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COEXISTENCE CHALLENGES FOR HETEROGENEOUS COGNITIVE WIRELESS NETWORKS IN TV WHITE SPACES

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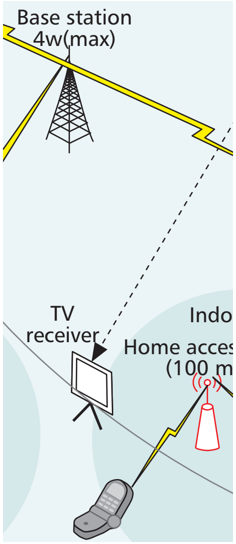

The authors discuss the current regulatory scenario, emerging standards for cognitive wireless networks targeting the TVWS, and possible coexistence scenarios and associated challenges.

ABSTRACT

In order to improve utilization of TV spectrum, regulatory bodies around the world have been developing rules to allow operation by unlicensed users in these bands provided that interference to incumbent broadcasters is avoided. Thus, new services may opportunistically use temporarily unoccupied TV channels, known as television white space. This has motivated several standardization efforts such as IEEE 802.22, 802.11af, 802.19 TG1, and ECMA 392 to further cognitive networking. Specifically, multiple collocated secondary networks are expected to use TVWS, each with distinct requirements (bandwidth, transmission power, different system architectures, and device types) that must all comply with regulatory requirements to protect incumbents. Heterogeneous coexistence in the TVWS is thus expected to be an important research challenge. This article introduces the current regulatory scenario, emerging standards for cognitive wireless networks targeting the TVWS, and discusses possible coexistence scenarios and associated challenges. Furthermore, the article casts an eye on future considerations for these upcoming standards in support of spectrum sharing opportunities as a function of network architecture evolution.

INTRODUCTION

The TV broadcasting spectrum is seen as one of the first opportunities to adopt and implement innovative and more efficient dynamic spectrum access (DSA) models supported by cognitive radio (CR) [1] technology. With the transition to digital TV (e.g., June 2009 in the United States), a considerable amount of vacant spectrum has been generated in the TV spectrum. This group of non-contiguous vacant channels is collectively known as TV white space (TVWS) [2]. Regulatory efforts are currently ongoing in many countries to enable secondary access to TVWS, provided that harmful interference to incumbent services is avoided. Some examples include Federal Communications Commission (FCC) regulations [2] in the United States, initiatives by the Office of Communications (OFCOM) in the United Kingdom, and the Electronic Communications Committee (ECC) in Europe. TVWS availability is time- and location-dependent, and it may include the following portions of the radio spectrum: 54–72 MHz, 76–88 MHz, 174–216 MHz, and 470–806 MHz.

The prospects of new spectrum availability subject to TVWS regulations have triggered development of new wireless standards. Standardization activities targeting TVWS include IEEE 802.22 [3] for Wireless Regional Area Networks (WRAN), European Computer Manufacturers Association (ECMA) 392 [4] for personal/portable devices in TVWS, and, most recently started, the IEEE 802.11af and 802.19.1 Task Groups. As a result, one can envision coexistence scenarios involving heterogeneous secondary systems and incumbents. An example is shown in Fig. 1 where a TV broadcasting station and a low-power wireless microphone serve as incumbents. Secondary systems could include 802.22 WRANs [3] consisting of a base station (BS), fixed customer premises equipment (CPE) and mobile devices, as well as Wi-Fi home networks and hot spots operating in the TVWS. A number of scenarios involving low-power devices for multimedia and Internet access in home and outdoor settings could also be envisioned.

Heterogeneity and coexistence are characteristics of any operating spectrum and are not unique to TVWS. However, the dynamic nature of TVWS coupled with incumbent protection requirements poses new and subtle challenges that should be considered in this context. The objective of this article is to provide an overview of heterogeneous coexistence issues in the TVWS and describe upcoming regulations and wireless standards that provide a framework to facilitate such coexistence. The coexistence issues can be broadly classified into three categories: *spectrum availability detection*, *interference mitigation*, and *spectrum sharing*. The outstanding issues encompass regulation requirements (e.g., spectrum

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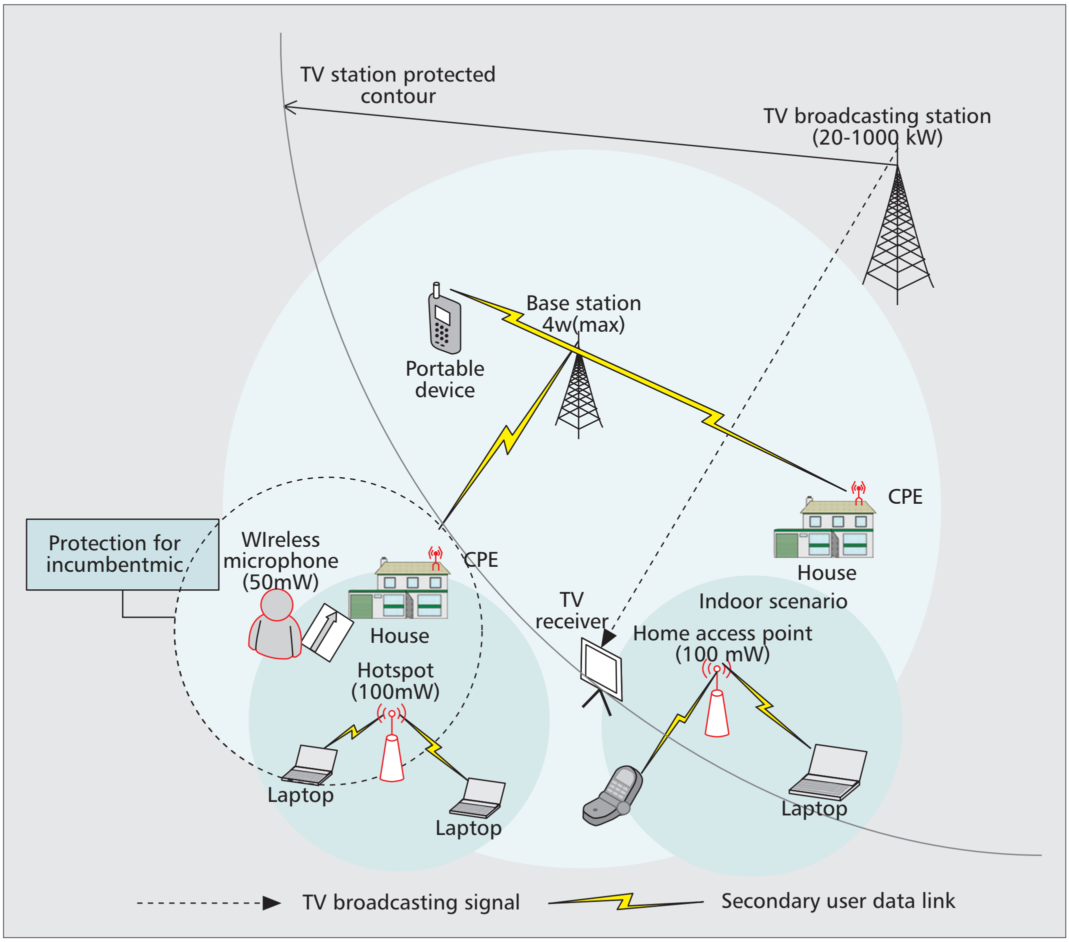

Figure 1. *A typical heterogeneous coexistence scenario with various networks and user applications with transmission power limits.*

Mode I devices must be located within the receiving range of a fixed or Mode II device in order to receive an enabling signal once every 60 sec, otherwise they must cease operation and must re-initiate contact with the enabling device.

sensing thresholds) and heterogeneities in operational characteristics of the secondary systems, including network architecture (e.g., master-slave, peer-to-peer, mesh), device category (fixed vs. personal/portable), transmission power limits, operational bandwidth, modulation/coding schemes, and medium access control (MAC) schemes (e.g., reservation or contention-based access). Furthermore, we look at ideas proposed in standards for TVWS and highlight open questions central to heterogeneous coexistence.

OVERVIEW OF REGULATIONS AND COGNITIVE RADIO STANDARDS

Global regulatory efforts to achieve enhanced spectrum utilization include FCC regulations in the United States and similar initiatives in Europe and the United Kingdom. The FCC recently published the final rules [2] that regulate unlicensed secondary operation in TVWS (Table 1), where the devices are divided into two categories: fixed and personal/portable. Fixed devices can transmit up to 4 W equivalent isotropically radiated power (EIRP) with a power spectral density (PSD) of 16.7 mW/100 kHz, and they must have geolocation capability and a means to retrieve a list of available channels from an authorized database. The fixed devices are restricted of operating in adjacent channels of active TV broadcasting channels. Personal/portable devices are allowed a maximum EIRP of 100 mW (with PSD of 1.67 mW/100 kHz) on channels non-adjacent to TV broadcast services and 40 mW (with PSD of 0.7 mW/100 kHz) on channels adjacent to an active TV broadcasting channel. Personal/portable devices are classified into two modes: Mode I and Mode II. Similar to fixed devices, Mode II devices must possess geolocation and database access in order to obtain a list of available channels. In contrast, Mode I devices are not required to have geolocation and database access, but they must obtain a list of available channels from a fixed or Mode II device. Therefore, Mode I devices must be located within the receiving range of a fixed or Mode II device in order to receive an enabling signal once every 60 s; otherwise, they must cease operation and re-initiate contact with the enabling device. Additional restrictions on channel operation are applicable to both fixed and portable devices as shown in Table 1. Fixed devices may operate in channels 2 to 51, excluding channels 3, 4, and 37.[1] Moreover, some of the channels between 14 and 20 are used for land mobile operations (i.e., public safety and commercial mobile radio services) in major metropolitan areas, and must be avoided by TVWS devices in such areas. Person-

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[1] *The FCC is prohibiting fixed operation in channels 3 and 4 to prevent direct pickup when TVs are connected to VCRs, DVRs, and set-top boxes using these channels. Channel 37 is reserved for radio astronomy and wireless medical telemetry systems (WMTS).*

Device types/ capability		Allowed TV channels	Max EIRP	Incumbent protection requirements	Allowed on adjacent channels
Fixed		Ch 2–51 (except Ch 3, 4 and 37)	4 W	Geolocation/database	No
Personal/ portable	Mode I	Ch 21–51 (except Ch 37)	100 mW	Enabling signal from Mode II or fixed device.	Yes (< 40 mW EIRP)
	Mode II		100 mW	Geolocation/database	Yes (<40 mW EIRP)

Table 1. *Overview of the FCC rules for TVWS.*

al/portable devices are only allowed in channels 21 to 51 (excluding channel 37). The main expectation is that fixed devices will most likely be used in rural areas, whereas portable devices may be highly used in metropolitan areas. The idea behind this channel allocation is to avoid the risk of interference with primary services, especially in high population density areas.

The FCC rules also define sensing requirements, although fixed and Mode I and II devices are not required to implement sensing capabilities. Sensing only devices are enabled according to the FCC rules [2], but are subject to special FCC tests in order to obtain certification. The FCC requires [2] that digital TV (DTV) and wireless microphone signals must be detected at a received signal level of –114 dBm. For the first use of a channel by TVWS devices, it must be sensed over 30 s before determining its availability. Once occupied, sensing must be performed at least once every 60 s. If an incumbent is detected, the channel must be vacated within 2 s. These sensing rules require adoption of CR techniques to deal with the fundamental challenges related to coexistence with incumbents as well as with other secondary systems, as discussed later. Although sensing is not required by the most recent FCC rules, most wireless standards being developed for operation in the TVWS do include features to support sensing, which can provide additional tools for optimization of the system performance and protection of incumbents.

STANDARDS FOR COGNITIVE WIRELESS NETWORKS

The IEEE 802.22 Working Group (WG) developed a physical (PHY) and MAC layer specification for WRANs operation in TVWS. The primary application is geared toward *fixed broadband access*. The 802.22 standard adopted an orthogonal frequency-division multiple access (OFDMA) PHY and a centralized, connection-oriented MAC, where a BS controls the resource allocations within its cell. The MAC layer is expected to provide user data rates of 1.5 Mb/s in the downlink and 384 kb/s in the uplink per 6 MHz TV channel [3]. The 802.22 PHY and MAC layers include new CR features to protect incumbents and achieve efficient spectrum utilization such as reliable incumbent detection combining spectrum sensing, geolocation, and database, frequency agility, and self-coexistence mechanisms.

Different initiatives have also been proposed within the IEEE WGs 802.11, 802.22, and 802.19 targeting personal/portable device use cases that are considered to be future market drivers. The Task Group 802.11af (TGaf), approved in December 2009, is expected to define a new PHY and associated MAC layer modifications for TVWS operation. The 802.22 standard has also expanded its scope to allow portable CPEs to connect to the BSs, when they are in close proximity to the BS. However, the 802.22 standard does not cover fully mobile CPE at vehicular speeds. Unlike 802.22 and 802.11, 802.19 TG1 will not develop a new air-interface specification, but will focus on recommendations for coexistence protocols and policies across platforms to achieve efficient spectrum utilization. Additionally, the recently released Ecma 392 standard [4] specifies PHY and MAC layers for operation in TVWS aimed at multimedia distribution and internet access for personal/portable devices. Other standardization efforts related to CR technology are ongoing in the IEEE SCC 41 group [5].

Other than ECMA 392 and IEEE 802.22, the 802.11af and 802.19 TG1 groups are in early stages, and specific technical solutions have not yet been finalized. However, some of the basic CR concepts, such as spectrum sensing and geolocation mechanisms, incumbent database access, and dynamic frequency selection will most likely be adapted to the specific requirements of each standard.

HETEROGENEOUS COEXISTENCE CHALLENGES AND CONSIDERATIONS IN TVWS

Once new standards and compatible products are developed, one can envision scenarios where multiple TVWS networks, hereafter referred to as cognitive wireless networks (CWNs), will likely overlap with each other, creating a need for coexistence mechanisms. A generic heterogeneous scenario is illustrated in Fig. 1, where multiradio devices take advantage of the TVWS to achieve higher capacity and/or larger transmission ranges. In one typical case, a fixed broadband network (e.g., 802.22) could provide wireless backhaul to homes, which use Wi-Fi (e.g., 802.11af) or ECMA 392 for in-home coverage. Alternately, 802.11af or ECMA 392 devices could form a neighborhood mesh network. Figure 2 illustrates the main challenges in heterogeneous CWNs with implications for all layers of the protocol stack. The issues, typically related to PHY and MAC layers, can be grouped in

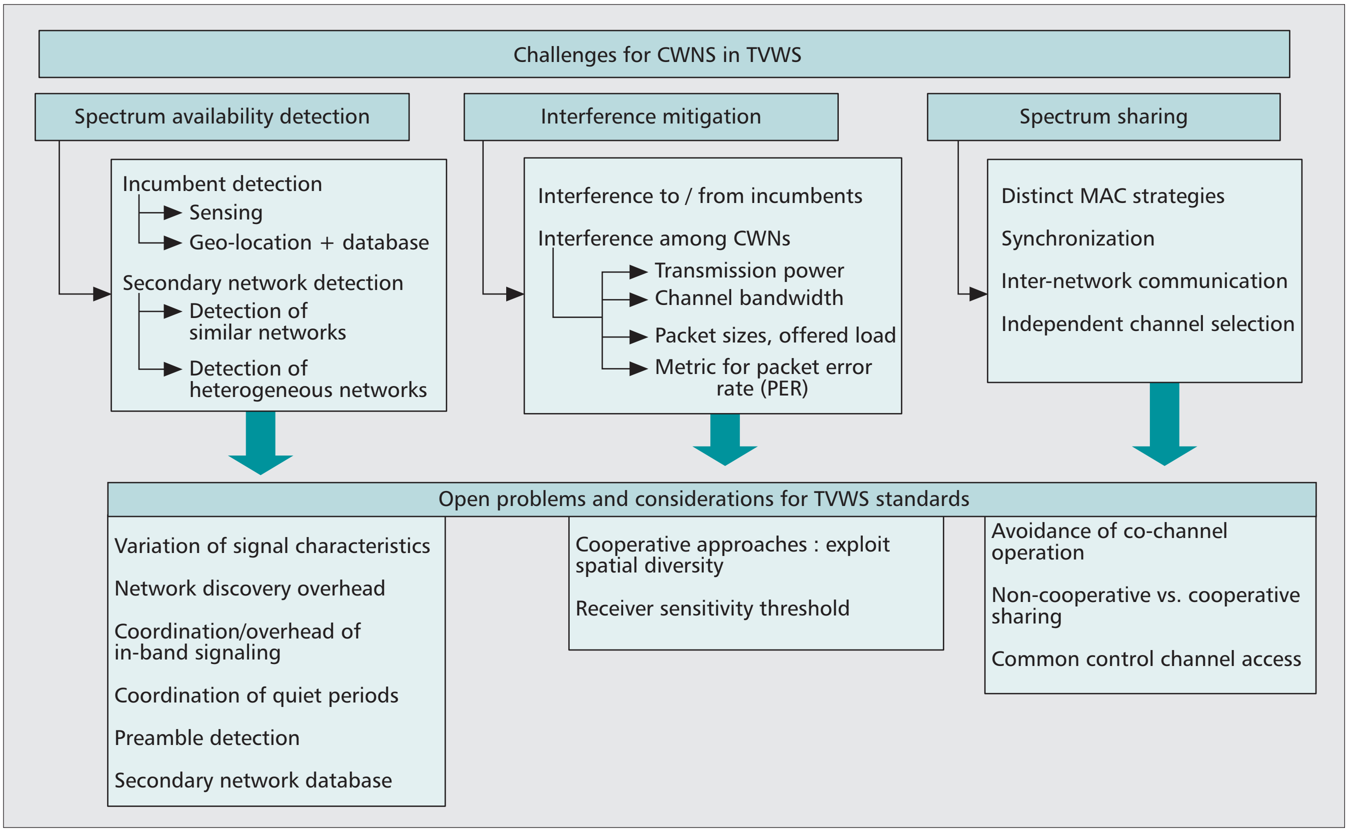

Figure 2. *Coexistence issues, open research problems, and considerations for TVWS standards enabling heterogeneous coexistence.*

three categories: spectrum availability detection, spectrum sharing, and interference mitigation; these are discussed next. Although these challenges are typical to most CWNs, the practical requirements defined by regulatory bodies (e.g., the U.S. FCC) for operation in TVWS impose specific constraints to the CR technologies adopted, which are not always taken into account in the literature applicable to generic CWNs. Therefore, in the following section we highlight these specific regulatory requirements and their implications for the design of standards for CWNs in TVWS.

SPECTRUM AVAILABILITY DETECTION

Spectrum availability detection refers to identifying TV channels available for use without causing harmful interference to incumbents. In addition, detection of coexisting secondary networks is also important, primarily to enable optimized decisions when selecting operating channels.

Incumbent Detection — The CWNs must apply reliable methods to detect available TVWS. For instance, the FCC (Table 1) requires secondary systems to determine an available TV channel using mainly an incumbent database, but spectrum sensing is also defined in the rules with very challenging requirements.

White Space Database — A white space database (WSD) is a central repository managed by a secure and reliable authority. It stores information about primary user operations (i.e., location of incumbent users, their transmission power requirements, channels used, and expected duration of usage) [6]. Secondary systems will query the WSD to determine availability of a TV channel while providing their own geographic locations. On receiving a query, the WSD sends information about the channels available at the specified location and allowed power levels for transmission [2] on such channels. As shown in Table 1, certain secondary (fixed and Mode II) devices are required to self-geolocate in order to access the WSD. In fixed CWNs, the BS and CPE will likely be equipped with satellite-based geolocation [6], although an alternative over-the-air mechanism is proposed in the 802.22 standard [3]. In the case of Wi-Fi-like CWNs, access points (APs) will need to implement self-geolocation, in order to operate as master (Mode II) for lower-power slave devices (Mode I). In many indoor use cases, availability of satellite signals could be an issue; hence, over-the-air localization techniques and cooperation with other networks are feasible options, especially given the relatively low resolution required by the geolocation mechanism (e.g., ±50 m proposed by the FCC).

Spectrum Sensing — Spectrum sensing is the process of scanning the radio frequency (RF) spectrum in order to detect the presence of incumbent signals, usually above a certain sensing threshold, which defines the minimal signal level at which the incumbent signal must be detected. Any methodology used for spectrum sensing is calibrated in terms of two parameters:

> It will be critical for 802.11af and ECMA 392 networks to detect the presence of nearby 802.22 networks, since they may impose serious interference, and avoid network capacity drop due to interference.

probability of *false alarms* (P_{fa}) and *probability of missed detections* ($1 - P_d$). Typically, there is a trade-off between sensing efficiency and the overhead required for sensing (i.e. sensing duration required to achieved a desired (P_d, P_{fa})) [7].

Reliable spectrum sensing techniques to date are classified into five broad categories [7]: *energy detection*, *waveform-based sensing*, *matched filtering*, *radio-identification-based sensing*, and *cyclostationarity-based sensing*. Energy detection [7] deals with sensing a signal by comparing the output of the energy detector to a predefined threshold based on the noise floor. The advantage of this method is its simplicity as it does not require any information on the primary user's signal. However, drawbacks of energy-detection-based sensing are in the selection of a suitable threshold, differentiation between interference, noise, and primary user signal, and its inferior performance in the low signal-to-noise ratio region. Known signal patterns are used in waveform-based sensing [7], in which a secondary device senses a primary user by correlating the received signal with a known version of itself. This sensing mechanism outperforms energy detection in terms of reliability and convergence time, and its performance enhances with increasing duration of known signal pattern.

Matched filtering [7] requires perfect signaling information like bandwidth, operating frequency, modulation type and order, pulse shaping, and frame format. This implies that the sensing devices are required to demodulate the received signal for sensing decisions, which is a drawback. Matched filtering also suffers from large power consumption due to execution of receiver algorithms for detection and implementation complexity. In spite of all its disadvantages, detection time is least among all other sensing techniques to achieve a specified probability of false alarm. One of the other feature-based sensing techniques is radio-identification-based sensing [7], where selective features of the received signal (e.g., channel bandwidth, center frequency) are extracted and used for sensing decisions by employing various classification methods. Cyclostationarity features of the received signals are exploited in cyclostationarity-based sensing [7] to distinguish a signal from noise, which is a wide-sense stationary signal with no correlation. These features are developed by the periodicity in the signal or in signal statistics like mean and autocorrelation. This differentiates this from the energy detection technique, which uses power spectral density for sensing.

Secondary User Detection — Future CWNs will also need to detect coexisting secondary systems operating in the same or different TV channels. This will require detection of potentially different air interfaces. For instance, it will be critical for 802.11af and ECMA 392 networks to detect the presence of nearby 802.22 networks, since they may impose serious interference, and avoid network capacity drop due to interference. Now, we focus on detection challenges of similar and heterogeneous secondary networks.

Coexistence of similar networks (i.e., networks that operate with the same set of technologies and protocols, also called self-coexistence) is considered in the scope of current standards, such as 802.22 [3]. The first step in any self-coexistence mechanism is the ability to detect neighboring networks. Otherwise, this may lead to the following problems:

- Performance loss may be experienced due to interference within the overlapping regions.
- Undetected asynchronous sensing intervals among similar networks may result in transmission during sensing time and, in turn, high P_{fa}.
- Incomplete discovery of neighboring networks (i.e., hidden nodes) may cause data loss and impact the effectiveness of communication among networks. For example, the Coexistence Beacon Protocol (CBP) [3] packets exchanged between neighboring 802.22 BSs could be interfered with by a third (hidden) network, preventing the self-coexistence process from converging.

The above problems highlight the importance of detecting similar networks; some of the challenges are discussed below.

Network discovery overhead: Most standards include some form of beacon transmission to facilitate network discovery. The 802.22 BS transmits regular superframe control headers (SCHs) [3], which carry information about the cell and are transmitted using the most robust modulation/code option [2]. In ECMA 392, all devices transmit regular beacons [4]. Similarly, 802.11af APs will also transmit regular beacons as the current 802.11 APs do. One fundamental difference in TVWS is that the list of channels to be scanned may change dynamically, and the frequency of scanning those channels may have to be increased due to incumbent protection.

Coordination and overhead of in-band signaling: The use of common control channels to enable network discovery has been proposed before for CWNs [6]. However, the current and upcoming standards for TVWS are not expected to support a dedicated (out-of-band) over-the-air control channel option. Instead, an in-band signaling approach has been adopted in 802.22 and ECMA 392 based networks. The CBP mechanism enables communication between 802.22 networks through a self-coexistence window (SCW) scheduled by BSs at the end of each frame [3]. However, SCWs incur considerable overhead and should be used carefully. Notably, detecting CBP packets in SCWs may require a relatively long scanning duration.

Another challenge is detection of heterogeneous CWNs, networks based on different technologies and protocols that are not compatible. Some of the problems when detecting heterogeneous secondary networks include:

Channel bandwidth definitions by each of the coexisting networks: Operating channel bandwidths are not identical for different networks. For example, 802.22 specifies 6 MHz as the operating bandwidth,[2] while the current 802.11a/b/g uses 20 MHz bandwidth, and the upcoming 802.11af may use 5 MHz or bonding of multiple channels up to 20 MHz.

Transmission signal power variations among operating standards: Some networks have users with low power requirements while others have high power users. For example, 802.22 stations

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[2] *7 or 8 MHz channels may also be supported depending on the regulatory domain.*

may transmit up to 4 W EIRP, while personal/portable devices under the current FCC rules are limited to a maximum of 100 mW EIRP. Detection of low power users will be a key issue.

Signal characteristics among heterogeneous PHY modes: The broadcast DTV standard specifies known pilots and/or preambles, an inherent characteristic that is exploited for effective spectrum sensing. For secondary system signals, the characteristics will differ from one standard to another and therefore need to be known in order to apply sensing based on signal characteristics. Otherwise, detection using signal characteristics is not a viable option.

Incumbent and Secondary Detection Considerations for Upcoming TVWS Standards — In order to increase sensing-based incumbent detection reliability, new techniques to address the sensing coordination in heterogeneous scenarios are needed. In 802.22, the BS schedules quiet periods for sensing during which no transmission takes place. Similar methods are used in ECMA 392. Hence, coordination and synchronization of quiet times across CWNs is one possible option. Another approach could be to use sensing techniques that take into account the transmission characteristics of other CWNs in the sensing process for low P_{fa}. Furthermore, it is important to define not only standard sensing thresholds, but also minimal sensing requirements in terms of overhead needed to meet the regulations. The heterogeneous scenarios could also enable opportunities to share capabilities amongst networks. For instance, a Wi-Fi AP may be connected to the home CPE (Fig. 1) and share the satellite interface to obtain its own location and access the WSD through the 802.22 BS.

Some of the possible solutions that could be adopted in upcoming standards to support efficient and reliable detection of secondary CWNs in TVWS are:

Intelligent management of out-of-band sensing: Future standards should enable intelligent management of out-of-band[3] sensing during stations' idle time together with cooperative sensing techniques. Furthermore, new standards may have to support reporting mechanisms, which stations use to send spectrum utilization updates with respect to neighboring networks to a central spectrum manager or share with other peer stations in a distributed system.

Preamble detection: Usually, a data packet consists of three sections: preamble, header, and data payload. Definition of a distinct preamble in a data packet for a CWN can help in the detection process. Correlation of a received data packet preamble with known preamble sequences can be a potential solution to detection of heterogeneous networks. Lower values of correlation imply packets from undesirable networks and detection of the same.

Secondary network database: A database approach for storing information about secondary systems may also help detection of fixed networks such as 802.22, but it would be less effective for low-power personal/portable and peer-to-peer networks (e.g., 802.11af or ECMA 392 based) due to high mobility and need for connection to the infrastructure in order to update the database.

INTERFERENCE MITIGATION IN TVWS COEXISTENCE SCENARIOS

Interference in the TVWS will be a challenging issue, especially in areas of limited channel availability and where network coverage overlaps. Currently, heterogeneous networks share the unlicensed 2.4 GHz band, and interference among them has been the subject of extensive research [8]. Similar interference problems will exist as these technologies migrate into the TVWS. However, new interference situations will evolve in the TVWS, such as that between low-power personal/portable devices (e.g., 802.11af and ECMA 392) and high-power fixed systems (e.g., 802.22). Furthermore, the good propagation characteristic of TVWS may also contribute to increased interference as transmission and interference ranges increase. For instance, Wi-Fi home networks typically operating co-channel without serious performance degradation in the 2.4 GHz due to spatial reuse, and could potentially experience higher interference while operating in the same TV channel due to larger transmission and interference ranges. Last, but not least, interference from incumbents, mainly high-power TV stations, is another specific problem to the TVWS. In summary, new interference scenarios specific to TVWS need to be addressed in the upcoming TVWS standards.

Interference related issues in TVWS are classified into two categories: interference to/from incumbents and interference among CWNs.

In addition to incumbent detection, requirements to limit out-of-band emissions are defined for all TVWS devices, with extra restrictions on adjacent channel operation in order to reduce probability of interference on incumbents

Interference to/from Incumbents — In addition to incumbent detection, requirements to limit out-of-band emissions are defined for all TVWS devices, with extra restrictions on adjacent channel operation in order to reduce probability of interference on incumbents (Table 1). On the other hand, high-power incumbents (TV stations transmitting from 20 to 1000 kW) may also interfere with secondary systems. In some cases, these high-power interferers may actually prevent secondary devices to report incumbent detection. Avoidance of such interference depends largely on location, channel gain between the TV station and secondary users, and the difference in operating frequency between them. Location proximity as well as smaller differences (i.e., adjacent channels $N \pm 1$ of an active broadcasting channel N) in their operating frequencies will severely degrade performance of a secondary device. An incumbent detection recovery protocol is adopted in the 802.22 standard that enables CPE affected by strong incumbent interference to reconnect with its BS [3].

Cognition will be instrumental in techniques for interference minimization due to coexistence by exploiting knowledge of the wireless environment and signal characteristics. The techniques are broadly classified into three groups: *interference avoidance*, *interference control*, and *interference mitigation*.

In interference avoidance [1], the primary

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[3] *Out-of-band refers to channels that are not the current operating channel* (N) *or its first adjacent channels (*N ± *1).*

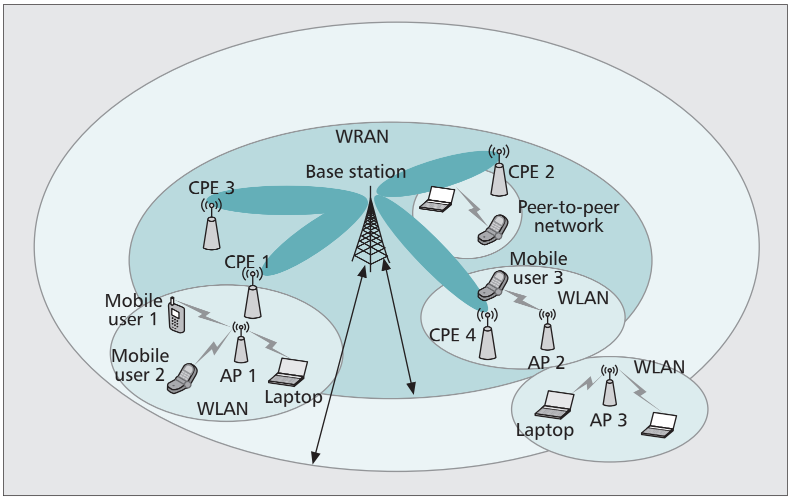

Figure 3. *Interference scenarios among heterogeneous cognitive wireless networks.*

and secondary networks access the spectrum using either time-division multiple access (TDMA) or frequency-division multiple access (FDMA) to avoid inadmissible interference to primary users. Cognition required in this approach is in detecting and allocating the spectral gaps in the TVWS. The conventional approach of spectrum sensing methods described earlier, detection of white spaces followed by sharing, is the key idea in interference avoidance mechanisms. Detection errors creep in, affecting both the primary and secondary user networks; this impact is well studied [12, 13].

Interference control [14] allows primary and secondary users to coexist on the same spectrum with interference within tolerance limits (captured by the quality of service [QoS] constraints) of primary users. Knowledge of such tolerance limits and effect of interference at primary receivers is absolutely necessary in interference control techniques. In this context, multiple-input multiple-output (MIMO) techniques are also proposed [15] for interference avoidance or control, where the cognitive users place their transmission signal in the null space on the receive channels of primary users. Moreover, secondary users can also adjust their transmission power levels and ensure no inadmissible interference on incumbents. Capacity [14, 16] of cognitive networks under various tolerance constraints is well investigated.

Finally, interference mitigation techniques are similar to interference control approaches with the additional knowledge of primary system operation in the form of side information of primary users' codebooks [17, 18] or partial or full knowledge of their transmitted messages. Interference mitigation is further classified as opportunistic interference cancellation (OIC) [17] and asymmetric cooperation [18]. In OIC, the secondary users have information about the primary users' codebooks, which are utilized in decoding primary user transmissions and thereby subtracting from their received signals, enabling increased secondary channel transmission rates. In asymmetric cooperation [18], the secondary users have knowledge of the primary users' codebooks as well as their messages. The side information facilitates secondary users in mitigating interference while cooperating with primary users in boosting their signal at their receivers. Achievable rates of cognitive users are studied [18] in the context of OIC and asymmetric cooperation, coupled with coding techniques and MIMO broadcast channel.

Interference Among CWNs — Multiple CWNs may select the same TV channel due to an uncoordinated selection process or limited availability. In such situations, ignorance of each other's transmission may result in overlapping packets. Consider the worst case situation in which all networks operate co-channel. Several interference problems could occur in such a setup as shown in Fig 3. The main aspects that contribute to interference in TVWS scenarios are listed below.

Different transmission powers: Transmit power control may result in better packet reception by the desired network but adversely affect other collocated networks. In addition, CPE's upstream transmissions may also contribute to interference to nearby networks that overlap with the main lobe of the CPE's directional antenna. Since the CPE's back-lobe antenna gain is expected to be small, interference range of CPE in other directions will be much smaller. For instance, mobile user 3 and the peer-to-peer network in Fig 3 will suffer stronger interference from CPE 4 and 2, respectively, than other secondary devices in the figure. Also, if CPE 4 in Fig. 3, away from the BS, increases its signal power for better performance, it may increase its interference to neighboring co-channel users.

Channel bandwidth: As illustrated before, 802.22 wireless radio access networks (WRANs) will operate on 6 MHz wide channels, while 802.11af may consider signal bandwidths of 5, 10, and 20 MHz [9] based on availability of two or more contiguous channels. Suppose AP 2 in Fig. 3 operates using four contiguous TV channels using a 20 MHz channel bandwidth mode. Hence, interference from the 802.22 BS and CPE 4 could affect only a section of the data packet received by the mobile user 3 under AP 2 in the WLAN.

Offered load and packet size: The overlap in time between transmissions of heterogeneous CWNs will also result in interference, and the degree of this overlap and the overall traffic load define the level of interference. Transmission time is directly proportional to packet size for a given data rate. It is intuitive that shorter packets incur lower interference (i.e., smaller packet loss probability) than larger ones, other parameters being equal. Additionally, packet loss due to interference is proportional to the offered load in the system.

Inadequacy of signal-to-interference ratio: Typically, SIR (or signal-to-interference plus noise ratio [SINR] more generally) is used as a surrogate for predicting packet error rate (PER). As is well known, this implies treating interference as additive Gaussian noise; in heterogeneous scenarios, this is often insufficient [8] and leads to incorrect estimates of PER, which depend on not only the interference power but also other aspects such as the modulation and coding.

Interference Related Considerations for Upcoming TVWS Standards — To combat the interference challenges that may arise due to coexistence in the TVWS, we provide some considerations for upcoming TVWS standards.

Cooperative approaches can be utilized in terms of synchronization of quiet periods and sharing of sensing information as well as usage patterns between networks. In practice, however, implementing cooperation among competing networks is not a simple problem, as discussed in the next section. Spatial diversity in terms of MIMO options can also be exploited with smart antenna technology to avoid interference from the direction of the interferer. For example, spatial diversity embedded in the 802.22 and wireless LAN (WLAN) will mitigate interference in several scenarios depicted in Fig. 3. Directional antennas used by CPE 3 and CPE 1 will reduce interference at AP 1 and its associated stations in Fig 3.

The *receiver sensitivity threshold* needs to be considered carefully in order not to trigger the receiver on unintended signal transmissions. This implies the idea of differentiating between users in the same network and the presence of interference from different networks. The thresholds can be set based on interference patterns of coexisting WRAN, WLAN, or WMAN networks.

SPECTRUM SHARING

Avoiding operating channel overlap between CWNs is always desirable. However, given the dynamism of TVWS, it is possible that overlapping CWNs share available TVWS channels. Typical spectrum sharing solutions can be broadly classified as cooperative or non-cooperative mechanisms [10]. Examples of non-cooperative mechanisms include power control and listen before talk features, such as carrier sense multiple access with collision avoidance (CSMA/CA) used in 802.11 networks. Cooperative schemes require coordination among coexisting networks and tend to be more complex. Recent wireless standards defining cooperative coexistence mechanisms include 802.16h and 802.22. In the case of similar networks, implementation of both cooperative and non-cooperative approaches is facilitated by the fact that the networks operate according to the same PHY/MAC protocols. For instance, if all stations apply the same CSMA algorithm, some level of long-term fairness can be achieved. Similarly, internetwork communication capabilities necessary for cooperative mechanisms is supported in 802.22. In heterogeneous CWNs, spectrum sharing becomes even more challenging, given the intrinsic differences in the protocol stacks. The major spectrum sharing challenges in heterogeneous scenarios in TVWS are described next.

Spectrum Sharing Challenges in Heterogeneous CWNS

Distinct MAC Strategies — CWNs may operate according to different MAC techniques like TDMA, FDMA, code-division multiple access (CDMA), or contention-based protocols. For instance, the 802.22 MAC is TDM-based with PHY resources allocated on demand using OFDMA, while 802.11af will use its CSMA-based protocol, and ECMA 392 uses a combination of reservation- and contention-based access. While 802.11af users can back off when the medium is occupied by 802.22 transmissions, the reverse may not be true, since 802.22 devices do not need to listen before transmitting. The differences in MAC strategies may limit the effectiveness of the non-cooperative listen-before-talk mechanism in achieving fairness in TVWS coexistence.

Inter-Network Communication — Currently, most MAC/PHY standards do not support over-the-air communication across heterogeneous networks, limiting the applicability of cooperative sharing strategies. For example, in order to achieve cooperative sharing between an 802.22 BS and WLAN APs, these networks would have to communicate over a common control channel about usage of the same TV channel. A cognitive pilot channel (CPC) [11] is a centralized cellular-based beaconing approach proposed as a possible control channel implementation in order to share relevant coexistence information. A distributed beaconing mechanism is one option for peer-to-peer information sharing in IEEE 802.22, 802.11af, and ECMA 293 networks. In such a distributed approach, clusterheads can exchange beacons to share relevant information on TVWS coexistence. The advantage of distributed beaconing over the CPC approach is that a clusterhead listens to beacons from neighboring clusterheads only, while users in a CPC need to listen to a long beacon with information related to all networks covered by the CPC base station.

One possible cooperative sharing approach is to multiplex transmissions of multiple overlapping networks in the time domain, as is done across 802.22 networks [3]. This sharing approach is illustrated in Fig. 4 where certain time slots are reserved for use by the 802.22 system, and others are reserved for contention-based access (Wi-Fi clients). Although this concept seems simple, its implementation in the TVWS is not straightforward. First, it would require communication and negotiation between many competing networks. The 802.22 BS would cover a large number of 802.11 WLANs, ECMA 392 networks, or other low-power systems involved in the negotiation process. Second, the overhead in adapting the sharing schedule could be large depending on the number of coexisting systems, and could also result in instability or convergence issues.

Synchronization — Assuming there are mechanisms that enable discovery of heterogeneous CWNs, the implementation of such cooperative strategies would only be possible with tight time synchronization across all devices from different networks. This, indeed, is a challenging problem. Although it is possible to keep tight synchronization within an 802.22 WRAN, or even across different WRANs, extending the synchronization to a potentially large number of personal/portable networks may not be possible, unless all systems

In the case of similar networks, implementation of both cooperative and non-cooperative approaches is facilitated by the fact that the networks operate according to the same PHY/MAC protocols.

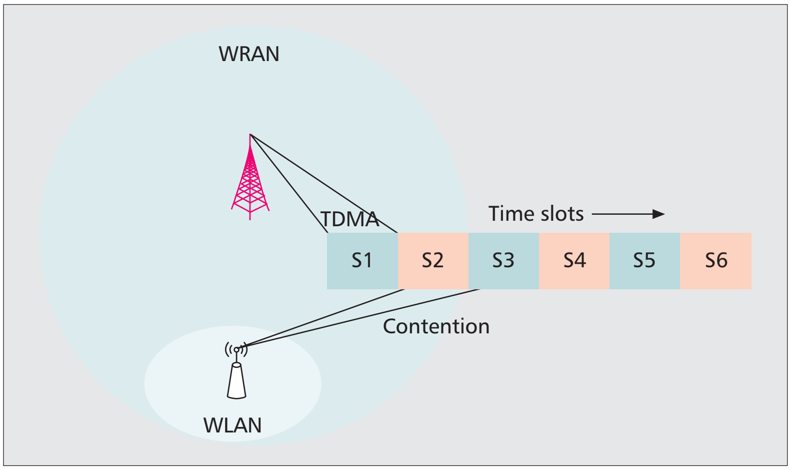

Figure 4. *Spectrum sharing between WRAN and WLAN in the TVWS.*

and protocols are based on a universal reference clock.

Independent Channel Selection — Consider the scenario where one CWN is using TV channel A with channel B as backup. Simultaneously, a second CWN operating in channel C (with channels B and D as backup) detects the first network in channel A. Let us assume that the second network detects an incumbent on its operating channel. In the sequel, which backup channel should the second network move to: B or D? Typically, channel selection is an implementation-dependent procedure in most wireless standards. In TVWS, however, channel selection may be needed in more instances than just at network initialization; for example, to protect incumbents or avoid co-channel operation with other secondary networks, as in the example above. In this situation, a completely independent selection procedure may result in suboptimal operation. Both networks could end up in channel B after the incumbent is detected. Making use of sensing information about other secondary networks could be useful in this example to avoid co-channel operation. For instance, in the above example, if the second network on channel C could not only detect the first network on channel A, but also detect the backup channel of the first network (channel B), it could easily reduce the chance for co-channel operation and avoid more coordination by selecting channel D when a primary user appears in channel C. Using additional information about secondary networks will add to the overhead of advertising network parameters (e.g., by adding extra bytes for the backup channel list), but it is still less costly than other cooperative spectrum sharing schemes that require negotiations among secondary systems, such as the scheme shown in Fig. 4.

Spectrum Sharing Considerations in Upcoming TVWS Standards — The first step toward efficient utilization of TVWS is to avoid co-channel operation if enough channels are available. This can only be done with reliable network discovery mechanisms for heterogeneous scenarios. Furthermore, being able to detect specific characteristics (e.g., transmit power) or operational parameters, such as a priority list of backup channels of heterogeneous CWNs would also be useful to non-cooperative channel selection strategies that avoid co-channel operation. One example of such strategies is the spectrum etiquette mechanism adopted in 802.22 to ensure that neighboring WRANs reduce the probability of co-channel operation by selecting operation and backup channels that are less likely to be used by neighboring networks. This is achieved by exchanging information about backup channel lists, which would of course require some form of communications across heterogeneous CWNs. Another example of non-cooperative strategies for low-power personal/portable devices is to give priority to the first adjacent channels of an active TV channel, since higher-power fixed devices (e.g., 802.22 BSs and CPE) are not allowed on adjacent channels according to the FCC rules. In this case, the personal/portable devices would still have to reduce the maximum power (40 mW), but this could be a good trade-off to avoid potential interference from high-power secondary users in the area.

If co-channel operation cannot be avoided, non-cooperative mechanisms to avoid interference could also be applied, but the effectiveness will depend on the characteristics of the specific scenario, including relative location of the devices, traffic load, transmit power, and so on. The cooperative strategies that require internetwork communication and time synchronization are the most challenging as they would require a broad standardization effort across all secondary systems. There have been some proposals for utilizing a simple common control channel across networks in the context of the 802.19 coexistence standard, but it adds extra cost, and it is unclear whether other standards will reach a consensus on the "universal" PHY mode as the coexistence control channel. As discussed above, even if such a control channel is available, the synchronization and negotiation process among competing secondary systems would still need to be addressed.

CONCLUSION

TVWS is considered for potential coexistence of heterogeneous CWNs including licensed, typically primary users, and unlicensed systems. This article briefly introduces the existing and upcoming standards in the TVWS and identified the prominent challenges to be encountered by these heterogeneous CWNs, while also taking into account the imposed FCC regulations. Additionally, this article also provides insights and important considerations for the successful development of new wireless standards to achieve heterogeneous coexistence in the TVWS with an ultimate motif of efficient and enhanced spectrum utilization.

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