IEEE 802.22: The First Worldwide 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[1] 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 architecture, its requirements, applications, and coexistence considerations that not only form the basis for the definition of this groundbreaking wireless air interface standard, but that will also serve as foundation for future research in the promising area of CRs.

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. While land and energy constituted the most precious wealth creation resource during the agricultural and industrial eras respectively, radio spectrum has become the most valuable resource of the modern era [1]. Notably, the unlicensed bands (e.g., ISM and UNII) play a key role in this wireless ecosystem given that many of the significant revolutions in radio spectrum usage has originated in these bands, and 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 through its Spectrum Policy Task Force (SPTF) [2]) to analyze the way spectrum is currently used and, if appropriate, make recommendations on how to improve radio resource usage.

As indicated by the SPTF and also by numerous reports [3], the usage of radio resource spectrum experiences significant fluctuations. For example, based on the measurements carried out in [4] for the frequency bands below 3GHz and conducted from January/2004 to August/2005, we conclude that, on an average, only about 5.2% of the spectrum is actually in use in the US in any given location and at any given time (please refer to [4] for more detailed information). Interestingly enough, these measurements reveal that heavy spectrum utilization often takes place in unlicensed bands while licensed bands often experience low (e.g., TV bands) or medium (e.g., some cellular bands) utilization. These striking results coupled with recent advancements in radio technology led the FCC to revisit the traditional way of spectrum management. It has been realized that not only spectrum usage is very low in certain licensed bands, but also that the scarcity of radio resources is becoming a crisis hindering the development of many wireless applications including broadband access (not only in urban/suburban areas, but especially in rural/remote areas), public safety, health care, business, and leisure.

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

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

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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 CRs for unlicensed operation in the TV broadcast bands, and as of the writing of this paper, the 802.22 WG has essentially finalized the specification of its technical requirements (with minor details yet to be defined) [11]. 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[2]. 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. Finally, to the best of this paper authors' knowledge, this is the first article ever on 802.22.

The rest of this paper is organized as follows. In Section II we introduce the 802.22 project by presenting its application areas, membership and regulatory framework. Section III 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 IV, while Section V describes one of the most crucial aspects of the 802.22 design, namely, coexistence. Finally, Section VI concludes this paper.

[2] All the technical approaches discussed in this paper constitute the authors' opinion.

II. 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 (i.e., target applications and markets), its membership and timeline, as well as briefly analyze the regulatory framework in which it is based upon.

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. Here, we note that there is a good reason for this core application. 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 [12][13][14]. While availability of broadband access may not be so critical in urban and perhaps suburban areas, although costs remain high [14], 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][13][15][16].

In fact, broadband access in rural and remote regions was one of the reasons why FCC selected the TV bands for providing such service, as this lower spectrum of frequencies features 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.

This is not to say, however, that the applicability and market of 802.22 is restricted to rural and remote areas.

As a matter of fact, 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. The 802.22 system is being defined in such a way that it could potentially be used in other settings as well, such as urban and suburban environments.

It is also worth mentioning the type of services that an 802.22 network shall provide. This includes data, voice, as well as audio and video traffic with appropriate Quality-of-Service (QoS) support.

Finally, it is important to understand the core differences between 802.22 and 802.16 (WiMAX) [17] as confusion often arises when discussing these two IEEE projects. Since 802.22 is mostly targeted at rural and remote areas, its coverage range is considerably larger than 802.16 (see Figure 2) to allow for a good business case, and this is why 802.22 is the first standard ever for WRANs. 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.

B. Membership and Timeline

Members participating in the development of the 802.22 standard come from a diverse background, which is primarily due to the unique requirement of incumbent protection of the final 802.22 standard. Hence, the key to the success of 802.22 depends not only on representatives from wireless companies but also from the incumbent community. Thus, members of the IEEE 802.22 WG include the more traditional corporations (e.g., Philips, Intel, Motorola, ST Micro, CRC, Samsung, Nokia) as well as delegates from the incumbent world (e.g., Fox, CBS, NAB, MSN, Shure Inc.). As for the timeline, currently it is expected that the first draft of the standard be ready around mid 2006.

C. 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)[3]. 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.

III. THE IEEE 802.22 SYSTEM

While the major push (not only technical, but specially regulatory) 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 (e.g., US, Canada, Europe, Japan, Australia, etc.). 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, since there is no worldwide uniformity in channelization for TV services, 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[4] 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

[3] 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.

[4] 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.

downstream direction to the various CPEs (which can be user-installable), which respond back to the BS in the upstream direction. In order to ensure the protection of incumbent services, the 802.22 system follows a strict masters/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 the traditional role of a BS, which is to regulate 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 (this is discussed in more detail later on in this paper).

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

A 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.

IV. 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.

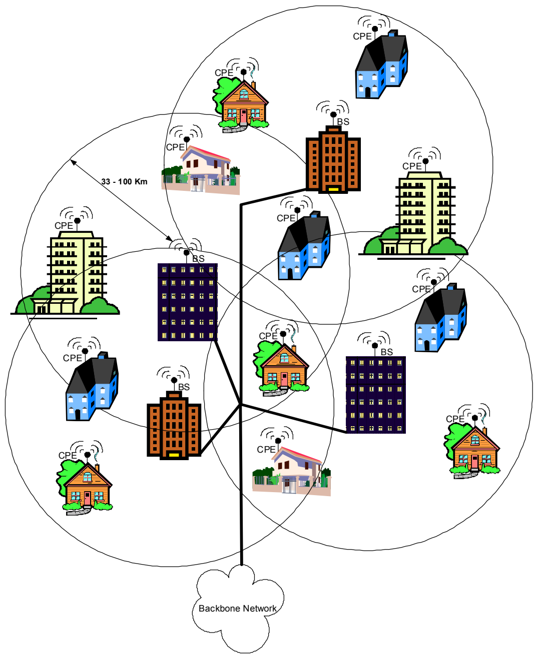

Figure 1 – Exemplary 802.22 deployment configuration

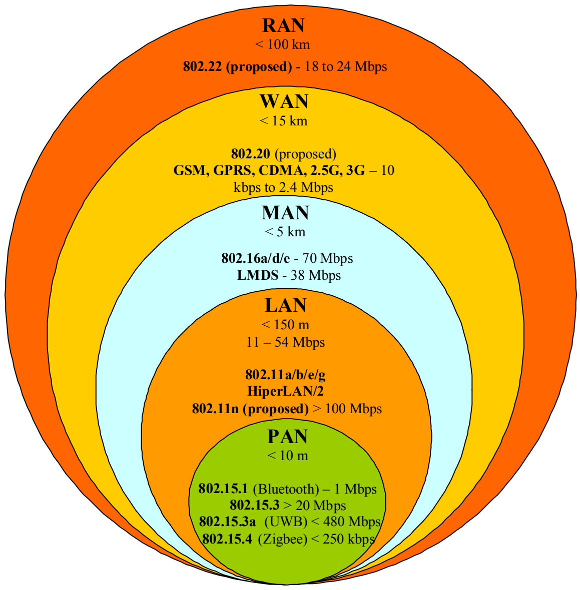

Figure 2 – 802.22 wireless RAN classification as compared to other popular wireless standards

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. For example, if an OFDM-based system is adopted, the number of carriers has a significant impact on performance as well as cost. Recent studies reveal that in order to obtain a flat fading channel the number of subcarriers per TV channel would have to exceed two thousand, which may increase cost and complexity for a standard whose core application is broadband access in rural and remote areas. On the other hand, performance can be considerably enhanced.

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 modulation and coding on, at least, a per CPE basis. In 802.22 terminology, these aspects are included in what is referred to as *flexible adaptive performance*.

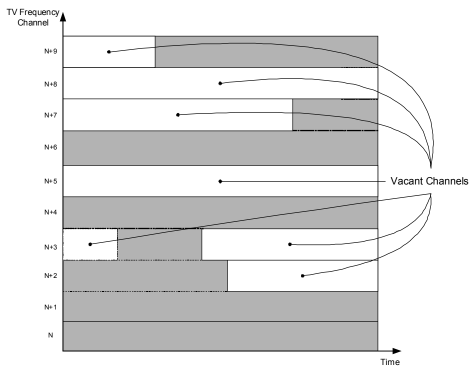

Figure 3 – Example of TV band occupancy over time and frequency

Another important issue to consider in the 802.22 PHY design is in regards to Transmission Power Control (TPC) and frequency agility. In order to minimize interference not only to incumbent services but also self-interference, effective power control is important. To meet this requirement, 802.22 specifies the TPC dynamic range to be at least 30 dB with 1 dB steps. Frequency agility is the other ingredient to the coexistence mechanisms of the 802.22 PHY that shall be able to adjust its frequency of operation not only within a short period of time, but also as often as necessary while conserving energy.

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 services such as medium access control and robust data delivery, the 802.22 MAC is required to perform an entirely new set of functions for effective operation in the shared TV bands.

B.1 Initialization

Generally, when there is a reliance on a centralized BS for access, initialization 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.

For example, in 802.22 whenever a CPE starts up it may need to first perform the time consuming process of scanning (perhaps all) the TV channels and building a spectrum occupancy map that identifies for each channel whether incumbents have been detected or not [18][19]. This information may be later conveyed to the BS and is also used by the CPE to determine which channels are vacant and hence use them to look for BSs.

The process in the CPE to search for a BS is itself not so straightforward. 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. To make matters worse, 802.22 BS may utilize channel bonding techniques to group multiple vacant channels together and hence improve performance. If this is the case, the task of synchronizing to a BS becomes considerably harder for CPEs. Thus, the 802.22 MAC must be carefully designed to address these issues, which have never been addressed in any existing wireless MAC protocols.

B.2 Measurements and Spectrum Management

A critical component of the 802.22 MAC that forms a reasonable 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 used by the BS to communicate with the CPEs (and also those affected by this communication such as adjacent channels), while out-of-band correspond to all other non-affected channels. In in-band measurements, the BS may need to quiet the channel for data transmission so that measurements 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 V) 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 [20][21].

During an in-band measurement activity, CPEs may not communicate with the BS, which clearly affects the system performance. The longer a measurement takes, the higher the penalty (e.g., lost access opportunity, energy consumption, etc.). 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 are returned to the BS that analyzes them and take actions, if appropriate. All these aspects of the duration and frequency of the measurement activity, which device(s) should measure and what channel(s) to measure are part of the 802.22 MAC design scope.

The 802.22 MAC 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.

B3. Other Issues

Another important consideration in the design of the 802.22 MAC is the propagation delay it must support. As illustrated in Figure 1, 802.22 proposes to provide service in locations up to 100 Km away from the transmitting BS, and hence imposes roundtrip propagation delays in excess of 300 µs. Delays of this magnitude impose severe restrictions in the MAC and requires it to compensate for the different propagation delays experienced by the various CPEs. Also, such large delays may prohibit the use of access schemes that would otherwise be highly desirable in an environment where coexistence is the norm, and not the exception. This is the case, for instance, with contention-based protocols as depicted in Figure 4, which analyzes the normalized throughput of both CSMA [22] and MACA [22] under propagation delays of 150 µs and 300 µs, and increasing load. As we can see from this figure, the throughput performance degrades as the propagation delay increases, which may disqualify this class of access mechanism when applied to WRANs.

V. COEXISTENCE IN IEEE 802.22

Coexistence is critical to the 802.22 air interface, which, contrary to other IEEE wireless standards, is required to include coexistence mechanisms in the initial phases of conception of the standard. To this end, CR techniques are incorporated into 802.22 by means of distributed spectrum sensing, measurements, detection algorithms, and spectrum management. The combination of these mechanisms provides a radio that is highly flexible and adaptive to the environment and can react to sudden changes in it.

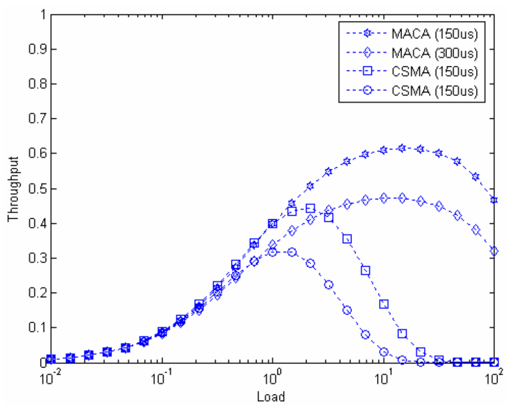

Figure 4 – Performance analysis of contention-based protocols under large propagation delays

As discussed earlier, the TV broadcast bands in which 802.22 shall operate are already used by TV broadcasting, wireless microphones and the PLMRS/CMRS. Therefore, in this section we discuss in detail the present status of coexistence aspects in 802.22 to protect these incumbents, and also to mitigate self-coexistence.

A. Antennas

The primary goal for 802.22 is to define a technology that not only provides its own intended service, but also guarantees that existing incumbent services can continue to be provided. With these two goals in mind and the clear coexistence challenge, it is believed in 802.22 the need for each CPE radio to possess two separate antennas (under the control of a single MAC and PHY): one directional and one omni-directional (with gain of 0 dBi or higher). The directional antenna would be 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 [23]. In addition, these antennas offer the ability to improve the effectiveness of TPC which further facilitates coexistence. 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. With an omni-directional antenna, CPEs are capable of searching for incumbents in its entire neighborhood, and not only in a single direction as would be the case with the directional antenna.

B. TV and Wireless Microphone Sensing and Protection

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[5] 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[6] 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 Response Times

The response time is the time during which TV broadcast and wireless microphone operation can withstand interference before the 802.22 system vacates the channel. For the purpose of detecting a new DTV station, this response time is not likely to be critical (e.g., TV broadcast stations typically come on overnight). The minimum rate of sensing for TV broadcast could be 1 hour and the vacate time could be no more than 30 minutes, allowing for the distributed sensing mechanism to confirm presence of DTV operation. However, in the case where TV stations are not operating in a continuous mode (e.g., turned off during the night), much faster sensing is needed to vacate the channel when the TV station comes on. Here, the minimum rate of sensing could be 5 minutes and the vacate time no more than 1 minute.

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, the 802.22 WG is currently considering two options, not necessarily exclusive, to protect this service[7]: ordinary sensing and detection, and beacons. The sensing and detection is based on the Dynamic Frequency Selection (DFS) model ordered by the FCC for the 5 GHz band [24], whose recommended parameters for wireless microphone protection are indicated 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

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

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

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

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.

B.3 Spectrum Usage Table

Another functionality required by 802.22 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 for wireless microphones

Parameter	Value
Channel Availability Check Time	30 sec
Non-Occupancy Period	10 minutes
Channel Detection Time	500 msec – 2 sec
Channel Setup Time	2 sec
Channel Opening Transmission Time (Aggregate transmission time)	100 msec
Channel Move Time (In-service monitoring)	2 sec
Channel Closing Transmission Time (Aggregate transmission time)	100 msec
Interference Detection Threshold	-107 dBm

B.4 Maximum Power Limits

It is important for 802.22 to study the interference potential that an 802.22 BS/CPE may create to a DTV receiver. For this study, some of the assumptions made are:

- 4 Watts CPE EIRP (Effective Isotropic Radiated Power) transmit power.
- For the CPE, antenna mounted outdoors at 10 m above ground (to maintain compliance with TV planning factors).
- A minimum separation distance of 10 m between the BS/CPE and DTV receiving antennas.
- In the case of co-channel and first adjacent channel operation, both antennas are assumed to be looking away from each other since the BS has to be located at a certain distance outside the DTV station Grade B contour. Thus, the backlobe rejection of both antennas can be relied upon.
- Main beam coupling will exist between the antennas for channels N±2 and beyond inside the Grade B contour, where N is the reference channel of operation.
- For channels N±2 and beyond, polarization discrimination is the only way to increase isolation based on the fact that the transmit antenna and the DTV receive antenna will be orthogonally polarized.
- The antenna polarization discrimination is assumed to be equal to the DTV antenna backlobe rejection.
- No signal depolarization is assumed between the two antennas.

Based on this, a preliminary conclusion is that a 802.22 BS needs to control the CPE such that its transmit power does not exceed the values shown in the last column of Table 2 (in the following tables, D/U stands for Desired to Undesired ratio). Hence, CPEs would have to operate according to the EIRP profile given in Figure 5. Similarly, Table 3 and Figure 6 present the corresponding results in the case of the BS. Please note that for all these calculations the 802.22 WG has assumed that the impact of the 802.22 waveform on TV broadcasting is similar to that of a DTV signal.

B.5 Out-of-Band Emission Mask

Based on the above study [25], 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 4 (for more information, please refer to [25]).

Table 2 – Maximum CPE power

ATSC A-74 DTV Rx Performance Guidelines	D/U at Grade B contour (-84 dBm) (dB)	CPE Tx and DTV Rx antenna discrimination (dB)	Polarization discrimination (dB)	Max. CPE transmit EIRP (dBW)
N (continuous)	23	30	0	-66.8
N (impulsive)	5	30	0	-48.8
N±1	-33	30	0	-10.8
N±2	-48.2	0	14	-11.5
N±3 Grade B	-56.5	0	14	-3.3
N±4	-64.7	0	14	4.9
N±5	-70.8	0	14	11.0
N±6 to N±13	-69.7	0	14	9.9
N±14 and N±15	-55.3	0	14	-4.5
RF front-end overload	-8	0	14	16.1

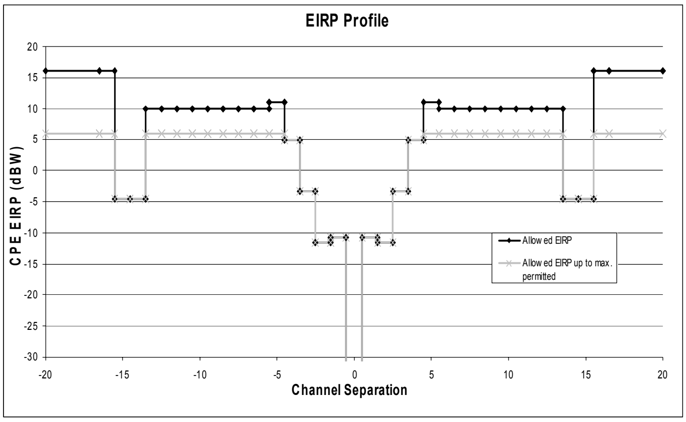

Figure 5 – CPE EIRP profile

Table 3 – Maximum BS power

ATSC A-74 DTV Rx Performance Guidelines	D/U at Grade B contour (-84 dBm) (dB)	BS Tx and DTV Rx antenna discrimination (dB)	Polarization discrimination (dB)	Max. BS transmit EIRP (dBW)
N (continuous)	23	14	0	-88.2
N (impulsive)	5	14	0	-64.8
N±1	-33	14	0	-26.8
N±2	-48.2	0	8	-17.5
N±3 Grade B	-56.5	0	8	-9.3
N±4	-64.7	0	8	-1.1
N±5	-70.8	0	8	5.0
N±6 to N±13	-69.7	0	8	3.9
N±14 and N±15	-55.3	0	8	-10.5
RF front-end overload	-8	0	8	10.1

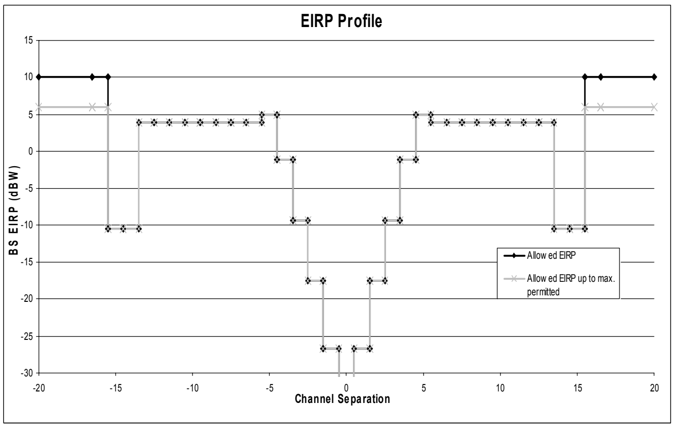

Figure 6 – BS EIRP profile

C. PLMRS/CMRS *Protection*

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.

Table 4 – 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

VI. 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, and conclude that 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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