IEEE 802.22: An Introduction to the First Wireless Standard based on Cognitive Radios

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***Abstract* – In November/2004, we witnessed the formation of the first worldwide effort to define a novel wireless air interface (i.e., MAC and PHY) standard based on Cognitive Radios (CRs): the IEEE 802.22 Working Group (WG). The IEEE 802.22 WG is chartered with the development of a CR-based Wireless Regional Area Network (WRAN) Physical (PHY) and Medium Access Control (MAC) layers for use by license-exempt devices in the spectrum that is currently allocated to the Television (TV) service. Since 802.22 is required to reuse the fallow TV spectrum without causing any harmful interference to incumbents (i.e., the TV receivers), cognitive radio techniques are of primary importance in order to sense and measure the spectrum and detect the presence/absence of incumbent signals. On top of that, other advanced techniques that facilitate coexistence such as dynamic spectrum management and radio environment characterization could be designed. In this paper, we provide a detailed overview of the 802.22 draft specification, its architecture, requirements, applications, and coexistence considerations. These not only form the basis for the definition of this groundbreaking wireless air interface standard, but will also serve as foundation for future research in the promising area of CRs.**

***Index Terms* – Cognitive radio, incumbent, sensing, spectrum agility, IEEE 802.22, coexistence.**

I. INTRODUCTION

The proliferation of wireless services and devices for uses such as mobile communications, public safety, Wi-Fi, and TV broadcast serve as the most indisputable example of how much the modern society has become dependent on radio spectrum[1]. Notably, the unlicensed bands (e.g., ISM and UNII) play a key role in this wireless ecosystem since the deployment of applications in these bands is unencumbered by regulatory delay sand which resulted in a plethora of new applications including last-mile broadband wireless access, health care, wireless PANs/LANs/MANs, and cordless phones. This explosive success of unlicensed operations and the many advancements in technology that resulted from it, led regulatory bodies (e.g., the FCC [2]) to consider opening further bands for unlicensed use. Whereas, spectrum occupancy measurements [3][4] show that licensed bands, such as the TV bands, are significantly underutilized.

Cognitive Radios (CRs) [5][6][7] 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 are enabled by the rapid and significant advancements in radio technologies (e.g., software-defined radios, frequency agility, power control, etc.), and can be characterized by the utilization of disruptive techniques such as wide-band spectrum sensing, real-time spectrum allocation and acquisition, and real-time measurement dissemination (please also refer to the DARPA neXt Generation (XG) program RFCs [8] for a good overview of issues in and the potential of CRs).

With all these facts and foundations in place, the TV band Notice of Proposed Rule Making (NPRM) [9] was the natural next step taken by the FCC. This NPRM, released in May/2004, proposes to allow unlicensed radios to operate in the TV broadcast bands provided no harmful interference is caused to incumbent services (e.g., TV receivers), which can be accomplished by employing CR-based technologies.

All these important events created a mindset within the IEEE that culminated in the formation of the IEEE 802.22 WG (or simply, 802.22) for WRANs in November/2004 [10]. This WG has been chartered with the specific task of developing an air interface (i.e., PHY and MAC) based on

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CRs for unlicensed operation in the TV broadcast bands, and as of the writing of this paper, the 802.22 WG has approved its baseline document and is working on drafts. In this paper, we provide a detailed overview of the present status of the work in the 802.22 WG (from the authors' perspective), including the requirements for incumbent service detection and protection, the techniques employed for sensing and detecting such incumbents, coexistence issues, the air interface, applications, among others. As it will be clear throughout this paper, 802.22 plays a key role in the evolution of CRs and its outcome will serve as foundation for many major future developments.

The rest of this paper is organized as follows. In Section II we overview the related work in the area, while in Section III we introduce the 802.22 standard by presenting its application areas and regulatory framework. Section IV covers the 802.22 system wide aspects such as topology, entities, service capacity, and coverage issues. The details of the air interface are given in Section V, while Section VI describes one of the most crucial aspects of the 802.22 design, namely, coexistence. Finally, Section VII concludes this paper.

II. Related Work

The IEEE 802.22 activity is the first worldwide effort to define a standardized air interface based on CR techniques for the opportunistic use of TV bands on a non-interfering basis. Due to this fact, the work being done in IEEE 802.22 is in many respects unique and the first of its kind, with little relevant related work. Its development process is a combined effort of traditional companies as well as representatives from the incumbent community (TV broadcasting and Wireless Microphones), and is scheduled to produce version 1.0 of the draft standard around January 2007.

It is important to understand, however, the core differences between 802.22 and 802.16 (WiMAX) [16] as confusion often arises when discussing these two IEEE projects. 802.22 is mostly targeted at rural and remote areas and its coverage range is considerably larger than 802.16 (see Figure 2). Also, 802.16 does not include incumbent protection techniques necessary to operate in licensed bands, while it has an ongoing project (802.16h) currently concentrating on coexistence among 802.16 systems only.

III. IEEE 802.22 Preliminaries

Before we delve into the specifics of the 802.22 system, it is important to first understand the ultimate goals of this standard.

A. Applications and Markets

The most prominent target application of 802.22 WRANs is wireless broadband access in rural and remote areas, with performance comparable to those of existing fixed broadband access technologies (e.g., DSL and cable modems) serving urban and suburban areas. In the last five years, the US has dropped from third to sixteenth place both in terms of the share of the population with broadband and the speed of these connections [11][12][13]. While availability of broadband access may not be so critical in urban and suburban areas, this certainly is not the case in rural and remote areas where about half of the US population is concentrated (a similar argument possibly applies to other countries too, especially those located in South America, Africa and Asia). Therefore, this has triggered the FCC to stimulate the development of new technologies (e.g., based on CRs) that increase the availability of broadband access in these underserved markets [9][12][14][15].

FCC selected the TV bands for providing such service because these frequencies feature very favorable propagation characteristics, which would allow far out users to be serviced and hence provide a suitable business case for Wireless Internet Service Providers (WISPs). In addition, it has been realized that many TV channels are largely unoccupied in many parts of the US [4], given that most households and businesses rely on cable and satellite TV services. Last, but not the least, another added advantage is that 802.22 devices in the TV bands will be unlicensed, which further lowers cost and is conducive to providing a more affordable service.

The other key target markets addressed by 802.22 WRAN networks include single-family residential, multi-dwelling units, small office/home office (SOHO), small businesses, multi-tenant buildings, and public and private campuses. 802.22 network shall provide services such as data, voice, as well as audio and video traffic with appropriate Quality-of-Service (QoS) support.

B. Regulatory Framework

As mentioned earlier, the 802.22 was formed in light of the TV band NPRM released by the FCC, which proposes to open the spectrum allocated to the TV service for unlicensed operation based on CRs. In the US, TV stations operate from channels 2 to 69 in the VHF and UHF portion of the radio spectrum. All these channels are 6 MHz wide, and span from 54-72 MHz, 76-88 MHz, 174-216 MHz, and 470-806 MHz. In addition to the TV service, also called primary service, other services such as wireless microphones are also allowed by FCC to operate on vacant TV channels on a non-interfering basis (please refer to Part 74 of the FCC rules), and so are Private Land and Commercial Mobile Radio Services (PLMRS/CMRS) including Public Safety (please refer to Part 90 of the FCC rules)[1]. While it is recognized by the 802.22 WG that FCC is yet to release the final rules for unlicensed operation in the TV broadcast bands (expected to be out within the next few months), there is a common feeling that these rules will not be a roadblock, but rather will serve as a catalyst to the development of this new CR-based standard and promote the emergence of new markets, applications and services.

[1] Throughout this paper, the terms incumbent and primary services are used interchangeably to refer to the TV broadcast service, wireless microphones and PLMRS/CMRS. Accordingly, 802.22 devices are seen as secondary users of the band and hence are called secondary services.

IV. THE IEEE 802.22 SYSTEM

While the major push towards the commercial deployment of CRs is coming mostly from the US, the goal of IEEE 802.22 is to define an international standard that may operate in any regulatory regime. Therefore, the current 802.22 project identifies the North American frequency range of operation 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, the standard shall accommodate the various international TV channel bandwidths of 6, 7, and 8 MHz.

A. 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[2] and all associated Consumer Premise Equipments (CPEs), as depicted in Figure 1. The BS (a professionally installed entity) controls the medium access in its cell and transmits in the downstream direction to the various CPEs, which respond back to the BS in the upstream direction. In addition to the traditional role of a BS, it also 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 of different TV channels. Based on the feedback received, the BS decides which steps, if any, are to be taken.

B. Service Capacity

The 802.22 system specifies spectral efficiencies in the range of 0.5 bit/(sec/Hz) up to 5 bit/(sec/Hz). If we consider an average of 3 bits/sec/Hz, this would correspond to a total PHY data rate of 18 Mbps in a 6 MHz TV channel. In order to obtain the minimum data rate per CPE, a total of 12 simultaneous users have been considered which leads to a required minimum peak throughput rate at edge of coverage of 1.5 Mbps per CPE in the downstream direction. In the upstream direction, a peak throughput of 384 kbps is specified, which is comparable to DSL services.

C. Service Coverage

Another distinctive feature of 802.22 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). As shown in Figure 2, 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.

[2] 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 802.22 BS can be received by associated 802.22 CPEs with a given minimum SNR quality.

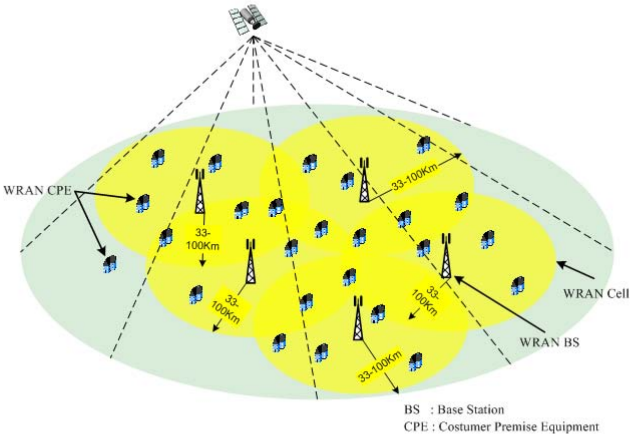

Figure 1. Exemplary 802.22 deployment configuration

V. THE 802.22 AIR INTERFACE

The distinctive and most critical requirement for the 802.22 air interface is flexibility and adaptability, which stem from the fact that 802.22 operates in a spectrum where incumbents have to be protected by all means. Further, since 802.22 operation is unlicensed and a BS serves a large area, coexistence amongst collocated 802.22 cells (henceforth referred to as *self-coexistence*) is of paramount importance. Therefore, in this section we discuss the PHY and MAC design supporting such flexibility and adaptability, which provides the ideal foundation to approach coexistence issues in the next section.

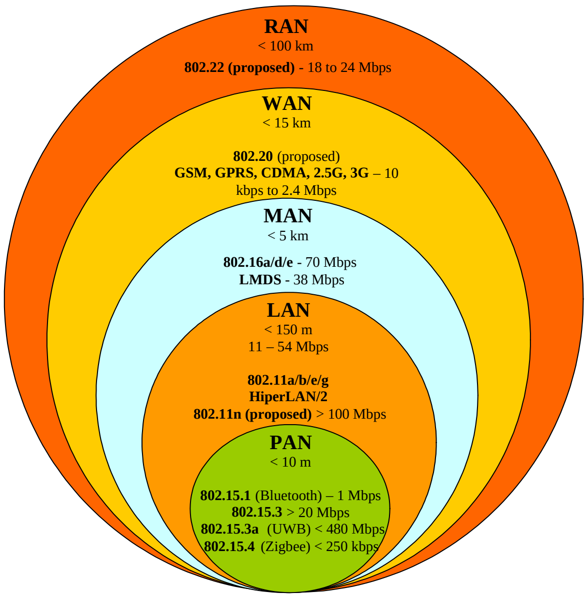

Figure 2. 802.22 wireless RAN classification as compared to other popular wireless standards

A. The PHY

Figure 3 depicts what could be the pattern of TV channel occupancy by incumbents over time and frequency. As we can see, transmission opportunities (i.e., time during which a channel is vacant) by 802.22 BSs and

CPEs usually experience a random behavior which impacts the design of both MAC (discussed in the next subsection) and PHY. In the specific case of the PHY, it needs to offer high performance while keeping the complexity low. In addition, it needs to exploit the available frequency in an efficient manner to provide adequate performance, coverage and data rate requirements of the service. WRAN applications require flexibility on the downstream with support for variable number of users with possibly variable throughput. WRANs also need to support multiple access on the upstream. Multi-carrier modulation is very flexible in this regard, as it enables to control the signal in both time and frequency domains. This provides an opportunity to define two-dimensional (time and frequency) slots and to map the services to be transmitted in both directions onto a subset of these slots. The current 802.22 draft is based on OFDMA modulation for downstream and upstream links with some technological improvements such as channel bonding.

WRAN are characterized with long delays spread (25us and up to 50us in large terrain or metropolitan areas). This requires the use of a cyclic prefix on the order of 40us. In order to reduce the impact of the overhead due to cyclic prefix, approximately 2K carriers is used in one TV channel.

The 802.22 PHY has also to provide high flexibility in terms of modulation and coding. For example, consider the scenario in Figure 1 where CPEs may be located at various distances from the BS and hence experience different Signal-to-Noise Ratio (SNR) quality. To overcome this issue and improve system efficiency, the BS must be 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. One current proposal is to divide the subscribers to 48 subchannels. Modulation schemes are QPSK, 16-QAM, 64QAM with convolution coding schemes of rate ½, ¾,2/3. This result in a data rate starting from a few Kbps per sub channel up to 19 Mbps per TV channel, providing sufficient flexibility.

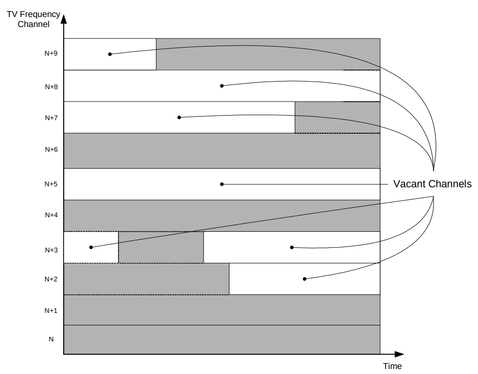

Figure 3. Example of TV band occupancy over time and frequency

It is well known, in general, that wider bandwidth decreases frequency-non-selective flat fading and provides more frequency diversity in a frequency selective fading channel environment. In addition, wider bandwidth provides more capacity. Thus, whenever spectrum is available, it is beneficial to use wider bandwidth system. Such available wider spectrum can be used to tradeoff data-rate with distance. For example, those devices that are closer to the BS can enjoy high capacity while the ones that are far away can benefit from the multi-path diversity and from more transmitted and received power.

Preliminary link budget analysis has shown that it would be difficult to meet the 802.22 requirements (about 19 Mbps at 30Km) by using just 1 TV channel for transmission. The use of channel bonding by aggregating contiguous channels allows this requirement to be met. There are two channel bonding schemes: bonding of contiguous and non-contiguous channels. The current 802.22 draft supports both these schemes. However, emphasis below will be on contiguous channel boding.

Figure 4 shows the simplified diagram of the contiguous channel bonding scheme. In principle, bonding as many TV channels as possible is desirable. However, practical implementation limitations impose constraint on how many channels can be bonded. For implementation purposes, it is desirable to limit the bandwidth of the RF front-end part of the communication system. The current US grade-A TV allocation restricts adjacent allocated TV channels to have at least 2 empty channels between them. This is done so to reduce interference from one high-power TV channel to the other. Thus, the minimum vacant TV channel spacing needed for the WRAN device to operate is 3 TV channels. Based on this, RF bandwidth is limited to 3 contiguous channels only. For 6 MHz TV channels, this implies in a RF bandwidth of 18 MHz.

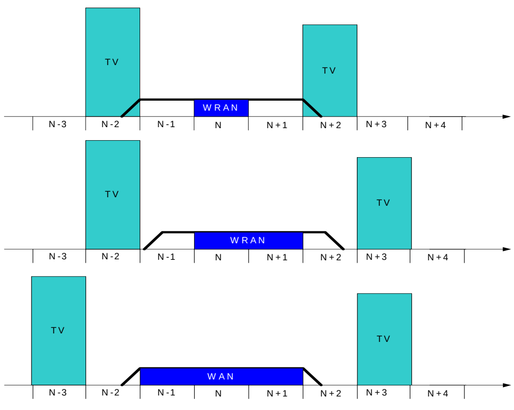

Figure 4. Simplified diagram of the channel bonding scheme illustrating 1 (top), two (middle), and three TV channels (bottom)

In order to simplify implementation, the current channel boding scheme uses fixed inter-carrier spacing. This facilitates implementation, as the transceiver does not have to change its system clock based on the number of channels bonded. This approach translates into requiring more FFT bins as the channels are bonded. In general, the system is based on 6K FFT for 3 TV channels bonded. When only one TV channel is used, the outer carriers of this FFT will be set to zero such that only a few subcarriers (say, about 1.7K) are active. When two channels are bonded, then about 3.4K sub carriers will be active and the remaining outer subcarriers are set to zero. For 7 and 8 MHz TV channels, the inter-carrier spacing will be adjusted accordingly. Nevertheless, the bonding approach remains the same as that of the 6 MHz TV channels.

When a device is starting to synchronize, it would not know a-priori the channels that are bonded. To facilitate initial synchronization, we have defined a superframe structure (shown in Figure 5 and also discussed in the next subsection). The header of this supper frame will be transmitted in known 6 MHz mode. The new device can initially start scanning in 6 MHz mode. When it finds the superframe header, it then obtains the necessary information of the frames following the superframe header (see next subsection). The superframe header is based on about 5 MHz bandwidth. This relaxes the filtering requirements to reduce interference from adjacent channels. The header contains a preamble for time synchronization, AGC setting and channel estimation. The preamble is then followed with 1 symbol header containing the actual information bits. The same information is transmitted repeatedly in all the TV channels being bonded.

B. The MAC

The CR-based MAC needs to be highly dynamic in order to respond quickly to changes in the operating environment. Besides providing traditional MAC services, the 802.22 MAC is required to perform an entirely new set of functions for effective operation in the shared TV bands.

B.1 Superframe and Frame Structure

The current 802.22 draft MAC employs the superframe structure depicted in Figure 5. At the beginning of every superframe, the BS sends special preamble and SCH (superframe control header) through each and every TV channel (up to 3 contiguous) that can be used for communication and that is guaranteed to meet the incumbent protection requirements. CPEs tuned to any of these channels and who synchronizes and receives the SCH, are able to obtain all the information it needs 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 a single or multiple channels. During each MAC frame the BS has the responsibility to manage the upstream and downstream direction, which may include ordinary data communication, measurement activities, coexistence procedures, and so on.

The MAC frame structure is shown in Figure 6. As we can see, a frame is comprised of two parts: a downstream (DS) subframe and an upstream (US) subframe. The boundary between these two segments is adaptive, and so the control of the downstream and upstream capacity can be easily done. The downstream subframe consists of only one downstream PHY PDU with possible contention intervals for coexistence purposes. An upstream subframe consists of contention intervals scheduled for initialization (e.g., initial ranging), bandwidth request, UCS (Urgent Coexistence Situation) notification, and possibly coexistence purposes and one or multiple upstream PHY PDUs, each transmitted from different CPEs.

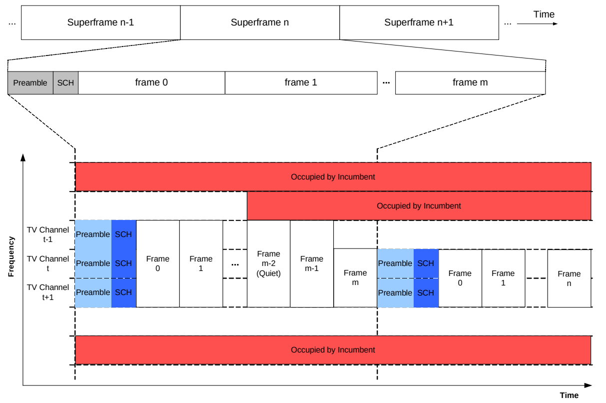

Figure 5. General superframe structure

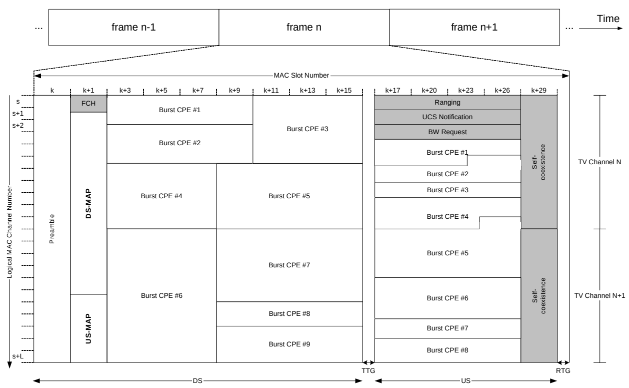

Figure 6. Time/Frequency structure of a MAC frame

B.2 Network Entry and Initialization

Generally, when there is a reliance on a centralized BS for access, network entry is a straightforward process in any MAC protocol. However, this is not the case when operating in a shared band and on an opportunistic basis such as depicted in Figure 3. Contrary to existing wireless technologies, there is no pre-determined channel (here, channel may mean frequency, time, code, or any combination therein) a CPE can use to look for a BS. Thus, the MAC must be designed to address network entry, which is typically a simple procedure in existing wireless MAC protocols.

In the 802.22 draft MAC, whenever a CPE starts up it first scans (perhaps all) the TV channels and builds a spectrum occupancy map that identifies for each channel whether incumbents have been detected or not [17][18]. This information may be later conveyed to a BS and is also used by the CPE to determine which channels are vacant and hence use them to look for BSs.

In those vacant channels, the CPE must then scan for SCH transmissions from a BS. The duration a CPE stays in a channel is at least equal to the superframe duration. Once the CPE receives the SCH, it acquires channel and network information that is used to proceed with network entry and initialization.

B.3 Measurements and Spectrum Management

One of the components of the 802.22 draft MAC that forms an important portion of the cognitive features of this standard relates to measurements and channel management. So that an 802.22 cell can operate without causing harmful interference to incumbents, the BS shall instruct its 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 periodically quiets the channel so that incumbent sensing can be carried out, which is not the case for out-of-band measurements. In order to ascertain the presence of incumbents, 802.22 devices need to detect signals at very low SNR levels (discussed in Section VI) and with certain accuracy, which should be dynamically controlled by the BS. Since these measurements must be made in low SNR levels, it is assumed that the detection of TV signals is done in a non-coherent manner, that is, no synchronization is assumed [19][20].

Depending on the incumbent detection algorithms available at the various CPEs, measurements can take different amount of time. The BS must 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 may not need to require every CPE to conduct the same measurement activities. Rather, it may incorporate algorithms that distribute the measurement load across CPEs and that use the measured values to obtain a spectrum occupancy map for the entire cell. The measured values by the CPEs must also be returned to the BS, which then analyzes them and take actions, if appropriate.

The current 802.22 draft MAC provides for the support of all these aspects. It also incorporates a vast set of functions that allow it to efficiently manage the spectrum. Operations such as switch channels, suspend/resume channel operation, and add/remove channels are among the many actions the MAC may have to take in order to guarantee incumbent protection and effective coexistence.

B.4 Quiet Periods for Incumbent Sensing

For in-band channels, the current 802.22 draft MAC employs the quiet period mechanism shown in Figure 7. It is comprised of two stages which have different time scales: fast sensing and fine sensing.

Fast Sensing: The fast sensing stage is comprised of one or more fast sensing periods as depicted in Figure 7. During this stage, a fast sensing algorithm is employed (e.g., simple energy detection). 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, who then decides on the need for the following fine sensing stage (discussed next). For example, if during the fast sensing stage it is concluded that energy in the affected channel is always below the threshold, 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 based on the outcome of the previous fast sensing stage. During this stage, more detailed sensing is performed on the target channels. Typically, algorithms executed during this stage can take in the order of milliseconds (e.g., 25ms in the case of field-sync detection for ATSC[3]) for each single frequency channel, since they look for particular signatures of the primary user transmitted signal. However, considering the fact that TV stations do not come on the air frequently, this mechanism is highly efficient.

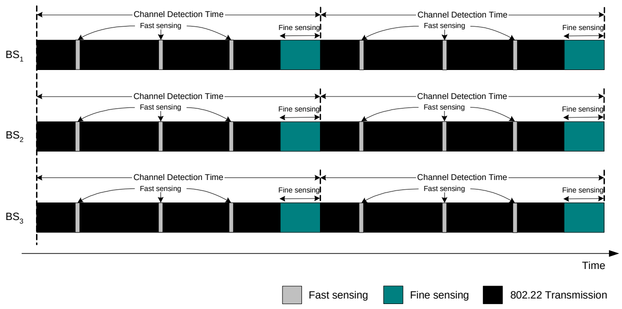

Figure 7. Two-stage quiet period mechanism

Clearly, the possibility of having multiple overlapping 802.22 BSs in operation in the same geographical region may undermine this two-stage quiet period approach. To overcome this problem, the 802.22 system incorporates a very efficient algorithm that is able to dynamically synchronize multiple overlapping cells (see VI). Based on this, quiet periods of overalapping BSs are also synchronized resulting in the arrangement depicted in Figure 7. So, sensing can be made with high reliability.

VI. COEXISTENCE IN IEEE 802.22

Coexistence is critical to the 802.22 air interface. To this end, CR techniques are incorporated into 802.22 by means of distributed spectrum sensing, measurements, detection algorithms, and spectrum management.

With this in mind, in the rest of this section we discuss in detail the coexistence aspects in 802.22 to protect incumbents, and also to mitigate self-coexistence.

A. Antennas

IEEE 802.22 requires two separate antennas for each CPE radio: one directional and one omni-directional (with gain of 0 dBi or higher). The directional antenna would be

[3] ATSC (Advanced Television Systems Committee) is the US standard for DTV systems.

the operational antenna generally used by a CPE to communicate with the BS. Directional antennas have the desirable feature that energy is not radiated in unwanted directions and so interference can be minimized [22]. The omni-directional antenna, on the other hand, would be used primarily for sensing and performing measurements. Therefore, to perform a reliable sensing this antenna would most likely have to be mounted outdoors.

B. Coexistence with TV and Wireless Microphones

In 802.22, both BSs and CPEs are responsible for incumbent protection which is based upon RF sensing and CR-based techniques. Since measurements performed by a single CPE may not be fully reliable, a periodic distributed sensing mechanism is employed by the BS, which uses techniques such as data fusion and referendums over all measured data to obtain a reliable spectrum occupancy figure.

B.1 Sensing Thresholds

In 802.22, BSs and CPEs are responsible for sensing licensed transmissions, possibly with the omni-directional antenna in any azimuthal direction and polarization. The BS vacates a channel if licensed signals are detected above the following thresholds (referenced to the receiver input):

- Digital TV (DTV): -116 dBm over a 6 MHz channel – For example, for ATSC this could be done by using spectrum analysis techniques to sense the pilot carrier of the DTV signal which is at -11.3 dB below the total DTV power (different threshold values may be needed to protect the various digital TV systems). Here, it is crucial to note that the 802.22 WG has concluded that if channel N is occupied by an incumbent within its protected contour, then this standard shall not operate on channels N or N±1.
- Analog TV: -94 dBm measured at peak of sync of the NTSC[4] picture carrier (different threshold values may be needed to protect the various analog TV systems).
- Wireless microphones: -107 dBm measured in a 200 KHz bandwidth.

B.2 Calculation of the Keep-Out Region

The primary goal of spectrum sensing is to determine which TV channels are occupied and which are vacant. That allows the WRAN to utilize the unused TV channels and avoid using the occupied TV channels. Additionally, it helps to reduce the limit on its transmit EIRP if needed as a function of the proximity of TV channels and/or Part 74 wireless microphones.

Identification of whether a TV channel is occupied is complicated by many factors such as noise in the receiver, shadow fading, multipath fading, wireless transmissions other than DTV, transmission of DTV signals in adjunct channels, etc.

The propagation characteristics of the TV broadcasting is expressed by means of spatial and temporal characteristics and is denoted by *F(X,Y)*. The TV signal propagation characteristics are expressed by field strength [25]. *F(X,Y)* represents the actual field strength that would exceed a certain threshold at *X*% of locations for *Y*% of time.

We have to convert the field strength to the received voltage. Field strength can be expressed as a function of received voltage, receiving antenna gain and frequency when applied to an antenna whose impedance is 50 ohms as:

$$E(dB\mu V/meter) = E(dB\mu V) - Gr(dBi) + 20\log f(MHz) - 29.8$$

Solved for received voltage this equation becomes:

$$E(dB\mu V) = E(dB\mu V/meter) + Gr(dBi) - 20\log f(MHz) + 29.8$$

For Power and Voltage calculations into a 50 ohm load:

$$P(dBm) = E\,(dB\mu V) - 107$$

$$P(dBm) = E\,(dB\mu V/m) + Gr(dBi) - 20\log F(MHz) - 77.2$$

where *Gr* is the isotropic gain of the receiving antenna. At 615 MHz the conversion from field strength to receive power is -133 dB. Additionally, the signals are subject to the typical lognormal shadow fading with a 5.5 dB standard deviation [25]. When this is converted to distance, one can conclude that any TV receiver outside the radius of 132 km will not be able to decode the signal successfully. According to the FCC NPRM for DTV, the Desired to Un-desired (D/U) ratio is 23 dB. For example, the location in the F(50, 90) propagation curve where the field strength is 41 dBu defines the DTV protection contour in the US. Based on this, the undesired signal level needs to be less than 18 dBu using an F(50,10) propagation curve for the interferer.

In the US, the transmission power of a WRAN station is limited to 36 dBm EIRP. The distance at which the field strength of the undesired signal reaches 18 dBu is approximately 23 km. Hence, adding 23 km to the DTV protection contour of 132 km, we obtain a keep-out region of 155 km around the DTV transmitter. At the edge of the keep-out region, 155 km from the DTV transmitter, the DTV field strength using the F(50,90) curve is 35.1 dBu. And the receive power assuming isotropic sensing antenna is -97.9 dBm. Therefore, a WRAN station would typically have to protect 155 km around a transmitting DTV station.

B.3 DFS Timing Requirements

The DFS timing parameters defines 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.

Table 1 illustrates the key DFS parameters which is based on the Dynamic Frequency Selection (DFS) model ordered by the FCC for the 5 GHz band [23]. In this table, one of the key parameters is the Channel Detection Time that is the time during which an incumbent operation can withstand

[4] NTSC (National Television System Committee) is the US standard for analog TV systems.

interference before the 802.22 system detects it. In other words, this parameter dictates how quickly and how well an 802.22 system must be able to detect incumbents.

B.4 Wireless Microphone Detection

Contrary to detection of TV transmission, detection of wireless microphone operation is much harder as these transmit at a much lower power (typically 50 mW for a 100 m coverage range) and occupy much lower bandwidths (200 KHz). Therefore, two options are considered, not necessarily exclusive, to protect this service[5]: ordinary sensing and detection, and beacons. The sensing and detection is based on the DFS model presented in Table 1. In addition, the other option is for wireless microphone operators to carry a special device that would transmit beacons in the channel to be used by these wireless microphones. For example, in a concert where wireless microphones are used at, say, channel C, these special devices would periodically transmit beacons (possibly at a higher power) through channel C. 802.22 BSs and CPEs receiving these beacons through channel C would vacate this channel and avoid interference.

The current 802.22 draft MAC includes an embedded wireless microphone beacon method that addresses this problem, and is totally integrated with the normal MAC operation.

B.5 Spectrum Usage Table

Another functionality in the 802.22 drat MAC is the maintenance of a table that classifies channels as per availability, such as occupied (e.g., by an incumbent), available (for use by 802.22), and prohibited (cannot be used at all by 802.22). This table is to be updated either by the system operator (e.g., setting certain channels as prohibited) or by the 802.22 sensing mechanism itself.

TABLE 1
DFS PARAMETERS

Parameter	Value for Wireless Microphones	Value for TV Broadcasting
Channel Availability Check Time	30 sec	30 sec
Non-Occupancy Period	10 minutes	10 minutes
Channel Detection Time	≤ 2 sec	≤ 2 sec
Channel Setup Time	2 sec	2 sec
Channel Opening Transmission Time (Aggregate transmission time)	100 msec	100 msec
Channel Move Time (In-service monitoring)	2 sec	2 sec
Channel Closing Transmission Time (Aggregate transmission time)	100 msec	100 msec
Interference Detection Threshold	-107 dBm	-116 dBm

[5] It is also possible that the FCC reserves certain channels for wireless microphone operation as requested by providers.

B.6 Out-of-Band Emission Mask

Based on the above study [24], it is possible to conclude that in order to protect both TV and wireless microphone operation, BSs and CPEs operating at 4 Watts shall meet the limits specified in Table 2 (for more information, please refer to [24]).

TABLE 2
OUT-OF-BAND EMISSION MASK

	802.22 Operation	
	First adjacent channel	**Second adjacent channel and beyond**
802.22 first adjacent channel limit	4.8 uV/m	200 uV/m
802.22 second adjacent channel and beyond limit	4.8 uV/m	4.8 uV/m

C. Coexistence with PLMRS/CMRS

Typically, licensed operation of PLMRS/CMRS is geographically based. So, since 802.22 BSs know their location and maintain a Spectrum Usage Table (discussed earlier), the task of coexistence with PLMRS/CMRS is simpler which eliminates the need for any 802.22 sensing of PLMRS/CMRS services to take place.

D. Self-Coexistence

Contrary to other IEEE 802 standards where self-coexistence issues are often considered only after the standard is finalized, the IEEE 802.22 WG takes a proactive approach and mandates that the air interface include self-coexistence protocols and algorithms as part of the standard definition. As depicted in Figure 1, multiple 802.22 BSs and CPEs may operate in the same vicinity and provided appropriate measures are taken at the air interface level, self-interference may render the system useless. This is further aggravated by the fact that 802.22 coverage range can go up to 100 Km, and hence its interference range is larger than in any existing unlicensed technology. Please note that contrary to other bands such as cellular where operators have a dedicated portion of the spectrum licensed for their specific use, 802.22 BSs and CPEs operate in an opportunistic way in an unlicensed spectrum and hence coordination amongst networks of different service providers cannot be assumed and will most likely not exist.

Self-coexistence implies that 802.22 networks that are within radio range of each other must be able to synchronize their superframes with each other. In the current draft standard, such synchronization is achieved by BSs and/or CPEs transmitting beacons with time stamps (called *coexistence beacons*), so that CPEs from a neighboring network may overhear them. CPEs within a network, when not communicating with their BS, look for coexistence beacons from a neighboring network. When a BS receives a neighbor's coexistence beacon (either directly or from one of its CPEs), it adjusts the start time of its superframe according to certain rules. Note that this operation is completely distributed, and hence the convergence of the synchronization must be ensured by these rules. In the current draft standard, a simple set of such rules is described.

We have conducted extensive simulations to study how quickly and reliably the different networks converge to the same superframe start time, and results are shown in Figure 8. The simulation consists of a number of networks (x-axis), placed randomly in square area (either 50x50, 100x100, or 150x150 km), with random start times and fixed range of 25 km. Each network issues the coexistence beacon as described above, and synchronizes according to the rules. On the y-axis is the convergence time in units of superframe. As can be seen, even when a large number of networks are placed in the square area, they converge very rapidly, even though the synchronization operation is completely distributed in nature.

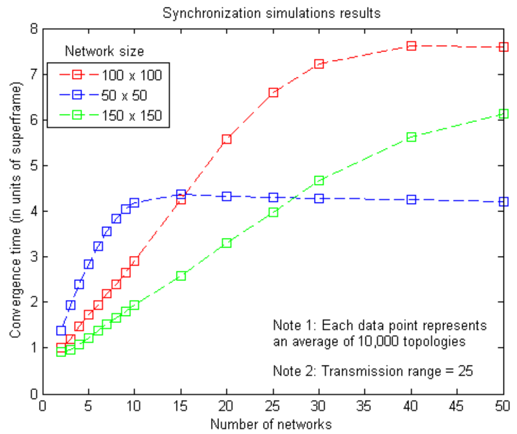

Figure 8. Convergence times in the synchronization of 802.22 networks within radio range of each other

VII. CONCLUSIONS

The IEEE 802.22 WG is in the process of defining the first worldwide air interface standard based on CR techniques. This new standard, which will operate in the TV bands, makes use of techniques such as spectrum sensing, incumbent detection and avoidance, and spectrum management to achieve effective coexistence and radio resource sharing with existing licensed services. In this paper, we have provided an in-depth overview of the status of the work being conducted at 802.22, including its draft PHY and MAC specification, and coexistence techniques. As we can see, the future of CR-based wireless communication holds great promise. Certainly, the 802.22 has a leading and key role in this process and its outcome will serve as the basis for new and innovative research in this promising area.

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