Chapter 13
Cognitive Radios in Television White Spaces

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Abstract On February 17, 2009, the transition to digital television broadcasting in the US will finally be complete. All full power television stations will cease their analog (NTSC) broadcasts and switch to digital (ATSC) broadcasts. This transition will free up channels in the VHF and UHF frequencies that can potentially be used for other wireless services and applications. Among the various possible scenarios is one which is being pursued most actively: that of secondary usage of the TV spectrum by unlicensed devices. In order to enable such usage, “cognitive radios” i.e. radios that are aware of their spectral environment and can dynamically access available spectrum without causing interference to the primary user are essential. In this paper we describe recent developments in cognitive radios that make them suitable for use in the television bands.

Introduction

Historically, spectrum allocation for various services: radio, television, public safety, cellular etc. has been based on a command and control regulatory structure, i.e. spectrum is allocated by the FCC for a certain service with accompanying rules of usage and no other legal use of the spectrum is permitted [1]. For example, UHF and VHF bands from 54 to 806 MHz have been allocated for terrestrial television broadcasting with each television channel occupying a 6 MHz bandwidth. As television channels are allocated, in a particular way in a given geographical area many channels may be unused. However, current FCC rules do not allow any other service to utilize that spectrum for any other purpose. Historically, reasons for doing so were based on interference caused to adjacent and co-channel television receivers. However with improvements in technology, it is now possible to build “cognitive radios” [2–4] that are aware of their spectral environment and can adjust their transmissions so as not to create unwanted interference to incumbents. This advancement, coupled with digital television transition that will free up large swathes of spectrum, creates an unprecedented opportunity for the FCC to change rules and allow spectrum-sharing and thus open up a whole new area of applications. In this paper we describe how cognitive radios can be used to harness the promise of television white spaces.

D. Gerbarg (ed.), *Television Goes Digital*,

This chapter is organized as follows. The first section discusses the spectrum regulatory scenario and recent efforts to open up the white-spaces. Section “White Spaces: What, When, Why” introduces the topic of cognitive radios and the requirements that need to be met to satisfy goals of no interference. The next section describes a standardization effort being pursued in IEEE 802.22 for developing a wireless regional-area-network (WRAN) using cognitive radios in the television band and sensing algorithms that can be used to protect incumbents. The next section describes some lab and field tests that have been performed to test sensing algorithms. The final section concludes this paper.

White Spaces: What, When, Why

In the US, terrestrial television broadcasting is over Channels 2–69, covering frequencies 54–806 MHz as follows: Channels 2–4 (54–72 MHz), Channels 5–6 (76–88 MHz) Channels 7–13 (174–216 MHz), Channels 14–69 (470–806 Hz). Channel 37 is allocated nationwide for radio astronomy and medical telemetry. There are other services in the gaps in this frequency range such as land-mobile radio and FM radio [1]. With the introduction of digital television broadcasting beginning in 1997, the FCC allocated one channel for digital broadcasting to every existing licensed analog channel. Thus it is clear that “white spaces” or empty spaces in television frequencies have existed as long as television spectrum has been allocated and these were used fruitfully in the transition from analog to digital broadcasting. The first digital channel on the air was KITV in Honolulu in fall 1997 and initially the digital transition was supposed to have been completed by 2006. This digital transition is expected to finally be complete in 2009. On February 17, 2009, all analog television broadcasts will cease, which means that those channels will now become “white spaces”. Why, one may ask, should one consider these channels as available, when these white spaces have existed in the past as well and not been considered for alternate uses? The reason is that, unlike analog television, digital television signal does not suffer from interference when there is an adjacent signal in an adjacent frequency band and hence guard frequency bands are not required. Moreover, the total number of channels allocated for television broadcasting is the same nationwide, even though in rural and less-populated areas of the country most of these do not have actual broadcasts, creating almost an 80% vacancy rate [5].

There are at least two ways that one might use this spectrum: licensed or unlicensed. In order to license any spectrum and auction it to the highest bidder, there has to be nation-wide availability of that spectrum. However, television allocations vary across the nation and a certain channel would not necessarily be unused in all television markets across the nation. The unlicensed model would be more flexible but would require the use of cognitive technology that could dynamically detect available spectrum in a certain region. The unlicensed model in the ISM (900 MHz, 2.4 GHz) and U-NII (5 GHz) bands have proved enormously beneficial over the past decade in spawning applications such as Wi-Fi, Bluetooth, wireless internet etc. Hence, as far back as 2002, following the release of the report on improving spectrum efficiency by the Spectrum Policy Task Force [6], the FCC issued a Notice of Inquiry (NOI) regarding alternate uses of TV white spaces. Based on responses, a Notice of Proposed Rule Making (NPRM) was issued in May 2004 to allow unlicensed devices to utilize vacant television channels [7]. It was recognized that the superior propagation characteristics of these frequencies will enable a whole host of new applications that would require greater service range than that provided by existing Wi-Fi and cellular services. Two classes of devices were proposed: low-power personal/portable devices such as Wi-Fi, and higher power fixed access services that will cover a larger region with broadband access. Both kinds of devices would need some measures for ensuring protection to incumbent television stations in these bands, as well as wireless microphones that operate as licensed secondaries under Part 74 rules [8]. Following this, a first report and order and NPRM was issued in October 2006 inviting more comments on the proposal to allow unlicensed services in the television bands [9]. Channels 52–69 (698–806 MHz), which had no television broadcasts nationwide, were reallocated for other applications, with some parts of the spectrum being set aside for auction [10]. This auction concluded in March 2008 with bids totaling about US $19 billion. This value indicates the premium companies were willing to put on this spectrum.

Measurements and analysis made by different groups [11, 12] over the last few years indicate that even in the crowded metropolitan areas such as New York city, 18–30% of channels would be available as white spaces after the DTV transition. If we consider only UHF channels 21–51, that would be about ten channels, each 6 MHz wide which is 60 MHz of spectrum. This is equivalent to the amount of spectrum available in the 2.4 GHz band, where there are three non-overlapping channels, each 22 MHZ wide. In rural markets, the percentage of vacant channels could be as high as 70%. Hence it is clear that significant services can be provided with the white spaces.

Cognitive Radio

It is well accepted in academia, industry and regulatory bodies such as the FCC that due to the legacy command-and-control method of allocating spectrum, spectrum access appears to be more of a problem than spectrum scarcity [4–6]. In many frequency bands there are “spectrum holes” i.e. frequency bands that are allocated but unused in certain geographical areas and certain times. Cognitive radios have been proposed as a solution to this problem. Various definitions of cognitive radio exist in literature, but in its simplest form, a cognitive radio is one that that can adapt its transmission characteristics such as power, bandwidth, frequency of operation etc. in response to the RF environment it detects. This method is also sometimes referred to as listen-before-talk. A true cognitive radio is more than just a software-defined-radio: it needs to smartly sense spectrum availability and react accordingly, based on existing policies, FCC rules etc. for that frequency band. In a network of multiple such radios, other issues need to be addressed as well: network coordination of spectrum sensing, dynamic spectrum access and sharing, coexistence between multiple cognitive networks competing for the same spectrum, as well as quality-of-service (QoS) considerations. The October 2006 NPRM [9] mentioned three ways in which one could use the television bands for unlicensed services in a way that incumbents would be unaffected by interference:

1. Use of a database, based on location information of the unlicensed device that would inform unlicensed users of incumbents of the need for protection. The problem with this approach is that while it may work for television stations that are fixed in frequency and location, wireless microphones that are also using this band would not be protected. Moreover, the database needs to be up-to-date and accurate in terms of coverage of television stations, and every unlicensed device would need a GPS receiver to accurately determine location as well as have access to the database. This would preclude applications which rely on ad-hoc networking.
2. Use a control signal that is issued when a certain frequency is available for use by unlicensed devices in a service area. This control signal could be transmitted from a TV transmitter, or possibly from an unlicensed device itself. This would require separate infrastructure to generate and receive this control signal. The wireless beacon signal being developed by IEEE 802.22.1 [13] to protect wireless microphones falls under this category.
3. Use cognitive radios that employ signal processing methods to detect spectral occupancy by either television or wireless microphones.

Of the above, the cognitive radio option offers the most flexible solution to the problem, provided adequate protection parameters could be defined for sensing TV signals and wireless microphones. Cognitive radios would need no additional infrastructure like GPS to detect spectrum holes and could easily adapt to different policies in different regulatory domains. DARPA's Next generation (XG) program started in 2006 has successfully tested cognitive radio technologies such as spectrum sensing and dynamic spectrum access in the context of establishing ad-hoc wireless mesh networks [14].

Overview of IEEE 802.22

Spurred by the NPRM in May 2004, the IEEE 802.22 Working Group was started in November 2004 [13] as the first worldwide group with the charter of developing an air interface specification based on cognitive radios for unlicensed operation in the television bands. Television broadcasters, wireless microphone manufacturers, research labs and wireless companies worldwide came together to begin the task of drafting a physical layer (PHY), medium-access-control (MAC) protocols and, unique to IEEE 802.22, sensing mechanisms that would enable unlicensed operations in the television bands. The primary application being targeted here was wireless broadband access in rural and remote areas where broadband access via cable and DSL was either scarce or non-existent. In recent years the US has fallen behind both in terms of percentage of population with access to broadband connections as well as speed of these connections. According to the ITU, the US is 15th in the world in broadband penetration [15] and one of the reasons is the cost of providing services to populations in rural areas. Since IEEE 802.22 would be implemented in the unlicensed television bands, the cost of offering services would be a lot lower than, for example WI-MAX based on 802.16 which would offer services over licensed bands. Moreover, superior propagation characteristics of the television frequencies allow much larger service areas as compared to WI-MAX. Other application areas for IEEE 802.22 would be in single-family residential, multi-dwelling unit, small office/home office (SOHO) and campuses. Services offered would include data, voice as well as audio and video with appropriate QoS. While immediate applications are in the US, IEEE 802.22 is being designed as an international standard that would meet regulatory requirements elsewhere in the world and can be used in 6, 7 and 8 MHz channels.

Topology, Entities and Relationships

The IEEE 802.22 system specifies a fixed point-to-multipoint (P-MP) wireless air interface whereby a base station (BS) manages its own cell[1] and all associated Consumer Premise Equipments (CPEs), as depicted in Fig. 13.1. 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 order to ensure 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, 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, of regulating data transmission in a cell, an IEEE 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 various CPEs to perform distributed measurement activities. Based on the feedback received, the BS decides which steps, if any, are to be taken.

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[1] Here, we define an 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.

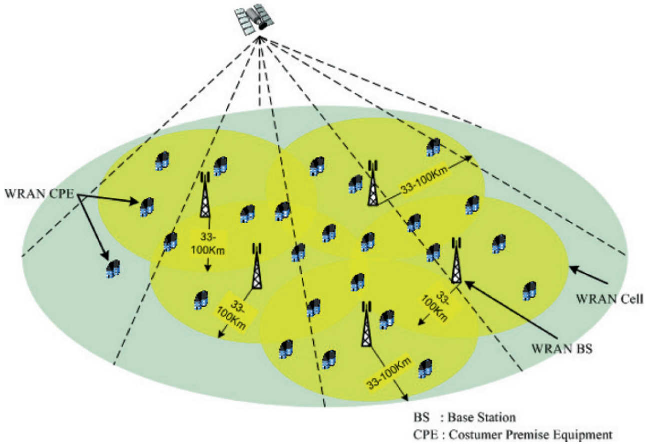

Fig. 13.1 Exemplary 802.22 deployment configuration

Service Capacity

The 802.22 system specifies spectral efficiencies in the range of 0.5–5 bit/(s/Hz). If we consider an average of 3 bits/s/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 are 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 Cable/DSL services.

Service Coverage

A distinctive feature of 802.22 WRAN as compared to existing IEEE 802 standards is the BS coverage range, can go up to 100 km if power is not an issue (current specified coverage range is 33 Km at 4 W CPE EIRP). As shown in Fig. 13.2, WRANs have much larger coverage range than today's networks, which is primarily due to its higher power and favorable propagation characteristics of TV frequency bands. This enhanced coverage range offers unique technical challenges as well as opportunities.

DFS Timing Requirements

The Dynamic Frequency Selection (DFS) timing parameters defines the requirements that the 802.22 standard must adhere to in order to effectively protect

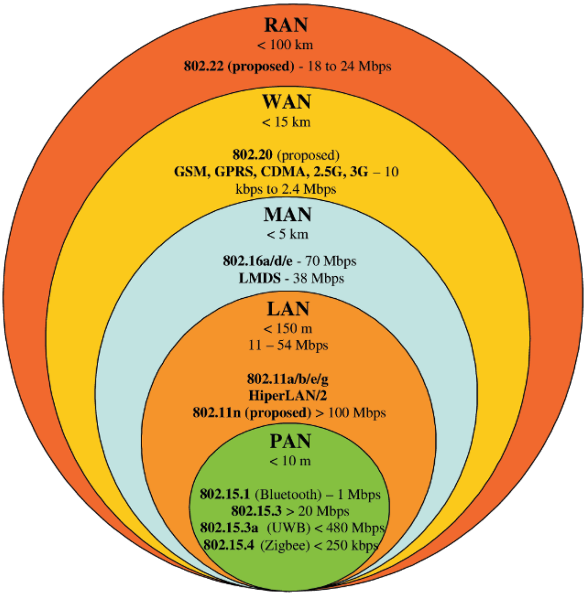

Fig. 13.2 802.22 wireless RAN classification as compared to other popular wireless standards

Table 13.1 Selected DFS parameters

Parameter	Value for wireless microphones	Value for TV broadcasting
Channel detection time	≤2 s	≤2 s
Channel move time (in-service monitoring)	2 s	2 s
Channel closing transmission time (aggregate transmission time)	100 ms	100 ms
Incumbent detection threshold	−107 dBm (over 200 KHz)	−116 dBm (over 6 MHz)
Probability of detection	90%	90%
Probability of false alarm	10%	10%

incumbents. These parameters serve as the basis for design of coexistence solutions, and are keys to understanding mechanisms presented later on.

Table 13.1 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 [16]. Two key parameters are Channel Detection Time (CDT) and 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 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 design schemes that cause minimal impact on the operation of the secondary network (e.g., QoS support).

The level of −116 dBm for sensing of digital television signals was chosen to be 32 dBm below the −84 dBm signal level required by an ATSC receiver to display a viewable digital signal. This was assumed to be enough clearance to account for the following losses:

1. *Antenna height*. The television antenna can be roof mounted and directional towards the television station whereas the unlicensed device will have an antenna lower in height.
2. Building penetration losses between external antenna and internal antenna.
3. Fading due to multi-path and shadow fading.

It is anticipated that with this threshold, hidden-node problems will be avoided. Similar argument hold true for the −107 dBm threshold for the detection of wireless microphones.

Spectrum Sensing Algorithms

The topic of spectrum sensing algorithms for detection of incumbent signals has recently been receiving a lot of attention [13, 17, 18]. Within IEEE 802.22, 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 via simulations using captured real-world ATSC signals. In this section we discuss a novel method based on detecting pilot energy and location that can be used with either one or multiple sensing dwells, and hence fits well with the MAC sensing architecture by allowing the QoS of secondary services to be preserved despite regularly scheduled sensing windows.

At the MAC layer, existing work has not addressed the implications of spectrum sensing and its impact on QoS to secondary users [19–21]. The IEEE 802.11 h [22] standard includes basic mechanisms to quiet channels, but does not deal with the protocol mechanisms to synchronize quiet periods of overlapping networks or guarantee seamless operation in the presence of incumbents. The two stage sensing, incumbent detection and notification, and synchronization schemes described in this section, however, are designed for operation in highly dynamic and dense networks and have been adopted in the current draft of the IEEE 802.22 standard [13]. Variations of these schemes are also used in the Cognitive MAC (C-MAC) protocol introduced in [23].

TV Sensing Algorithms

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 [24, 32]. As presented above, the principal metrics for characterizing a sensing algorithm are Probability of Detection (P_{D}) and Probability of False Alarm (P_{FA}). In our discussion throughout the rest of this paper, we use Probability of Missed Detection (P_{MD}) instead of P_{D}. Both P_{MD} and P_{FA} are functions of received signal-to-noise-ratio (SNR) and threshold. Ideally, one would like to have $P_{\mathrm{MD}} = 0.0$ and $P_{\mathrm{FA}} = 0.0$. However, in a practical situation this will be hard to achieve and it might be more reasonable to allow a relaxed P_{FA} value of 0.01–0.1 and a P_{MD} of 0.05–0.10. From the incumbent protection point of view, a higher P_{FA} is more tolerable than a higher P_{MD}.

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 the signal energy is indeed due to the presence of an incumbent. Since 802.22 will be implemented in TV bands, digital television incumbent signals could be ATSC (North America), DVB-T (Europe), or ISDB (Japan). In this paper we consider feature detection only for ATSC [25].

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

- *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 averaging over more than one field would be necessary for detection reliability, the PN 511 sequence based sensing requires longer detection times.
- *Pilot*. The ATSC signal uses an 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.
- *Segment-sync*. The ATSC data is sent in segments of 828 symbols. A 4-symbol segment sync sequence (+5, −5, −5, +5) is transmitted at the beginning of each data segment. Detection of the segment sync sequence can be used in a feature detector.
- *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 very low signal level (−116 dBm). 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.

The ATSC VSB signal has a pilot at the lower band-edge in a known location relative to the signal. For this description, we will assume that the signal to be sensed is a band-pass signal at a low-IF of 44 MHz with nominal pilot location at 46.69 MHz (assuming single stage conversion) and is sampled at 100 MHz. However, basic steps can be implemented with suitable modifications for any IF and sampling rate. Essential features of the proposed method are as follows:

1. Downshift signal to baseband by multiplying it by frequency, $f_c = 46.69$ MHz. Hence, if $x(t)$ is the real, band-pass signal at low-IF, then $y(t) = x(t)\mathrm{e}^{-j2f_c t}$ is the complex signal at baseband.
2. Filter $y(t)$ with a low-pass filter of bandwidth e.g. 40 kHz (+/–20 kHZ). The filter bandwidth should be large enough to accommodate any foreseen frequency offsets.
3. Down-sample the filtered signal from 100 MHz to 53.8 kHz, to form the signal $z(t)$.
4. Take FFT of the down-sampled signal $z(t)$. Depending on the sensing period, length of the FFT will vary. For example a 1 ms sensing window will allow a 32-point FFT while a 5 ms window will allow a 256-point FFT.
5. Determine maximum value, and location, of the FFT output squared.

Signal detection can now be done either by setting a threshold on the maximum value, or by observing the location of the peak over successive intervals. Instead of the FFT, other well-known spectrum estimation methods, such as the Welch periodogram can also be used in step (4) above.

The basic method described above can be adapted to a variety of scenarios as described below:

1. Multiple fine sensing windows, e.g. 5 ms sensing dwells every 100 ms. The 256-point FFT outputs squared from each sensing window can be averaged to form a composite statistic as well as the location information from each measurement can be used to derive a detection metric.
2. If a single long sensing window, e.g. 10 ms is available, a 512-point FFT or periodogram can be used to obtain better detection performance.

Parameters of the sensor can be chosen depending on desired sensing time, complexity, probability of missed detection and probability of false alarm. Detection based on location is robust against noise uncertainty since the position of the pilot can be pinpointed with accuracy even if amplitude is low due to fading. Various combining schemes can be developed for both pilot-energy and pilot-location sensing.

1. *Pilot-energy sensing*. For a single sensing window, the FFT output is simply squared and maximum value is compared to a threshold. For multiple sensing dwells, there are two possibilities (a) decision from each dwell is saved and a "hard-decision" rule is applied to declare "signal detect" if the number of positives is greater than a certain number, or (b) the square of the FFT output of all dwells is averaged and the maximum level is compared to a threshold. Choice of threshold in all cases is determined by the desired probability of false alarm.

2. *Pilot-location sensing*. This is usually used for multiple dwells. Location of the maximum value of the FFT output squared is compared between multiple dwells. If the distance is less than a prescribed threshold, the signal is declared detected. Another method is to count the number of times a particular frequency bin is chosen as the location of the maximum: if greater than a certain threshold, the signal is declared detected.

Wireless Microphone Sensing Algorithms

Wireless microphones belong to the class of licensed secondary users of the TV band. Operation of these devices is regulated by the FCC under Part 74 rules [8]. The bandwidth of wireless microphone signals is less than 200 kHz with the center frequency at an integer multiple of 25 kHz starting at the lower edge of the TV band. Maximum transmit power is limited to 50 mW in VHF band and 250 mW in UHF band. There is no standard specification for generation of wireless signals. Therefore, different manufacturers use their own propriety technology to generate these signals, though analog Frequency Modulation (FM) seems to be more prevalent.

To design and verify wireless microphone signal detection algorithms, we have used procedures described in [26] to model wireless microphone signals. The reference describes three profiles viz. silent, soft speaker and loud speaker, each generated with a unique combination of tone and deviation parameters.

The challenge with wireless microphone signal detection is that these signals do not have a unique identifying feature. In addition, multiple wireless microphone signals could be present in a single TV channel and frequency separation among different wireless microphone signals is also not clearly defined. Since wireless microphone signals do not have a unique feature, detection methods have to rely on signal energy in the band of interest to detect/identify wireless microphone signals.

The proposed basic wireless microphone signal detection algorithm relies on detection of signal energy in frequency domain. In the absence of spurious tones, wireless microphone signals will manifest as a group of tones that could span 200 kHz range in frequency domain. By sufficiently averaging across time, wireless microphone signals can stand out even at low signal levels.

Since we use the DTV tuner to tune to the channel of interest, the front-end processing in this case will be similar to that described in section "Lab Test Results". Assuming that the IF signal is located at 44 MHz and sampling rate is 100 MHz, the detection steps are:

1. Downshift signal to baseband by multiplying it by frequency, $f_c = 44$ MHz. Hence, if $x(t)$ is the real, band-pass signal at low-IF, then $y(t) = x(t)e^{-j2f_c t}$ is the complex signal at baseband.
2. Filter down-shifted signal $y(t)$ with a low-pass filter of bandwidth 7.5 MHz.
3. Down-sample filtered signal from 100 to 7.5 MHz, to form signal $z(t)$.
4. Take 2048 point FFT of down-sampled signal $z(t)$ to form $Z_n(k)$.

5. Average FFT output squared across multiple FFT blocks to improve reliability of detection. $P(k) = \sum_{n=1}^{N} Z_n^{\,2}(k)$ where $k = 1$–2,048. Parameter N is determined by the sensing time.
6. Determine maximum value of $P(k)$ and compare it against a threshold.

Threshold can be varied to achieve required PMD. The drawback, however, is that it impacts the PFA.

As it relies on energy detection, the above method will trigger on TV signals as well as spurious tones. In the detection flow, wireless microphone detection is enabled only when the sensor does not detect TV signals in that channel. More advanced algorithms are required to avoid false detections due to spurious tones. These algorithms will be implemented in subsequent versions of the sensor prototype.

Spectrum Sensing at the MAC

In order to maximize reliability and efficiency of spectrum sensing algorithms described in the previous section, and meet CDT requirement for detecting presence of incumbents, the network can schedule network-wide quiet periods for sensing. During these quiet periods, all network traffic is suspended and stations can perform sensing more reliably. In 802.22, for example, the base station (BS) is responsible for managing and scheduling these quiet periods.

To meet these requirements while satisfying the QoS requirements of the secondary network, initially we propose a two stage sensing (TSS) management mechanism. The TSS mechanism enables the network to dynamically adjust duration and frequency of quiet periods in order to protect the incumbents. In the first stage, multiple short quiet periods are scheduled to attempt to assess the state of the sensed radio spectrum without causing impact to secondary network performance. In the second stage, more time consuming quiet periods can be scheduled in case target spectrum needs to be sensed for a longer period of time.

In addition to the TSS which provides timely detection mechanism, we also introduce a notification mechanism through which devices (e.g., consumer premise equipments (CPEs) in IEEE 802.22 terminology) can report results of the sensing process back to the BS. To ensure effective use of quiet periods to improve sensing reliability, nearby networks must also synchronize their quiet periods.

The TSS, notification, and synchronization mechanisms proposed here have been incorporated into current 802.22 draft MAC standard.

Quiet Periods Management and Scheduling

Quiet period management mechanism defined by the TSS mechanism has different time scales, namely, a short (or fast) sensing period that can be scheduled regularly with minimal impact on the users' QoS, and a long (or fine) sensing period that can be used to detect a specific type of incumbent signal. Short and long sensing periods correspond to first and second stage of the TSS, respectively. The TSS presented here is a more general and enhanced version of the MAC sensing scheme introduced in [23,27]. Within IEEE 802.22, the first stage of TSS is termed as intra-frame sensing, while the second stage is called inter-frame sensing.

- *Intra-frame sensing*. This stage uses short quiet periods of less than one frame size. The 802.22 MAC allows only one intra-frame quiet period per frame and it must be scheduled always at the end of the frame. This is important to ensure nearby 802.22 cells can synchronize their quiet periods. Based on results of spectrum sensing done over a number of intra-frame quiet periods, the BS decides whether to schedule an inter-frame quiet period over multiple frames in order to perform more detailed sensing.
- *Inter-frame sensing*. This stage is defined as taking longer than one frame size and is used when the sensing algorithm requires longer sensing durations. Since a long quiet period may degrade the performance for QoS sensitive traffic, allocation and duration of inter-frame sensing stage should be dynamically adjustable by the BS in a way to minimize impact on users' QoS.

The TSS mechanism in IEEE 802.22 is illustrated in Fig. 13.3. A first stage involving several intra-frame sensing periods can be followed by a longer inter-frame sensing period, if needed to detect the specific signature of a signal detected during the first stage. Considering the fact that incumbents in TV bands do not come on the air frequently, only the intra-frame sensing stage will be used most of the time; so QoS is not compromised. The longer inter-frame sensing stage will step in only when required.

In 802.22, the BS broadcasts schedule and durations of the intra-frame and inter-frame quiet periods in the superframe control header (SCH), which is transmitted at the beginning of every superframe.[2] This method incurs minimal overhead and allows scheduling of quiet periods well in advance, which enables tight synchronization

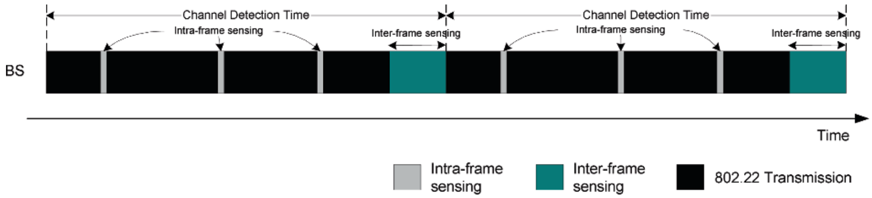

Fig. 13.3 TSS mechanism

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[2] The 802.22 MAC is based on a periodic superframe structure. A superframe contains ten frames of 10 ms each for a total duration of 160 ms.

of quiet periods amongst neighboring systems. The BS can also schedule quiet periods on an on-demand basis using management frames specified in the 802.22 draft [28].

One of the major benefits of the TSS mechanism is allowing the CR network to meet stringent QoS requirements of real time applications such as voice over IP, while ensuring required protection to incumbents.

Incumbent Detection and Notification

Once an incumbent is detected on an operating channel, say channel N, or in an adjacent channel (e.g. $N + 1$ and $N - 1$), the secondary system must vacate the channel, while satisfying DFS requirements (CMT and CCTT) described in Table 13.1.

In a cell-based system, like 802.22, detection of an incumbent must be notified in a timely fashion to the BS, so it can take proper action to protect them.[3] 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 (Urgent Coexistence Situation) slots available within the MAC frame. Since allocation of the UCS window is known to all CPEs, it can be used even when CPEs are under interference. As far as access method goes, both contention-based and CDMA can be used during the UCS window. Alternatively, the BS can poll CPEs to obtain feedback. In this case, the polled CPE can send a notification back to the BS, or else, if no response is received from CPEs, the BS can take further actions to assess the situation such as scheduling additional quiet periods or even immediately switching channels.

Synchronization of Quiet Periods

Self-coexistence amongst multiple overlapping CR networks is a key feature not only to efficiently share available spectrum, but also to ensure required protection to incumbents. For instance, multiple secondary networks may operate in the same geographical region, and in case overlapping, these networks share the same channel; it is paramount that they are able to synchronize their quiet periods, since transmissions during sensing periods could increase the probability of false detection considerably.

In the case of the 802.22 standard, it provides a comprehensive coexistence framework to enable overlapping networks to exchange information in order to

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[3] In 802.22 this is referred to as incumbent detection recovery and is performed through the Incumbent Detection Recovery Protocol (IDRP). IDRP maintains a priority list of backup channels that can be used to quickly re-establish communication in the event of an incumbent appearance.

share the spectrum and also synchronize their quiet periods. At the core of this framework is the Coexistence Beacon Protocol (CBP), which is based on the transmission of CBP frames (or packets) by CPE and/or BSs. The CBP packets are transmitted during coexistence windows that can be open by the BS at the end of a frame. During these windows, CPEs in overlapping areas can send CBP packets. These packets may be received by neighboring BSs or by CPEs in neighboring cells, which forward them to their corresponding BSs. The CBP packets carry information needed for establishing time synchronization amongst neighboring cells, as well as schedule of quiet periods. For the purpose of synchronization, CBP packets carry relative timestamp information about their networks. Mathematically speaking, when BSi, responsible for network i, receives a CBP packet from network j, controlled by BSj, it shall only adjust the start time of its superframe if, and only if, the following convergence rule is satisfied:

$$\left|\begin{array}{l}(\text{Frame\_Number}_j\text{-Frame\_Number}_i)\times\text{FDC}+\\ \text{Transmission\_Offset-Reception\_Offset}\end{array}\right| \le \frac{\text{FS}\times\text{FDC}+\text{GuardBand}\times\text{SymbolSize}}{2},$$

where Frame_Number is the frame number within the superframe, FDC is the frame duration code (equal to 10 ms), FS is the number of frames per superframe (equal to 16), GuardBand is a few OFDM symbols long to account for propagation delays, SymbolSize is the size of an OFDM symbol, and Reception_Offset and Transmission_Offset are the index of symbol number within the frame where the beacon was received/transmitted, respectively. By this mechanism, it has been shown [29] that co-channel networks are able to synchronize their quiet periods resulting in the arrangement depicted in Fig. 13.4. This way, sensing can be made with high reliability.

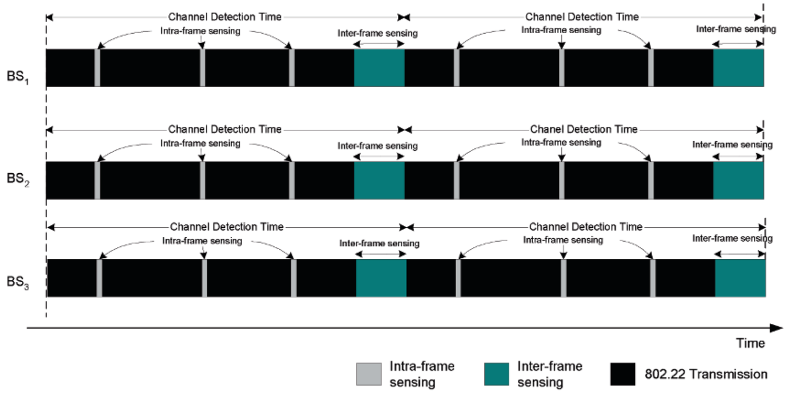

Fig. 13.4 Synchronization of quiet periods

Lab and Field Test Results

A prototype was built to test the spectrum sensing algorithms described above. This prototype used a consumer grade tuner for the RF front-end, followed by signal processing. The performance of this sensing prototype was evaluated in the lab using generated signals and field captured signals and in the field using over-the-air (OTA) signals.

Lab Test Results

We used an ATSC DTV signal generator to generate a clean (i.e. without any impairment) DTV RF signal. A RAM-based Arbitrary Waveform Generator (AWG) was used to regenerate RF signals from the low-IF field captured signals referred to in [30]. The RF signal was attenuated to the desired signal level by an external attenuator and then fed to the antenna input of the DTV tuner. Similar tests were performed by the FCC which are presented in [31], under the label "Prototype B". The sensitivity tests in Fig. 13.5 show a 100% detection capability at signal levels down to −115 dBm. The FCC recently released a report [33] with the results from the latest round of lab and field testing, showing that a sensing threshold of -123 dBm can be achieved with 100% detection capability.

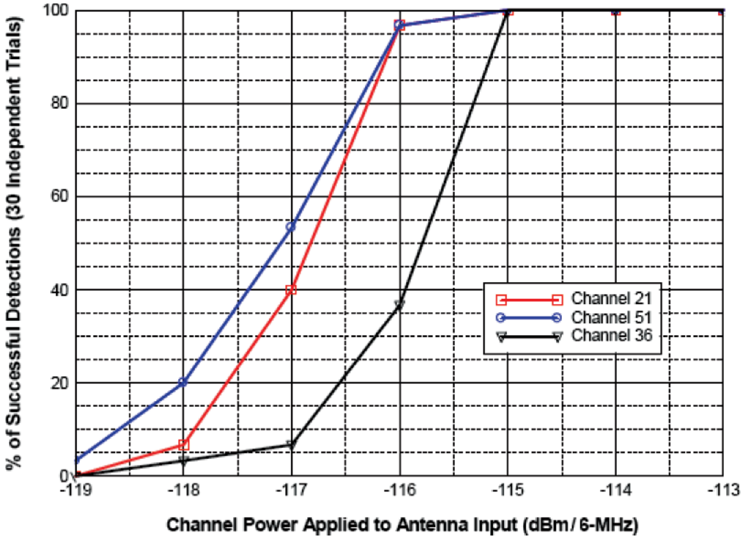

Fig. 13.5 Probability of successful detections vs. input channel power for three different UHF TV channels

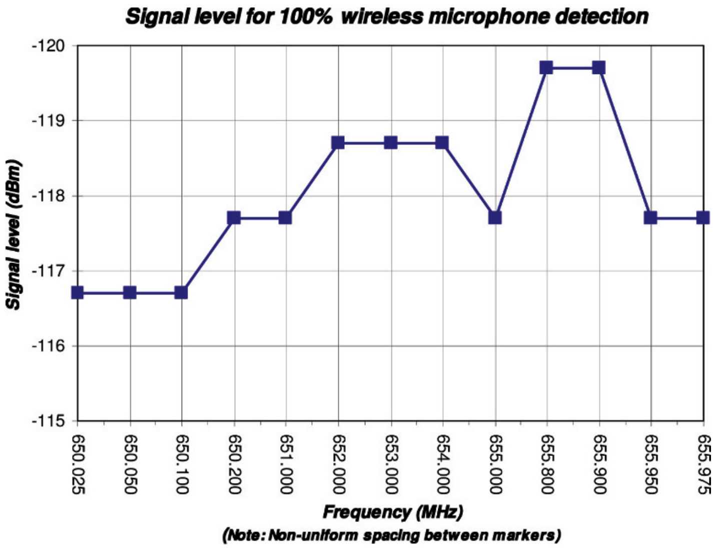

Fig. 13.6 Wireless microphone detection with a lab generated signal

To generate clean wireless microphone signals in the Lab we used an RF signal generator with FM capability. Different profiles were generated by adjusting the frequency deviation and tone frequency. The carrier frequency of the FM signal was placed at different frequencies in a 6 MHz UHF channel to measure performance variation within a TV channel. The input signal level to the tuner is controlled by an external attenuator. Figure 13.6 shows the detection capability of the sensing prototype in the presence of a wireless microphone signal. For this particular test, the wireless microphone signal was generated using a 1,000 Hz tone and 24 kHz frequency deviation. In this plot, Y-axis represents lowest signal level for which the sensor has 100% detection (averaged over 30 independent scans) and X-axis represents carrier frequency of input signal. The probability of false alarm was less than 0.1%.

Field Test Results

The sensing prototype was field tested in the New York metropolitan area in 18 sites, mostly residential structures such as single-family homes and apartments. While measurements were made on channels 21–51, we present results for Channel 22. The reason for this is that most of the sites tested were on or beyond the edge of coverage of Channel 22. Figure 13.7 shows coverage area (shaded portion) and sites where the sensor prototype was tested. Since power measurements at low signal levels such as −116 dBm are not very accurate, no attempt was made to actually measure power in the field.

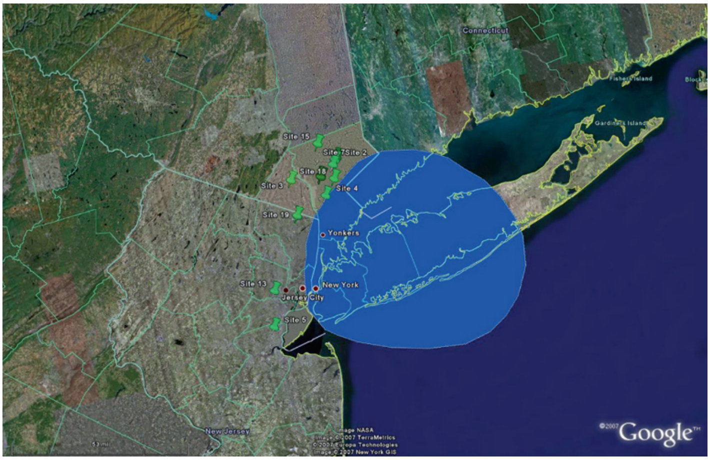

Fig. 13.7 Map of New York metropolitan area locations used for OTA sensing

Table 13.2 Summary of OTA channel 22 detection at different sites in New York metropolitan area

Site #	Site	Latitude	Longitude	Successful detections	Total attempts
1	Briarcliff Manor, NY	Lat: 41 09 05.59 N	Long: 73 51 16.14W	18	18
2	Chappaqua, NY	Lat: 41 12 16.32 N	Long: 73 45 29.43W	16	16
3	New City, NY	Lat: 41 09 41.24 N	Long: 74 01 37.56 W	17	17
4	Tarrytown, NY	Lat: 41 03 50.98 N	Long: 73 5115.16W	22	22
5	Edison, NJ	Lat: 40 33 51.74 N	Long: 74 18 17.9W	8	8
6	Mt. Kisco, NY	Lat: 41 12 50.91N	Long: 73 44 36.07W	12	12
7	Chappaqua, NY	Lat: 41 11 11.39N	Long: 73 46 30.98W	10	12
8	Ossining, NY	Lat: 41° 8'50.88"N	Long: 73°51'27.79"W	18	18
9	Ossining, NY	Lat: 41° 8'46.59"N	Long: 73°51'27.99"W	16	16
10	Ossining, NY	Lat: 41° 8'50.88"N	Long: 73°51'27.79"W	15	15
11	Ossining, NY	Lat: 41 09 10.07 N	Long: 73 51 3066W	14	14
12	Briarcliff Manor, NY	Lat: 41 09 05.59 N	Long: 73 51 16.14W	6	6
13	Maplewood, NJ	Lat: 40 42 55 N	Long: 74 15 28W	10	10
14	NYC Apt. 8th floor, NY	Lat: 40 46 54.24 N	Long: 73 58 59.54W	11	11
15	Yorktownheights, NY	Lat: 41 17 17.78 N	Long: 73 49 58.26 W	8	8
16	Brookefield, CT	Lat: 41 29 55.19 N	Long: 73 23 55.29 W	12	12
17	Danbury, CT	Lat: 41 26 22.12 N	Long: 73 30 45.21	12	12
18	Pleasantville, NY	Lat: 41 07 35.87 N	Long: 73 47 12.02 W	8	8
19	Hillsdale, NJ	Lat: 41 00 28.22 N	Long: 74 02 17.99 W	16	16

At each test site, multiple measurements were made in various rooms and locations within rooms. No attempts were made to optimize position of the sensing antenna, which was a simple whip-antenna. Where possible, measurements were made in basements as well.

Table 13.2 shows the sensing results for the 18 sites. We see that out of a total of 235 measurements, the sensor missed detection of Channel 22 on only two measurements for a detection rate of 99%. The missed detections were in Site 7, which is outside the Channel 22 contour and measurements were in the basement. Other measurements in that house were able to sense Channel 22.

The latest field tests are described in [33] and demonstrate conclusively that 100% of television receivers that are able to receive viewable pictures will be protected by sensing, while only 84% will be protected by an approach using databases alone.

Conclusions

While research into cognitive radios has been ongoing for a few years and some military applications do exist, the first commercial applications have yet to be widely deployed. The television white spaces offer an unprecedented opportunity to develop this new technology and thus provide new wireless applications and services to consumers. The past couple of years have seen advancements in sensing technology required to make cognitive radios a reality, using low-cost components. Standardization efforts have already begun within IEEE and other industry groups. However, as of now, the FCC has yet to release the final rule and order that would make cognitive radios in television white spaces a reality. Hopefully, this valuable slice of the spectrum will not be allowed to remain unused, while other parts of the spectrum get increasingly crowded with demand for more wireless service. The next few years certainly promise to be interesting ones as cognitive radio technology and new regulations evolve to create whole new applications in television white spaces.

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