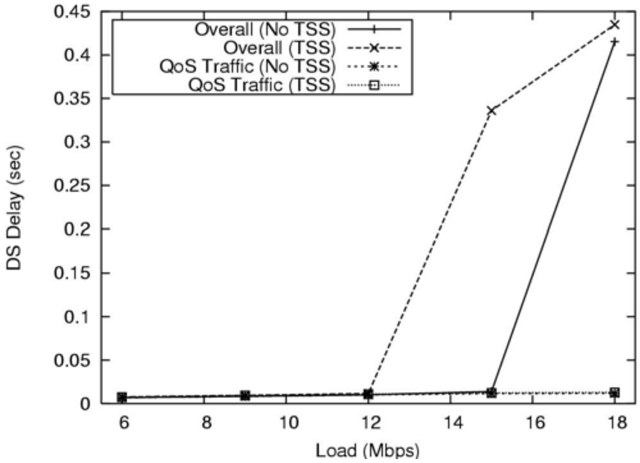


Figure 7 – DS delay with TSS

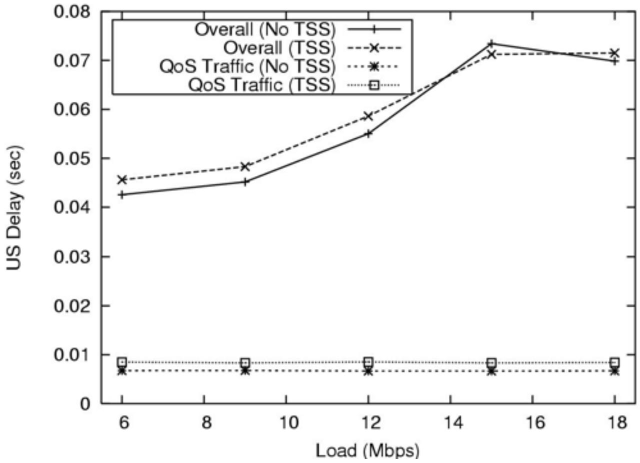


Figure 8 – US delay with TSS

4.1.2 Self-Coexistence

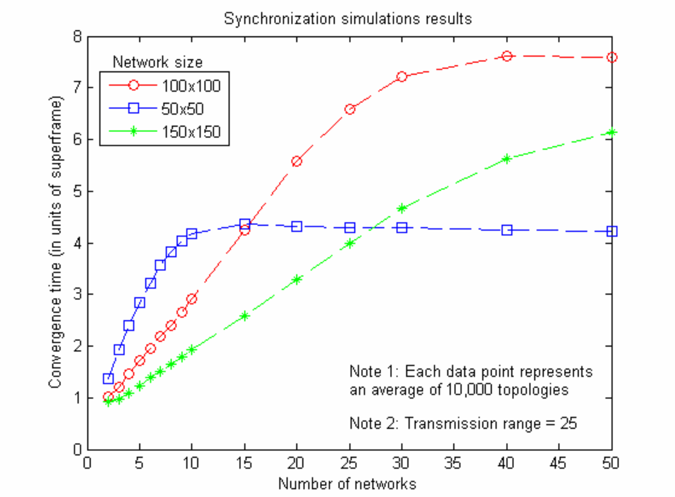
The performance of the two key self-coexistence schemes, namely, the CBP protocol and synchronization, are studied in this section.

4.1.2.1 Synchronization of Overlapping Cells

We have conducted extensive simulations to study how quickly and reliably overlapping networks converge to the same superframe start time, and results are shown in Figure 9. The simulation consists of a number of networks (x-axis), placed randomly in square area (50x50, 100x100, and 150x150 km), with random start times and fixed range of 25 km. Each network periodically issues CBP packets as described in section 3.2.2.4, and synchronizes according to the convergence rule. On the y-axis is the convergence time in units of superframe. As can be seen, even with a large number of networks the convergence is very quick, even though the synchronization operation is completely distributed in nature.

4.1.2.2 The CBP Protocol

Figure 10 depicts the aggregate throughput performance offered by CBP for a scenario with multiple collocated networks. For this simulation, a self-coexistence window of 3 OFDM symbols is reserved at the end of each MAC frame, and all collocated networks are fully loaded with traffic (saturated scenario). As we can see, CBP is able to significantly improve the performance as it takes the CPEs' schedules into account when making bandwidth reservations. The synchronization mechanism further strengthens CBP by establishing a logical channel amongst cells, which allows for a quick and efficient self-coexistence mechanism.



Note 1: Each data point represents an average of 10,000 topologies

Note 2: Transmission range = 25

Figure 9 – Convergence times in the synchronization of 802.22 networks within radio range of each other

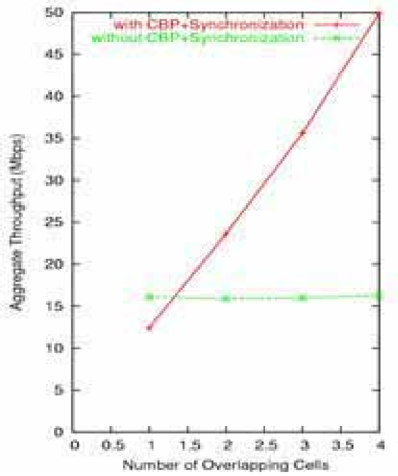


Figure 10 – Aggregate throughput with CBP protocol

4.2 Network Reliability

In this section we study the reliability of the cognitive radio MAC, which includes the joint application of the detection, notification and recovery (IDRP) mechanisms.

For this analysis, we consider the scenario depicted in Figure 11 consisting of 1 BS and a total of 9 CPEs. For this simulation, we impose that both stages of the TSS scheme are always executed. At a random point in time during the simulation run, a TV station begins operating co-channel with the 802.22 network as it is shown in Figure 11. Once in operation, the power level from the TV station signal generates enough interference so that nodes 1, 2, 6 and 9 (see Figure 11) can no longer hear from the BS. Through the TSS (indicated in Figure 12) and polling mechanisms, the BS realizes (within CDT) that the appearance of a TV station is the reason why these nodes are not communicating, and then initiates the recovery procedure by transmitting a channel switch command to all nodes within the network to go from channel A to channel B. In particular, Figure 12 shows the instantaneous throughput curves for nodes (CPEs) 5 and 6. As we can see from the highlighted portion of this figure, which indicates the appearance and detection of the of the TV signal, node 5's throughput is unaffected since it is able to correctly receive the channel switch command from the BS. Node 6, however, does not receive the command from the BS, but is nevertheless able to restore normal communication through the IDRP protocol, as it knows the backup channel (in this case, channel B) used by the BS. The entire notification and recovery procedure for the whole network takes at most two MAC frames, which is much less than required by CMT and CCTT.

As we can see, the reliability of the CR network is indeed affected by the incumbent, but properly design schemes can drastically minimize disruptions to the service offered by the secondary network and provide continued operation.

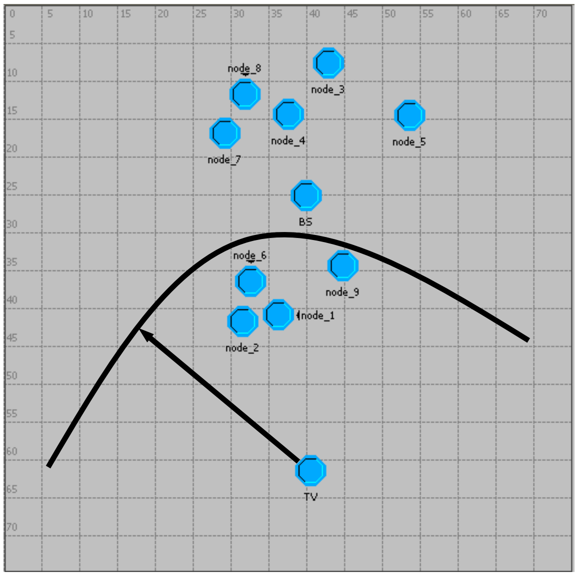


Figure 11 – Simulation scenario

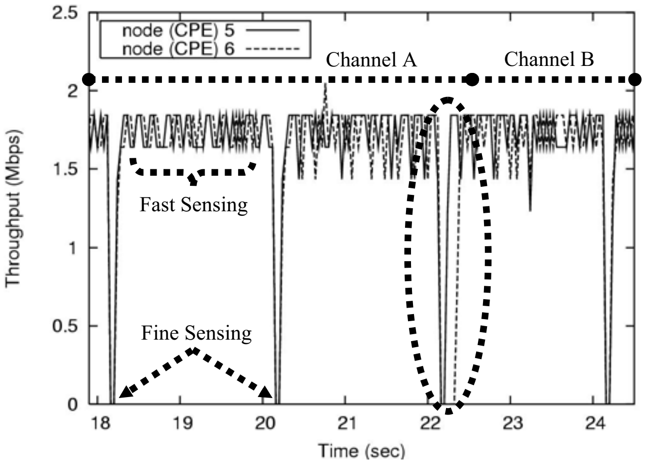


Figure 12 – Performance of the network reliability mechanisms

5. RELATED WORK

In terms of spectrum sensing algorithms for detection of incumbent signals, significant progress has been made at the IEEE 802.22 working group level [6]. A number of techniques such as energy detection (full bandwidth and pilot), ATSC field sync detection, cyclostationary detection, spectral correlation, multi-resolution spectrum sensing and analog auto correlation have been proposed and evaluated. In this paper, we have evaluated some of these techniques. Additional results can be found in [11][12].

Within the PHY layer, the notion of dynamic channel bonding has not been investigated so far. While the current IEEE 802.11n draft standard [13] allows for an optional 40 MHz (hence, bonding of two 20 MHz channels) mode, this choice is static and predefined beforehand. Since in the case of DSA channel availability changes over time, channel bonding also needs to be dynamic.

As far as the MAC layer for CRs goes, research is still in its infancy. In [14] a very high level overview of a DSA system is presented, with little or no details given as to the algorithms and protocols used. The Dynamic Open Spectrum Sharing (DOSS) MAC protocol is introduced in [15], and is a multi-channel MAC that incorporates the busy-tone concept to overcome the hidden and exposed node problem in wireless networks. While DOSS allows nodes to dynamically negotiate the channel to be used for data communication based on spectrum availability, it does not address all the critical aspects related to CR operation, such as sensing algorithms, dynamic device discovery without a fixed control channel, network recovery, and so on. DOSS also requires multiple radio transceivers. In [16] it is provided a theoretical formulation of a decentralized MAC, with no insights into protocol design, implementation and performance.

Although not designed for DSA networks, there have been a number of recent proposals addressing the problem of coordinated use of multiple channels at the MAC layer (i.e., multi-channel MAC). All these protocols, however, have similar limitations and do not deal with the new challenges posed by DSA operation. Nevertheless, for completeness purposes it is important to provide a description of their operation. These multi-channel MAC protocols can be classified based on how many radio transceivers they require for operation, namely, *single transceiver protocols* or *multiple transceiver protocols*.

5.1 Single Transceiver Protocols

This category of MAC protocols assume that every node is equipped with one half-duplex transceiver capable of switching channels dynamically, and it can only transmit or receive on exactly one channel at any given time. Protocols in this category often aim at incurring a complexity comparable to existing solutions (e.g., IEEE 802.11), while achieving better throughput and delay performance. Some protocol design challenges are how to overcome the hidden and exposed terminal problem with low control overhead, minimize channel switching, load balancing, achieve network connectivity comparable to single channel MAC protocols (e.g., IEEE 802.11), and so on.

The Hop Reservation Multiple Access (HRMA) protocol [17] is a multi-channel MAC scheme for slow FHSS wireless ad hoc networks where all nodes hop according to a pre-defined hopping pattern. Whenever a node has a data packet to send, it exchanges RTS/CTS packets with the intended receiver and both remain in the same hop for the entire data transmission. Other nodes not involved in communication do not stop and proceed by following the hopping sequence. Since different pairs of nodes can communicate simultaneously while in different hops, HRMA is considered as a multi-channel MAC. While in HRMA it is the sender node who initiates communication, in Receiver Initiated Channel-Hopping with Dual Polling (RICHDP) protocol [18] this responsibility is transferred to the receiver. Other than this, HRMA and RICHDP behave similarly. Since these protocols have been designed for FHHS, they cannot be applied to the popular DSSS systems.

In [19] it is considered that the number of nodes equals the number of available channels. Out of the total N channels, one is reserved as a default control channel while the others are employed for data transmissions. Before any data communication, the sender node has to negotiate with the receiver a data channel through a RTS/CTS handshake transmitted in the control channel.

In [20], every node is associated with a single channel which is derived on the basis of a node's MAC address. This particular channel is referred to as home channel and is used by the node to wait for incoming packets. A node S wishing to communicate to a node D would have to switch to node D's home channel before transmission, and return to its home channel after completion.

The Channel Hopping Multiple Access (CHMA) [29] and the Slotted Seeded Channel Hopping (SSCH) algorithm [30] use a similar channel hopping approach (with some variation on the hopping pattern generation). If a node wants to communicate with another node, it follows the other node's schedule. If two nodes are able to successfully exchange control information, they stay on that channel to complete the data transfer.

Switching amongst channels may take considerable time and hence may increase delay and degrade throughput. With this in mind, the On-Demand Channel switching (ODC) [21] mechanism aims at minimizing such negative impact by having nodes stay in its channel as long as traffic conditions on this channel are acceptable. Nodes continuously measure channel conditions and use this measurements for switching decision. As all channels are equal in ODC, finding intended receivers is more difficult. In addition, ODC performance is not uniform and is dependent on the traffic pattern.

The Multi-channel MAC (MMAC) [22] protocol has the primary goal of overcoming the multi-channel hidden terminal problem present in many multi-channel MAC protocols based on a single transceiver. It reuses the Power Saving Mode (PSM) concept of IEEE 802.11 and its corresponding Ad-Hoc Traffic Indication Messages (ATIM) control messages. On the basis of this, it defines a default control channel where all nodes must periodically switch to and synchronize for a pre-determined window of time. This is called the ATIM window and where nodes with packets to send employ a three-way handshake (ATIM/ATIM-ACK/ATIM-RES) as to negotiate a data channel. Communicating nodes may then switch to the selected channel and contend for medium access by using traditional RTS/CTS/Data/ACK mechanism.

The Multi-channel Access Protocol (MAP) [28] is based on a similar concept as MMAC, and divides the time into control periods, when nodes tune to the control channel for control message exchanging, and data periods, when data transfer takes place.

5.2 Multiple Transceiver Protocols

When multiple transceivers are in place, the task of designing a multi-channel MAC protocols is significantly simplified. Issues such as hidden and exposed terminal problems, connectivity, and channel switching can be overcome almost completely. Here, it is assumed that nodes have multiple half-duplex transceivers capable of tuning to and accessing different channels simultaneously, which is the key to overcoming the aforementioned challenges. Research here has mostly focused on channel selection strategies.

In [23] it is introduced the Dynamic Private Channel (DPC) protocol where nodes are assumed to be equipped with as many transceivers as the number of channels. Similar to other protocols, one particular channel is reserved as the default control channel for negotiation purposes. Given that a transceiver is always associated with the control channel, the multi-channel hidden terminal problem is eliminated. Special RTS and reply-to-RTS packets are employed in this control channel in order to select another traffic channel for data communication. Once the traffic channel is negotiated, nodes exchange CTS/Data/ACK packets through the transceiver associated with the selected channel.

The multi-channel MAC protocol proposed in [27] also assumes that each node has as many transceivers as there are channels, but here nodes are capable of listening to all these channels simultaneously. Whenever a node has a packet to send, it selects an idle for transmission. In case of multiple idle channels, the one employed in the last successful data transmission is preferred. This technique is referred to as “soft channel reservation”. An enhanced channel selection strategy for this protocol has been presented in [24] and consists in selecting the best channel based on the power level sensed at the transmitter. On the other hand, the Receiver-Based Channel Selection (RBCS) mechanism in [25] chooses the best channel on the basis of the SINR at the receiver. To this end, RTS/CTS packets are employed in a default control channel as to select the data channel with highest SINR.

The Dynamic Channel Assignment (DCA) protocol [26] operates similar to RBCS. It employs a default control channel while other channels may be used for data transmission. RTS/CTS packets are exchanged in the control channel and serve to negotiate a data channel for Data/ACK transmission. A distinctive feature of DCA is that is requires exactly two transceivers, one of which is permanently tune to the default control channel and the other which is free to tune to any of the data channels. As noted in [22], a drawback in DCA is that it dedicates one channel for exchanging control information only. When the number of channels is small (e.g., only 3 channels in IEEE 802.11b), this constitutes a considerable wastage of resources.

Finally, the Common Spectrum Coordination Channel (CSCC) protocol [31] is an extension of the DCA protocol that allows different types of wireless devices to share the radio spectrum. This is done via negotiation through the CSCC.

6. CONCLUSIONS

Efficient mechanisms for DSA and DSS are key to the success of cognitive radios. In spite of that, little has be done so far on designing such schemes, understanding their interplay, and how they impact the performance and service provided by a CR network. In this paper we have addressed these issues within the context of the IEEE 802.22 working group, which is in the process of defining the first worldwide air interface standard based on CR for reuse of vacant TV channels. Considering the DSA and DSS mechanisms available in the 802.22 draft standard, we have demonstrated that despite the additional responsibilities of a CR network operating in the TV bands, network performance is not substantially sacrificed, QoS can still be met if proper schemes are in place, and incumbent protection can be guaranteed as per required. Finally, we believe that the work being done within 802.22 is pioneering in many respects, and its outcome will serve as the basis for new and innovative research in this promising area.

7. REFERENCES

[1] J. Mitola et al., “Cognitive Radios: Making Software Radios more Personal,” *IEEE Pers. Comm.*, vol. 6, no. 4, Aug. 1999.

[2] J. Mitola, “Cognitive radio: An integrated agent architecture for software defined radio,” *PhD Dissertation*, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000.

[3] S. Haykin, “Cognitive Radio: Brain-Empowered Wireless Communications,” in *IEEE JSAC*, vol. 23, no. 2, Feb. 2005.

[4] C. Cordeiro and D. Agrawal, *Ad Hoc and Sensor Networks: Theory and Applications*, World Scientific Publishing, ISBN 981-256-681-3, 650 pp., March 2006.

[5] C. Cordeiro, K. Challapali, D. Birru, and S. Shankar, “IEEE 802.22: The First Worldwide Wireless Standard based on Cognitive Radios,” in *IEEE DySPAN*, Nov. 2005.

[6] IEEE 802.22 Working Group on Wireless Regional Area Networks, http://www.ieee802.org/22/.

[7] IEEE 802.22 draft standard, “IEEE P802.22$^{\text{TM}}$/D0.1 Draft Standard for Wireless Regional Area Networks,” IEEE 802.22 doc. no. 22-06-0068-00-0000, May 2006.

[8] Federal Communications Commission (FCC), “Revision of Parts 2 and 15 of the Commissions Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5GHz Band,” *ET Docket no. 03-122*, Nov. 18, 2003.

[9] K. Challapali, C. Cordeiro, and D. Birru, “Evolution of Spectrum-Agile Cognitive Radios: First Wireless Internet Standard and Beyond,” in *WICON*, Aug. 2006.

[10] G. Chouinard, D. Cabric and M. Ghosh, “Sensing Thresholds,” IEEE 802.22, doc. no. 22-06-0051-04-0000, May 2006.

[11] C. Cordeiro et al., “A PHY/MAC Proposal for IEEE 802.22 WRAN Systems,” IEEE 802.22 doc. no. 22-06-0005-05-0000, March 2006.

[12] S.-Y. Chang et al., “IEEE 802.22 WRAN Merger Framework,” IEEE 802.22, doc. no. 22-06-0030-03-0000, March 2006.

[13] IEEE 802.11n draft standard, “Standard for Enhancements for Higher Throughput,” http://grouper.ieee.org/groups/802/11/, May 2006.

[14] S. Seidel and R. Breinig, “Autonomous Dynamic Spectrum Access System Behavior and Performance,” in *IEEE DySPAN*, Nov. 2005.

[15] L. Ma, X. Han, and C.-C. Shen, “Dynamic Open Spectrum Sharing for Wireless Ad Hoc Networks,” in *IEEE DySPAN*, Nov. 2005.

[16] Q. Zhao, L. Tong, and A. Swami, “Decentralized Cognitive MAC for Dynamic Spectrum Access,” in *IEEE DySPAN*, Nov. 2005.

[17] Z. Tang and J. J. Garcia-Luna-Aceves, “Hop-Reservation Multiple Access (HRMA) for Ad Hoc Networks,” in *IEEE Infocom*, 1999.

[18] A. Tzamaloukas and J. J. Garcia-Luna-Aceves, “A Receiver-Initiated Collision-Avoidance Protocol for Multi-Channel Networks,” in *IEEE Infocom*, 2001.

[19] J. Li, Z. Haas, M. Sheng, and Y. Chen, “Performance Evaluation of Modified IEEE 802.11 MAC for Multi-Channel Multi-Hop Ad Hoc Network,” Int. Conf. on Advanced Information Net. and Applications (AINA), March 2003.

[20] S. Chaudhuri, R. Kumar, and A. Saha, “A MAC Protocol for Multi Frequency Physical Layer,” *Tech. Rep.*, Rice Univ., Texas, Jan. 2003.

[21] P. Porwal and M. Papadopouli, “On-Demand Channel Switching for Multi-Channel Wireless MAC Protocols,” *Tech. Rep. TR04-024*, Univ. of North Carolina at Chapel Hill, 2004.

[22] J. So and N. Vaidya, “Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using a Single Transceiver,” in *ACM Mobihoc*, May 2004.

[23] W.-C. Hung, K. Law, A. Leon-Garcia, “A Dynamic Multi-Channel MAC for Ad-Hoc LAN,” in *21st Biennial Symposium on Communications*, April 2002.

[24] A. Nasipuri and S. Das, “Multichannel CSMA with Signal Power-based Channel Selection for Multihop Wireless Networks,” in *IEEE VTC*, Sept. 2000.

[25] N. Jain and S. Das, “A Multichannel CSMA MAC Protocol with Receiver-based Channel Selection for Multihop Wireless Networks,” in *IEEE ICCCN*, Oct. 2001.

[26] S.-L. Wu et al., “A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks,” in *I-SPAN*, 2000.

[27] A. Nasipuri et al., “A Multichannel CSMA MAC Protocol for Multihop Wireless Networks,” in *IEEE WCNC*, 1999.

[28] J. Chen et al., “A new multichannel access protocol for ieee 802.11 ad hoc wireless lans,” in *IEEE PIMRC*, 2003.

[29] A. Tzamaloukas and J. Garcia-Luna-Aceves, “Channel-hopping multiple access,” in *IEEE ICC*, June 2000.

[30] P. Bahl, R. Chandra, and J. Dunagan, “SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks,” in *ACM MobiCom*, Sept. 2004.

[31] D. Raychaudhuri and X. Jing, “A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands,” in *IEEE PIMRC*, Sept. 2003.