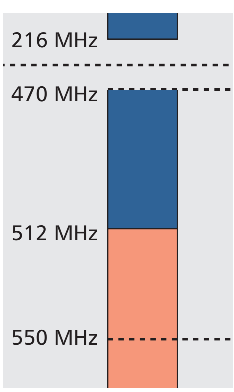
DEVELOPING A STANDARD FOR TV WHITE SPACE COEXISTENCE: TECHNICAL CHALLENGES AND SOLUTION APPROACHES

TUNCER BAYKAS, NICT
MIKA KASSLIN, NOKIA
MARK CUMMINGS, KENNESAW STATE UNIVERSITY
HYUNDUK KANG, ETRI
JOE KWAK, INTERDIGITAL
RICHARD PAINE, SELF
ALEX REZNIK, INTERDIGITAL
RASHID SAEED, SUDAN UNIVERSITY FOR SCIENCE AND TECHNOLOGY
STEPHEN J. SHELLHAMMER, QUALCOMM



The authors provide a detailed overview of the regulatory status of TVWS in the USA and Europe, analyze the coexistence problem in TVWS, and summarize existing coexisting mechanisms to improve coexistence in TVWS.

ABSTRACT

TV white space refers to TV channels that are not used by any licensed services at a particular location and at a particular time. To exploit this unused TVWS spectrum for improved spectrum efficiency, regulatory agencies have begun developing regulations to permit its use this TVWS by unlicensed wireless devices as long as they do not interfere with any licensed services. In the future many heterogeneous, and independently operated, wireless networks may utilize the TVWS. Coexistence between these networks is essential in order to provide a high level of QoS to end users. Consequently, the IEEE 802 LAN/MAN standards committee has approved the P802.19.1 standardization project to specify radio-technology-independent methods for coexistence among dissimilar or independently operated wireless devices and networks. In this article we provide a detailed overview of the regulatory status of TVWS in the United States and Europe, analyze the coexistence problem in TVWS, and summarize existing coexisting mechanisms to improve coexistence in TVWS. The main focus of the article is the IEEE P802.19.1 standardization project, including its requirements and system design, and the major technical challenges ahead.

INTRODUCTION

Cognitive radio has been an active field of academic research for a number of years. Television white space (TVWS) promises to be the first widespread commercial application born from this research. In 2002, the Defense Advanced Research Projects Agency (DARPA) embarked on the Next Generation Communications Program (XG) [1]. Developed for the U.S. military, the XG program goal was to equip troops with radios, which could exploit idle spectrum by providing dynamic ad hoc utilization of vacant frequency channels using cognitive radio techniques. XG radios can dynamically and stealthily identify idle channels and communicate on them while being able to immediately vacate the channel to yield to any primary user transmission. The Federal Communications Commission (FCC) took note and took action to draft the TVWS rules. This ability to use unused spectrum on a non-interfering basis, respecting the rights and privileges of the primary spectrum licensee, is a cornerstone of the white spaces revolution. New TVWS products and services will be the first civilian and commercial applications of the XG radio model, and TVWS is likely to be the first of a number of white space initiatives.

Today regulators worldwide are beginning to make new spectrum available by allowing secondary access to unused but licensed spectrum, starting with TV channels in the VHF/UHF bands. These unused segments of TV spectrum are referred to as TV white space, and a wireless device that operates in the TVWS is referred as a white space device (WSD). Secondary WSD users may use this spectrum on an "as available" basis, while primary licensed users retain their licensing rights, are protected from secondary user interference, and may access their licensed spectrum with priority at any time. In the United

1536-1284/12/$25.00 © 2012 IEEE

States, this scheme has been driven by the FCC, which has set the rules for the unlicensed TVWS operations with amendments to Parts 0 and 15 of Title 47 of the Code of Federal Regulations (CFR) [2, 3]. Other regulators have their own initiatives addressing this new opportunity for additional spectrum [4–12]. The FCC rules specify means for protecting incumbents such as TV broadcast stations and wireless microphones; however, neither the FCC nor other regulators currently address the problem of coexistence of multiple WSDs using different wireless technologies and different operators and service providers. TVWS is a result of the convergence of wireless technology research with regulators' need for increased spectral efficiency to meet rapidly increasing demands for wireless bandwidth.

It should be noted that the TVWS initiatives in the United States and around the world are likely to be just the first step toward a more flexible, dynamic, and efficient model for spectrum licensing and utilization. An efficient demand-driven approach to spectrum utilization appears to be a natural and necessary response to the dramatically increasing demand for wireless bandwidth. Already, a recent FCC Notice of Inquiry points to the U.S. regulator's view towards a similar liberalization of spectrum use in bands beyond the TV spectrum, other researchers and technologists worldwide are already working on technologies designed to enable dynamic spectrum access [9]. As such, the various efforts to deliver a practical TVWS solution represent an important precedent that is likely to have long-term repercussions on the way dynamic spectrum access develops in other areas.

A number of different unlicensed wireless technologies are expected to be deployed in the TVWS. For example, the IEEE 802.22 working group has developed a standard for wireless regional area networks (WRANs) in the TVWS [13, 14]. The IEEE 802.11 working group is developing an amendment to the 802.11 wireless local area network (WLAN) standard [15] for TVWS operations [16]. In addition, the European Computer Manufacturers Association (ECMA) has developed another standard, ECMA-392, intended for use in the TVWS [17]. It is likely that other wireless standards and technologies will also be deployed in the TVWS. This diverse set of wireless technologies will lead to interference issues in geographic locations with a limited number of TVWS channels. Since the number of TVWS channels available in any location decreases with the number of broadcast TV stations operating in that area, many U.S. metro areas and some urban areas will be limited to only a few 6 MHz channels for TVWS. Very high TVWS channel loads are expected in these densely populated areas. In addition, certain wireless microphones, those used by licensed primary users in the broadcast industry, are protected by regulation and have priority access to unused TV channels for special events, news coverage, and other purposes. Since the usage patterns of wireless microphones can change from day to day or even hour to hour, the number of available TVWS channels can vary with time as well as location. These conditions will lead to very high channel congestion and high levels of interference among users of the TVWS in most metro and many urban areas.

As a result, the TVWS coexistence problem is both more complex and more severe than in the current unlicensed bands. Standardized mechanisms and techniques to improve coexistence among various dissimilar WSDs and respective networks are needed in the TVWS.

Consequently, the IEEE 802.19 Working Group has taken action to work on the TVWS coexistence issue, and a task group, 802.19 TG1, was formed in early 2010. This task group was chartered with the specific task of developing a standard to improve coexistence in the TVWS.

We look at the regulatory status of the TVWS in different countries. We summarize current and completed TVWS wireless standards projects. Then we provide an analysis of the TVWS coexistence problem. We describe the technical challenges that must be addressed during the development of the TVWS coexistence standard. We give examples of coexistence mechanisms and solutions that may be included in the 802.19 TVWS coexistence standard. Finally, we give an overview of the 802.19.1 system design, including system architecture, reference model, and possible decision topologies.

Regulatory Status of TVWS

In terrestrial television broadcasting two frequency bands are used: the very high frequency (VHF, 30–300 MHz) band and the lower part of the ultra high frequency (UHF, 300–1000 MHz) band. Although many countries have studied the use of TVWS, only two countries currently have regulations permitting unlicensed use of TVWS: the United States and the United Kingdom. Figure 1 shows the TVWS spectrum in these two countries. The FCC has established TVWS in both the VHF and UHF bands, whereas in the United Kingdom only UHF is allowed. In the United States each TV channel is 6 MHz wide, whereas channel width in the United Kingdom is 8 MHz.

TVWS in the United States

The FCC has defined three mechanisms to protect licensed incumbent TV broadcasters from interference from unlicensed WSDs:

- WSD geolocation with access to a TV bands database
- WSD transmit power limitations (transmit spectral mask)
- Operating channel radio sensing of protected licensed users [2]

The TV bands database contains all licensed users, their operating frequencies, locations, areas of operation, and operating schedules. Before transmitting any signal in the TV band, WSDs must access the TV bands database and provide their geolocation information (their current position) in order to obtain a list of currently available TVWS channels at that location. Alternatively, a WSD that cannot access the TV bands database directly may be enabled for TVWS operation indirectly by an authorized master device. The master device must be able

The FCC has defined three mechanisms to protect licensed incumbent TV broadcasters from interference from unlicensed WSDs: WSD geolocation with access to a TV bands database; WSD transmit power limitations (transmit spectral mask); and operating channel radio sensing of protected licensed users.

If a personal/portable device operates on a channel adjacent to one being used by a protected licensee, it must operate with a lower power limit of 40 mW and with spectral density reduced to –1.8 dBm in any 100 kHz band.

to estimate the WSD location and access the TV bands database on behalf of the WSD. The master device provides the WSD with the list of currently available TVWS channels at its location. Radio sensing is mandated as a protection mechanism for WSDs that cannot access the TV bands database and are not enabled by an authorized master device.

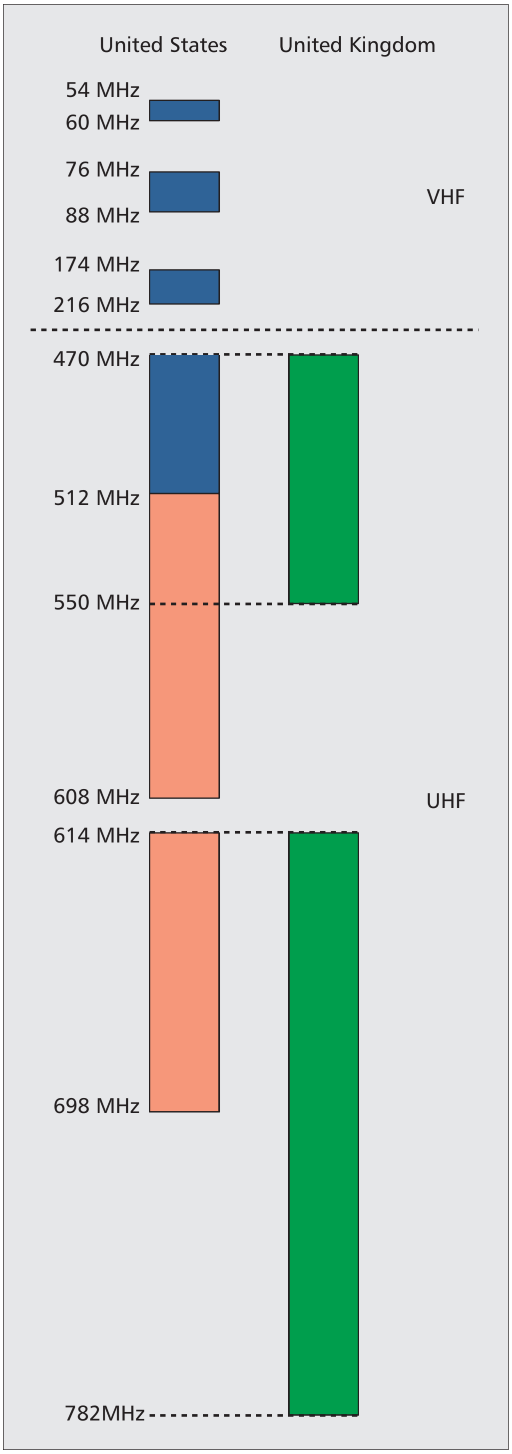


Figure 1. *TVWS spectrum in the United States and United Kingdom. Blue: operation allowed for fixed devices in the United States. Orange: operation allowed for fixed and personal/portable devices in the United States. Green: operation allowed in the United Kingdom.*

The FCC has defined four classes of WSDs, as listed in Table 1. A fixed device operates at a specific registered location, uses outdoor antenna(s), and may transmit a maximum of 1W into one or more 6 MHz TVWS channels. Antenna gains up to 6 dBi are allowed, thus permitting up to 4 W effective isotropic radiated power (EIRP). The power spectral density conducted from the fixed WSD to the antenna must not be greater than 12.2 dB when measured in any 100 kHz band. Due to this high transmit power limit, a fixed device is not allowed to operate on any channel adjacent to one being used by a TV broadcast signal.

A personal/portable device is a lower-power device, may be mobile, and is restricted to operate in the frequency bands 512–608 MHz (TV channels 21–36) and 614–698 MHz (TV channels 38-51). Its maximum EIRP must not exceed 100 mW (20 dBm) per 6 MHz of bandwidth, and the power spectral density must not be greater than 2.2 dB when measured in any 100 kHz band in any case. If a personal/portable device operates on a channel adjacent to one being used by a protected licensee, it must operate with a lower-power limit of 40 mW and with spectral density reduced to –1.8 dBm in any 100 kHz band. There are two types of personal/portable devices: mode I and mode II. A mode I device is not required to have geolocation capability or directly access the TV bands database. A mode II device must have geolocation capability with an accuracy of accuracy of ±50 m, and must have direct or indirect access to the TV bands database. A mode II device may access the TV bands database on behalf of a mode I device in order to enable the mode I device for TVWS operation. When enabled, the mode I device may transmit on any channel in the list of available TVWS channels the mode II device sends to the mode I device. In addition, the mode I device must periodically receive a contact verification signal from a fixed or mode II device. The contact verification signal ensures that the mode I device remains within the area associated with the list of available TVWS channels sent to that mode I device.

The final WSD class is the sensing only device, which uses radio sensing to detect protected licensees and avoid interfering with them. A sensing only device is limited to 50 mW transmit power and must be able to detect ATSC digital TV signals and NTSC analog TV signals at –114 dBm and to cease transmission within 2 s of signal detection. In addition, sensing only devices must be able to detect wireless microphone signals at –107 dBm. Laboratory and field tests by the FCC are mandatory for the approval of sensing only devices. The FCC plans to test and certify each TVWS sensing only device to ensure regulatory compliance. Table 1 summarizes the FCC requirements for the defined device classes.

TVWS in the United Kingdom

In the United Kingdom, the Office of Communications (Ofcom) is the independent telecommunications regulator and competition authority for the communication industries. According to reports from Ofcom, accessing the TV bands

Device class	Mobility	Transmit power (EIRP)	Geolocation and database access	Sensing	Enabling capability	Allowed on adjacent TV channels
Fixed	Fixed	≤ 4 W	Required (± 50 m)	Not required	Master	No
Portable mode II	Fixed, nomadic, and mobile	≤ 100 mW	Required (± 50 m)	Not required	Master	Yes, but ≤ 40 mW
Portable mode I	Fixed, nomadic, and mobile	≤ 100 mW	Not required	Not required	Slave	Yes, but ≤ 40 mW
Sensing only	Fixed, nomadic, and mobile	≤ 50 mW	Not required	Required –114dB	None	Yes, but ≤ 40 mW

Table 1. *TVWS device classes specified by the FCC.*

database with geolocation is the most reliable mechanism to protect licensed users in the short and medium terms [4–7]. As of 2011, Ofcom had specified two types of devices: master and slave devices. Master devices contact a database to obtain a set of available frequencies in their area and manage slave devices. Slave devices obtain the relevant information from master devices, but do not contact the database themselves. A slave device must cease transmission immediately when instructed by the master device or within 5 s of not receiving a response from the master device to a transmission. The maximum transmit power for a device is determined based on protection levels. For example, the signal level from a WSD should be at least 33 dB below the TV signal at the TV receiver for cochannel operation. According to Ofcom, implementation of sensing only devices is likely many years away, and Ofcom will not take any further action to support sensing only devices until operation using geolocation with TV band database access has been established.

TVWS in Other Countries

Canada's regulator, Industry Canada, has already established regulations for secondary, lightly licensed services in the TV band. This innovative service is called Remote Rural Broadband Systems (RRBS) and was conceived of by the Communications Research Center in 2003. In 2007, regulatory guidelines for operation and deployment of RRBS systems were released. In early 2010, this new service was launched in Canada. Canada is gaining very useful incumbent protection experience from the startup, operating issues, and lessons learned from RRBS. Recently, a consultation from Industry Canada indicates that the regulator is considering additional unlicensed TVWS operation following the lead and technical framework established by the FCC [8]. The consultation requests comments from industry participants concerning the details about unlicensed use of TVWS in Canada. The IEEE and other interested parties have provided formal responses to the questions asked in the Canadian TVWS Consultation. In particular, the IEEE response suggests several areas in which Canada could improve the market uptake of TVWS services by modifying several of the operating rules adopted by the FCC [9]. It is clear that Canada will proceed with additional regulatory changes to accommodate improved utilization of the TVWS north of the U.S. border.

Other regulatory bodies are conducting studies on TVWS as well. In Singapore, the Info Communications Development Authority (IDA) provided a TVWS information package to facilitate technical trials in Singapore [11]. As of 2011 these trials, which are called Cognitive Radio Venues (CRAVE), were continuing. IDA designed these trials so that participants would be able to obtain real-world measurements to facilitate the development of practical WSDs.

In Europe, the Radio Spectrum Policy Group (RSPG) published a Report and subsequent Opinion on Cognitive Radio, including sections on TVWS. This report may lead to further work by the European Commission to be undertaken through the Radio Spectrum Committee [18].

The European Communications Office published ECC Report 159 about cognitive radio systems in the TVWS in 470–790 MHz, which was completed in WGSE PT43 [10]. The report states that spectrum sensing, if employed by a standalone WSD (autonomous operation), is not reliable enough to guarantee protection of nearby TV receivers. However, collaborative sensing may improve reliability. Operation of a WSD assisted by geolocation with a TV bands database is currently the most feasible option. More investigation is needed to examine protection for aeronautical radio navigation service (ARNS, 645–790 MHz) and fixed/mobile bands, which are located above and below the TV UHF band.

All indications from these developments show that TVWS will be an important band for unlicensed wireless communication, in which coexistence between networks will be an important factor for the quality of communication. The next section focuses on details of some of the medium access control and physical (MAC/PHY) layer standards that will operate in TVWS.

Wireless Standards in TVWS

This section provides a summary of five projects specifying MAC/PHY standards for TVWS.

The first TVWS standard published is from ECMA International. Standard ECMA-392, MAC and PHY for Operation in TV White Space, was published in December 2009 [17]. ECMA-392 was mainly designed for communica-

Any free public resource which is available to anyone tends to be indiscriminately used until it is depleted. In the case of wireless communication this tendency manifests itself as spectrum congestion in unlicensed bands.

tion between personal/portable devices; specifically, in-home multimedia distribution. It supports both mesh and centralized networks. The standard defines an orthogonal frequency-division multiplexing (OFDM) PHY with modulation schemes of quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM. For forward error correction (FEC), concatenation of a Reed-Solomon (RS) outer code and a convolutional inner code with puncturing provides five different coding rates. Channel widths of 6, 7, and 8 MHz are supported for TV channels in any regulatory domain. The maximum data rate of ECMA-392 is 31.64 Mb/s. To protect incumbents, dynamic frequency selection and transmit power control are included in the specifications.

In 2004 the IEEE started the 802.22 project to develop a MAC and PHY to use TVWS for rural broadband services. In July 2011, the IEEE 802.22-2011standard was published [13]. Although mobility is supported, the main focus of this system is long-range communication between fixed devices. Typical range of an 802.22 fixed device can vary between 10 km to 30 km assuming outdoor directional antennas. Maximum supported range of the MAC layer is 100 km.

The IEEE 802.22 standard uses a centralized topology in which a base station (BS) serves up to 512 customer premises equipments (CPE). Radio downlink is based on time-division multiplexing, whereas uplink is based on orthogonal frequency-division multiple access to support simultaneous transmission from multiple CPE units. Details of the PHY layer design are as follows. OFDM is used with a fast Fourier transform (FFT) size of 2048 to cope with delay spread for long-range links. Similar to ECMA-392, QPSK, 16-QAM, and 64-QAM modulations are utilized and 6, 7 and 8 MHz channel widths are supported. FEC options include binary convolutional code, convolutional turbo code, shortened block turbo code, and low-density parity check (LDPC). The 802.22 standard incorporates many cognitive functions, both to protect incumbents and also for coexistence among 802.22 networks. These cognitive functions include channel classification and channel set management, quiet period scheduling for spectrum sensing, fusion of information from sensing, and database. BSs follow spectrum etiquette to coexist with other networks in the area. Another related standard published by this same group is IEEE 802.22.1; this related standard enhances the protection of licensed users from interference by 802.22 systems [19].

In 2009, the popular IEEE 802.11 WLAN working group launched a TVWS project. The 802.11af task group is drafting an amendment to the IEEE 802.11 standard, including MAC/PHY modifications and enhancements to meet legal requirements for channel access and coexistence in the TVWS [15]. The completed IEEE 802.11af standard will likely utilize the OFDM PHY proposed by project P80211ac. The 802.11af task group plans to enable the use of multiple contiguous and non-contiguous channels in TVWS.

In 2011 the IEEE 802.15 working group formed a new task group to develop an amendment to the 802.15.4 wireless personal area network (WPAN) standard for TVWS operations [20]. The new 802.15.4m task group is just beginning its work and will address device command and control applications including the smart grid in the TVWS band. Targeted data rates are in the 40 kb/s–2 Mb/s range. Another design target is to achieve high power efficiency.

Finally, there is the IEEE DySPAN Standards Committee (DySPAN-SC), which addresses cognitive radio and dynamic spectrum access. DySPAN-SC formed a new 1900.7 task group to create yet another MAC/PHY standard for TVWS [21]. According to its project authorization request, the new MAC/PHY will enable fixed and mobile operation in white space frequency bands, while avoiding harmful interference to incumbent users.

Analysis of the Coexistence Problem in TVWS

In this section we examine six aspects of the coexistence problem in TVWS. The first problematic aspect results from the use of TVWS as a public unlicensed resource. Any free public resource which is available to anyone tends to be indiscriminately used until it is depleted. In the case of wireless communication this tendency manifests itself as spectrum congestion in unlicensed bands. A particularly stark example of this occurred during the launch of Apple's iPhone 4, when the iPhone 4 on stage could not establish a Wi-Fi connection. The problem was eventually diagnosed as being due to the presence of 570 other Wi-Fi access points in the same spectrum. Steve Jobs (Apple's former CEO) eventually requested that some of these be shutdown so that the launch demonstration could proceed. What Mr. Jobs did is to request that use of spectrum be granted to an application that everyone agreed should have the highest priority. What was missing was a standard means for the devices involved to do this automatically, without the intervention of 570 (plus 1) human operators.

As noted in our introductory discussion, this problem is not unique to TVWS. In fact, Mr. Jobs was not operating in TVWS in the situation described above; he was using the unlicensed industrial, scientific, and medical (ISM) bands. In that spectrum, the coexistence problem is a well recognized challenge, one that is getting ever increasing attention as new services begin to be deployed. However, the propagation characteristic of the TV spectrum (which is located below 1 GHz) is likely to significantly exacerbate this problem. Quite simply, signals in the 2.4 GHz band and especially in the 5 GHz band lose power much faster with distance than do signals below 1 GHz. The ISM signals are attenuated by the environmental obstacles (e.g., walls) significantly more than TVWS signals below 1 GHz. It is precisely these excellent propagation characteristics that make TV spectrum so attractive for many of the use cases addressed in [22]. However, these propagation characteristics also severely exacerbate the coexistence problem by greatly increasing the size and coverage area of every

TVWS network cell. The much larger cell sizes tend to cover larger areas and serve many more users than smaller cells, thus increasing congestion. What was considered extraordinary congestion in the 2.4 GHz band (the iPhone 4 launch) may become a common condition in TVWS.

The second aspect of the coexistence problem is due to the multiple incompatible wireless networks that will be deployed in the TVWS. We listed a number of different MAC/PHY standards in the previous section. It is likely that Wi-Fi will take advantage of the spectrum using 802.11af. IEEE 802.15.4m-based devices may be used to enable many of the use-cases which involved machine-to-machine communication. Fixed wideband access will be provided by using 802.22-based or ECMA-392-based systems. Since these wireless networks are conformant to incompatible standards, the networks are not interoperable and hence cannot communicate over the air with each other. The benefit of increased radio propagation range also increases the area in which a TVWS transmitter may cause interference to other incompatible TVWS networks. One network's communication is perceived as interference to the other neighboring networks.

A third aspect of the TVWS coexistence problem is due to the way TVWS networks will be deployed. Individuals and competing network service providers may all deploy networks in the same area. These different operating entities deploy their networks independently and with no coordination or even knowledge about the other operators in the area. The 802.22 wireless regional area networks will be operator deployed with fixed high-power base stations serving fixed CPE and portable devices. On the other hand, 802.11 WLAN networks are commonly deployed by a consumer in the home or in small offices. It is very unlikely that the network operator will be aware of what consumer networks are deployed in any given area. Similarly, it is also unlikely that a consumer will be aware of any operator which has deployed networks in his area.

If an operator deployed WRAN and a consumer deployed WLAN operate on the same TVWS channel, it is very likely that the networks will interfere with one another. For example, the WLAN deployed within a home could cause interference to WRAN CPE connected to the WRAN BS. The WLAN may not even be aware of the interference it is causing to the WRAN CPE since the CPE is transmitting using a directional antenna directed toward the BS. So the WLAN does not detect much interference from the WRAN CPE. The WRAN may not have total flexibility in selecting its operating channel since fixed wireless networks are limited in the channels on which they can operate. So even though one of the CPEs is experiencing interference, it may not be able to correct the issue. Other scenarios can be considered in which the WRAN network causes interference to a WLAN network. For example, if the location of a WLAN network is directly between a WRAN base station and a WRAN CPE, the directional antenna from the CPE causes a significant antenna gain in the direction of the WLAN, causing interference to the WLAN.

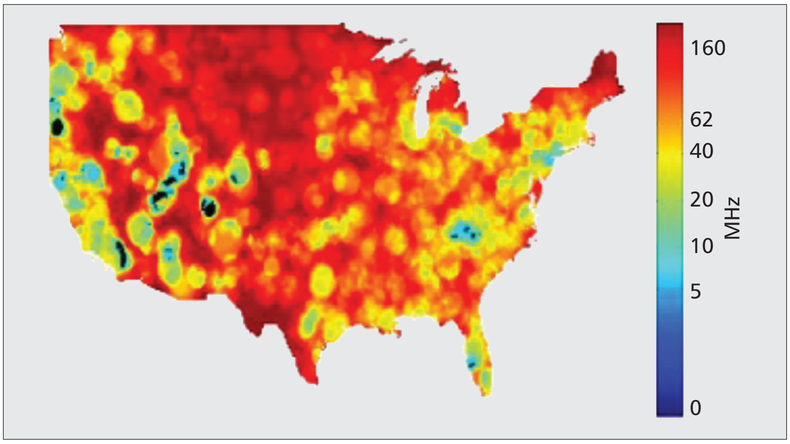


Figure 2. *TV channel availability in the United States based on the method in [23].*

A fourth aspect of the coexistence problem is due to the spectral performance of low-cost commercial WSDs. If two networks are very close to one another and operating on adjacent channels, the interference may also cause network degradation. This can happen due to out-of-band leakage from one network spreading into the adjacent channel being used by the other network.

A fifth aspect of the coexistence problem is caused by network cells with widely varying coverage areas. Some wireless networks may be high-power networks deployed for long-range communication by network service providers, while other networks may be low-power consumer networks deployed in a less controlled manner by individual consumers. High-power long-range networks tend to use high-sensitivity receivers, while short-range networks tend to use low-sensitivity receivers. A given interference level may be harmless to short-range networks but highly disruptive to long-range networks.

The last aspect of the coexistence problem deals with the scarcity of TVWS in populated areas. TVWS operation is only permitted on TV channels not locally used by primary systems (TV broadcasts and licensed wireless microphone). In urban areas with high population density there are numerous local TV stations, resulting in a very limited number of available TVWS channels. Several studies have been conducted on TV channel availability for unlicensed operation in the United State. Figure 2 is taken from one of these studies [23]. Similar results have been observed in other regulatory regions, although the degree to which the differences are observed vary with population density. For example, [24] presents a detailed study of TVWS availability in the United Kingdom. All of these studies make our point quite clear: while most of any county's geographical area may have significant numbers of TVWS channels, most people tend to live in areas where TVWS channels are scarce. Clearly, if this spectrum is to serve the largest number of people, the various players in the spectrum need to find an effective way to share this spectrum resource in densely populated areas.

More detailed discussion of the coexistence issues in TVWS is provided in [25], and of the

When transmitting with a directional antenna, energy is radiated only in the direction of the intended recipient, thus decreasing the interference in all other directions. This space division mechanism may be applied autonomously to decrease interference between networks.

coexistence problem in relation to performance-sensitive applications in [26].

Coexistence Mechanisms

This section provides a detailed overview of the existing coexistence mechanisms, which can generally be divided into two distinct groups based on the level of cooperation among the coexisting networks. Non-collaborative mechanisms, listed in Table 2, may be used autonomously by any network or device to facilitate coexistence with other networks and devices. These non-collaborative mechanisms may be used unilaterally and do not require any action by any other system in order to be effective. Most of these non-collaborative mechanisms may be used by any radio MAC/PHY, while others, like carrier sense multiple access (CSMA), are particular to one or several MAC/PHY designs.

It is important to note that for this discussion of coexistence mechanisms, collaboration refers to communication and cooperation between interfering spectrum users and networks. This collaboration is not related to the cooperative use of protocols to improve operation within a network. For instance, use of transmit power control (TPC) as a protocol within a network may increase battery life and reduce emitted transmit power levels [27]. Effective use of TPC requires cooperation inside the network. If the network using TPC operates on the same frequency as another nearby network, the TPC will also decrease interference and thus improve coexistence. Since the use of TPC within the network does not require communication or collaboration with another network, it is considered a non-collaborative coexistence mechanism.

Two popular non-collaborative coexistence mechanisms are dynamic frequency selection (DFS) and dynamic channel selection (DCS). DFS allows spectrum sharing systems to share spectrum with existing regulatory protected systems such as radar systems, satellite systems, TV broadcasting systems, etc. The DFS concept is to detect protected devices on the operating channel and, if detected, to switch frequency to another channel. DCS enables spectrum sharing systems to select the best channel (i.e., the least interfered channel) based on channel measurements [15]. A channel is regarded as an unusable channel if it has surpassed the acceptable threshold or degraded the bit error rate (BER) sufficiently. In this case there are two options; to move to a new channel or to use a more robust modulation and coding scheme. DCS is used to minimize or avoid interference with other networks. DFS detects and switches frequency, while DCS selects the best frequency for those available. In this way, DCS is quite different from DFS. DFS and DCS are typically used together in unlicensed systems like 802.11.

Listen before talk (LBT) is an effective mechanism for sharing spectrum among multiple 802.11 systems using different modulations [15]. The concept of LBT is that before transmitting over a shared channel, a transmitter decides if the channel is in use by using a clear channel assessment (CCA) check. During CCA observation time the energy in the channel is measured and compared to an energy detection threshold (EDT). If the energy level in the channel exceeds the predefined threshold, a transmitter must defer its transmission by an arbitrary time. In addition, LBT limits the maximum contiguous transmission time so that a transmitter provides reasonable opportunities for other transmitters to operate.

Modifying EDT is also an autonomous coexistence mechanism that affects the performance of CSMA and LBT. For transmit purposes, decreasing a network's EDT may serve to desensitize the network's receivers by desensitizing the CCA function. As the EDT is raised, additional "clear" channel time becomes available since low-energy packets on the channel are not detected. More clear channel time provides more channel time for network transmissions. Similarly, increasing the EDT may decrease the radio range of the network receivers, since low energy packets from network nodes are not detected or received. This has the effect of decreasing the network coverage area, decreasing the number of served network nodes and thus decreasing the network traffic load. Increasing EDT has the indirect negative effect of increasing interference to the neighboring networks by permitting network transmission during periods when the neighbor network is transmitting packets which are received at energy levels below the EDT threshold.

Finally, certain networks are equipped with directional antennas. Using multiple or steerable directional antennas for transmission decreases interference when compared to the use of an omnidirectional antenna. A transmitting omnidirectional antenna radiates energy in all directions, not only in the direction of the intended recipient. When transmitting with a directional antenna, energy is radiated only in the direction of the intended recipient, thus decreasing the interference in all other directions. This space division mechanism may be applied autonomously to decrease interference between networks.

Non-collaborative mechanisms are generally sufficient to promote coexistence in systems with adequate spectrum resources so that separate operating frequencies may be used by each network. The real coexistence challenge materializes when the available TVWS spectrum is insufficient to provide a separate operating frequency for each network or MAC/PHY design [27]. In the TVWS bands, this is a likely scenario due to the proliferation of unlicensed device designs and high consumer adoption, particularly in dense metropolitan areas where many TV channels are occupied by licensed broadcasters. With the exception of CSMA, non-collaborative coexistence mechanisms do not enable channel sharing. Yet channel sharing is required for coexistence where spectrum is limited. In the TVWS bands, the spectrum is expected to be quite limited in densely populated areas served by many TV broadcasters.

The collaborative mechanisms listed in Table 3 permit channel sharing to further enhance coexistence. The sharing of spectrum by networks requires that the networks agree on the operating parameters to enable spectrum sharing. The partitioning of the available spectrum

Mechanism		Description	Advantages	Disadvantages
Non-Collaborative (autonomous)	Dynamic frequency selection (DFS)/dynamic channel selection (DCS)	DFS: Sense, select to avoid channels in use. DCS: sense, switch to better channel	Widely implemented in many networks for initial channel selection on startup and for channel switching.	Ineffective when the number of channels is limited or already occupied. Does not address channel sharing.
	Transmit power xontrol (TPC)	Control of transmit power to minimize interference.	Most protocols provide adequate feedback for TPC	TPC must be used by all for fairness. Does not address channel sharing.
	CSMA/LBT	LBT and defer. Asynchronous contention, first come, first served, by devices from any network.	Already in 802.11. Permits self-coexistence and channel sharing among CSMA networks.	Incompatible with TDM protocols using time slot assignments. Limited QoS.
	Energy detection threshold (EDT)	This threshold sets the receiver sensitivity for CCA and for packet reception.	Increasing EDT makes more time available for transmission. Decreasing EDT decreases interference for neighbor networks	Increasing EDT also increases interference for neighbor networks. Decreasing EDT decreases network coverage area.
	Minimized RF footprint	Space division sharing of spectrum using hi-gain, steerable antennas, minimizes interference area.	Already used by many APs and BSs.	Complexity issue for mobile devices; must be used by all for fairness. Does not address channel sharing.
Collaborative	Time-division multiple access (TDMA)	Coordinated time sharing of channel between networks	Permits channel sharing.	Complex to implement unless two networks agree on frame rate.
	Frequency-division multiple access (FDMA)	Coordinated frequency sharing of channel by channel splitting and half rate clocking. DSP FFT firmware modifications for alternate OFDM channel bandwidths	Permits channel sharing.	Less efficient than TDMA, may require guard bands or filters.
	Code-division multiple access (CDMA)	Coordinated code division sharing of common channel.	Widely used in 3G cellular systems. Permits channel sharing.	Not used in any unlicensed standard. Requires power coordination/allocation among users.
	Hybrids of the above	Combinations of mechanisms are typically implemented, e.g. DFS/TPC/TDMA	Multiple techniques permit better coexistence in more scenarios.	Implementations vary widely as number of coexistence parameters increase. Complexity of negotiation for channel sharing increases.

Table 2. *Existing coexistence mechanisms.*

bandwidth or time between two networks is complex and should equitably consider the individual network traffic demand, priority, and user scenarios [28]. Collaborative mechanisms improve throughput for all networks in the shared spectrum.

An example of a collaborative time-division multiple access (TDMA) coexistence mechanism is the Contention Beacon Protocol (CBP) of the 802.22 standard. The CBP enables the sharing of a channel with other 802.22 systems (or possibly with other TDMA MAC/PHYs using scheduled operation). The CBP is best-effort protocol based on coexistence beacon transmissions, and can be exchanged between 802.22 systems over the air interface or through the backhaul. The CBP consists of two different modes: Spectrum Etiquette (SE) and on-demand frame contention (ODFC) [13]. In the SE mode, each 802.22 system tries to choose a channel which will minimize interference to neighboring systems. If there are not enough channels for each 802.22 system individually, the ODFC mode is initiated so that several 802.22 systems can share the same channel on a frame-by-frame basis. In the ODFC mode, the contention numbers are randomly generated by each neighboring 802.22 system and the winner with the smallest contention number has a right to access the frame.

Collaborative mechanisms depend on the ability to exchange information between heterogeneous networks, for example network characteristics and traffic load information, and to use this information to negotiate the partitioning of the shared channel. When the operating parameters (time assignment, frequency partitioning,

Info exchange mechanism	Description	Advantages	Disadvantages
Native PHY	Messages to support coexistence using native PHY	Works well for coexistence among networks using same PHY (self coexistence).	Limited use for heterogeneous networks. Requires multi-mode radios.
Common PHY Channel	Low complexity PHY on common channel for coexistence communication	Permits direct communication between heterogeneous devices.	Added complexity of second PHY in every device. Does not address means for negotiation for channel sharing.
Common database	Devices use native PHY to extend concept of internet access to FCC geolocation database, now expanded for local coexistence coordination	Easy access to coexistence environment and neighbor system parameters.	To be effective, all unlicensed users must register and provide operating parameters. Can be expanded to address means for negotiation for channel sharing.
Internet server facilitated messaging	Devices use native PHY to interact with internet-based messaging server that can translate/forward coexistence messages and policies.	Permits direct negotiation of sharing parameters between devices or networks operating in same local area on same channel.	Negotiation complexity does not scale well as number of affected users increases. Requires knowledge of IDs/addresses of local interferers. Requires common negotiation protocol.

Table 3. *Information exchange mechanism for collaboration.*

power partitioning, and space partitioning or code assignment) are agreed, the channel may be cooperatively shared [29]. The exchange of information for coexistence requires a means for two heterogeneous networks to communicate with each other, either directly or indirectly. Table 3 lists a number of options which can provide the information exchange needed for channel sharing and can also enhance the effectiveness of non-collaborative coexistence mechanisms. For instance, the transmit power level may be increased to use higher than minimum required data rate when a channel is time-shared with another network so as to provide more channel time for both networks.

Technical Challenges

This section focuses on technical challenges which need to be addressed to provide improved coexistence among TVWS networks. Coexistence occurs when two or more WSD networks share spectrum resources. One network's use of the spectrum necessarily limits or interferes with the other network's use of the same resource. The level or quality of coexistence directly relates to the quality of service experienced by both WSD networks. In simplistic terms, good coexistence is characterized by acceptable levels of interference, while poor coexistence is characterized by disruptive interference.

Improving coexistence among networks is usually a complex process involving multiple individual and often concurrent steps. The first step is always the discovery of an interference problem. This step is often called interference estimation which used with a threshold used to identify an interference problem. The second step is invoked when an interference problem is detected and involves the autonomous application of coexistence mechanisms to eliminate or decrease the perceived interference. If the second step does not resolve the identified interference problem, the third and fourth steps are needed. The third step requires discovery of neighbor networks that may be the source of the problematic interference. The fourth step requires communication between the network causing the interference and the network experiencing the interference. In many cases, the interference between networks is mutual, but it is not necessarily always the case. The fourth step uses direct network-to-network communication to negotiate a means to decrease the interference. The negotiated solution applies one or more collaborative coexistence mechanisms. The negotiated solution would normally involve one or more algorithms to determine the best solution for both networks. Both networks then reconfigure themselves to implement the agreed solution.

These challenges and others will be considered and addressed during the development of the 802.19.1 standard. The 802.19.1 coexistence system will provide services to subscribing networks to assist or implement the different coexistence solution steps described above.

Discovery

Coexistence discovery has two phases: discovery of interference and discovery of the neighbor network(s) that may be causing the interference. The first phase of discovery for a network is to detect the presence of interference. A good indicator of interference is degradation in network performance, measured by either a drop in network throughput or an increase in latency. However, there are many potential sources of network degradation, so the challenge is to isolate the conditions under which the network degradation is due to interference. The interference may only occur at one of the nodes. For example, in a WRAN there may be interference at one client device due to interference from a

WLAN in the vicinity of the WRAN client. This would likely only cause interference on the downlink for this one client. The WRAN network would then need to determine the source of the detected interference in order to take some action.

The second phase of discovery identifies nearby networks that may be causing the interference. To identify sources of interference, a radio propagation analysis of all neighboring networks is needed. Such an analysis requires network locations, transmit power levels, receiver sensitivities, and topographic features to determine the level of interference between radios of networks in any vicinity. Once interfering networks or radios have been identified, it is then necessary for the networks or radios to establish communications to decrease the interference and improve coexistence. There are numerous ways to discover neighbor networks and to establish communications with neighbor networks. A goal for the 802.19.1 system design is to standardize a technique for neighbor discovery and to assist in establishment of communications with neighbor networks.

Autonomous Network Reconfiguration

In some cases, depending on network traffic load and available spectrum resources, a network experiencing an interference problem can independently find a solution. If sufficient resources exist on another TVWS frequency, the network manager may reconfigure the network to the new frequency leaving the source of the interference on the old operating frequency. This is an autonomous network reconfiguration and usually uses one or more of the non-collaborative (autonomous) coexistence mechanisms listed in Table 2. An autonomous reconfiguration modifies some or all of the network parameters [14]. These network transmit parameters to be reconfigured may include the operating frequency, the transmit power, transmission schedule or even the signal bandwidth. Changing the operating frequency or the transmit power may be less difficult to reconfigure than the timing of transmissions or the operating signal bandwidth.

Negotiated Network Reconfiguration

If autonomous network reconfiguration is unable to solve the interference problem, the network experiencing the interference needs to negotiate spectrum sharing parameters with the network which is causing the interference. This presents a unique challenge for any coexistence standard since most unlicensed network management schemes are designed to operate at low channel loads, reserving unused channel resources to accommodate traffic variance and increasing loads. Sharing resources involves management decisions to decrease the amount of used or reserved spectrum resources which tends to increase channel utilization and can decrease network throughput. The 802.19.1 coexistence standard will need to define and standardize spectrum sharing decision algorithms which are fair and responsive to the needs of the affected networks.

After the network which is subject to interference has discovered the interfering network and established a communication link it is then necessary for the two networks to agree on what network or device reconfigurations are required to alleviate the interference. Even if a standardized algorithm can suggest a spectrum sharing solution, the two networks involved must agree on the suggested sharing solution and accept to operate using a subset of their current spectrum resources [28]. Furthermore, there is the need to monitor the neighbor network performance and spectrum utilization after reconfiguration. This monitoring information allows networks to evaluate the effectiveness of the negotiated reconfiguration.

IEEE 802.19.1 System Design

The 802.19 Task Group 1 produced a System Design Document (SDD) to describe the coexistence system to assist the call for proposal process [30]. The SDD includes system requirements, 802.19.1 architecture, terminology and a possible outline of the standard. In this section we summarize the coexistence system requirements and architecture defined in the SDD.

System Requirements

The coexistence system requirements can be grouped into four different categories: requirements related to discovery, general requirements, requirements related to communication, and requirements related to coexistence algorithms.

Requirement Related to Discovery — Only one requirement is related to discovery. The 802.19.1 system is required to enable discovery for 802.19.1 compliant WSD networks. The term discovery should be understood to mean the detection of other WSD networks and identification of their attributes, such as their IDs.

Requirements Related to Coexistence Algorithms — The first requirement in this group is related to TVWS environment analysis. After collecting operational environment information, such as available white space and current unlicensed users, from individual networks or other sources such as the TV bands database, an 802.19.1 system must analyze the data to determine if a coexistence problem exists.

Assuming there is a coexistence problem, the 802.19.1 system must have the capability and decision algorithms to alleviate or eliminate the coexistence problem.

The 802.19.1 system must support centralized, distributed and autonomous decision making for TVWS coexistence. This requirement underlines the possibility of having various approaches to implement decision making in coexistence scenarios. It also underlines that 802.19.1 must be capable to support these different approaches of decision making for coexistence.

Requirements Related to Communication — The 802.19.1 system must have a means to obtain and update information required to make TVWS coexistence decisions. Without constraining the mechanism of communication, this requires the

The coexistence system requirements can be grouped into four different categories: requirements related to discovery, general requirements, requirements related to communication, and requirements related to coexistence algorithms.

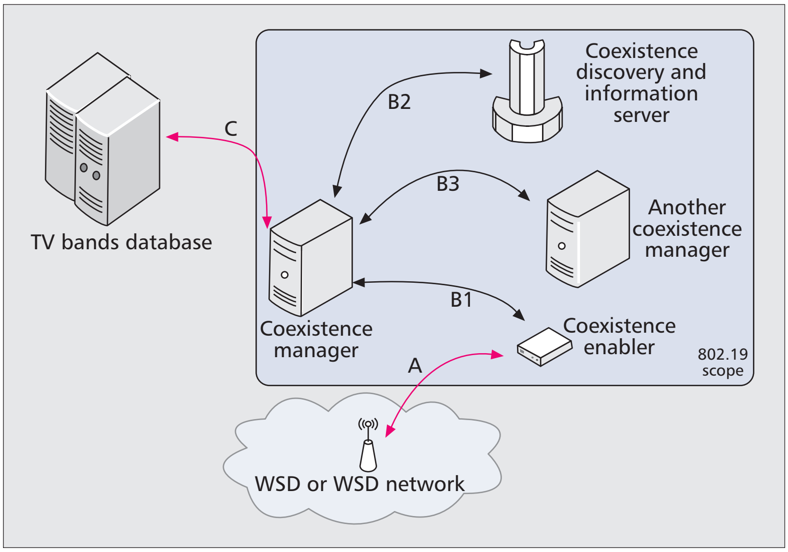


Figure 3. *The 802.19.1 system architecture.*

coexistence system to support one or more communications methods used by the 802.19.1 WSD networks. Additionally the TVWS coexistence system must be able to exchange information among its entities. The last requirement related to communication states that the 802.19.1 system must be able to provide network reconfiguration requests and/or commands as well as corresponding control information to 802.19.1 WSD networks to implement system coexistence decisions.

General Requirements — The last two requirements are related to security and general coexistence mechanisms. The 802.19.1 system must support appropriate security mechanisms, including but not limited to user/device authentication, integrity and confidentiality of open exchanges. Finally, the 802.19.1 system must utilize a set of mechanisms to achieve improved coexistence of WSD networks.

System Architecture

In the 802.19.1 architecture, logical entities are defined according to their functional roles [30]. There are five logical entities defined. Figure 3 illustrates the logical entities and interfaces between them.

In Fig. 3, the coexistence manager (CM), the coexistence discovery and information server (CDIS), and the coexistence enabler (CE) are entities of 802.19.1. The WSD (or WSD network) and TV bands database are outside the scope of the 802.19.1 standard [30].

Logical Entities — The WSD is the device which operates in the TVWS.

The TV bands database is the regulatory database which contains the location, operating area and schedule for all protected licensee stations, and provides lists of available TVWS channels to WSDs.

The CM is responsible for making coexistence related decisions. This includes generating and providing corresponding coexistence requests/commands and control information to CEs. The CM also assists network operators in management related to TVWS coexistence. Another responsibility of the CM is discovery of and communication with other CMs.

The CE is responsible for the communication between the CM and WSD. It obtains information required for coexistence from the WSD or WSD network, and translates reconfiguration requests/commands and control information received from the CM into WSD-specific reconfiguration requests/commands.

The CDIS provides coexistence related information to the CM and supports discovery of CEs. The CDIS also facilitates discovery and communication among CMs. Finally, the CDIS collects and aggregates information related to TVWS coexistence.

Logical Interfaces — There are six logical interfaces in the 802.19.1 system. Interfaces B1, B2 and B3 are between 802.19.1 entities, whereas interfaces A and D are between 802.19.1 entities and external entities. Interface A enables communication between the CE and the WSD. Reconfiguration requests or commands and coexistence related measurement requests flow from CE to WSD, whereas corresponding responses flow from WSD to CE. Interface B1 is between a CE and a CM. CM sends coexistence commands/requests to CE. CE provides coexistence related information. The B2 interface is between CM and CDIS. Through B2, information needed for discovery and coexistence flows both ways. For direct communication related to coexistence between CM's, interface B3 must be used. The last interface, interface C is between TV Bands Database and CM. It will be used mainly to obtain data related to available TVWS channels.

Reference Model

In the 802.19.1 system two service access points are specified:
- Coexistence Media SAP (COEX_MEDIA_SAP)
- Coexistence Transport SAP (COEX_TR_SAP)

COEX_MEDIA_SAP implements the interface A between the CE and a WSD. Figure 4 shows a typical reference model of a radio interface including data, control and management planes for physical layer, MAC sublayer, and convergence sublayer on the left side. The base station management entity is in the middle part of the figure and the right part shows the CE.

In Fig. 4, there are three service access points PHY_ME_SAP, MAC_ME_SAP, and CS_ME_SAP, which provide management interface for the base station management entity. These service access points can be used to obtain information from the radio interface and to request reconfiguration of the radio interface. Coexistence enabler can access those service access points through the base station management entity using COEX_MEDIA_SAP.

On the other hand, the COEX_TR_SAP provides means for CE, CM and CDIS to communicate with each other and with external entities by using transport services provided by underlying layers. The underlying layers could be the application layer, transport layer, network layer, and link layer.

CONCLUSIONS

To assist the wireless technology community in the process of developing strong and relatively easy to implement coexistence mechanism standards for TVWS, we have reviewed the need for coexistence and the technical challenges to address in the development of a TVWS coexistence standard. We have also provided an overview of the system design and various existing coexistence mechanisms that may provide a foundation for the development of the TVWS coexistence standard. The co-authors hope that by sharing this information with the larger engineering community, this article will trigger analytical thought and discussion to accelerate the development and improve the quality of the IEEE 802.19.1 TVWS Coexistence standard.

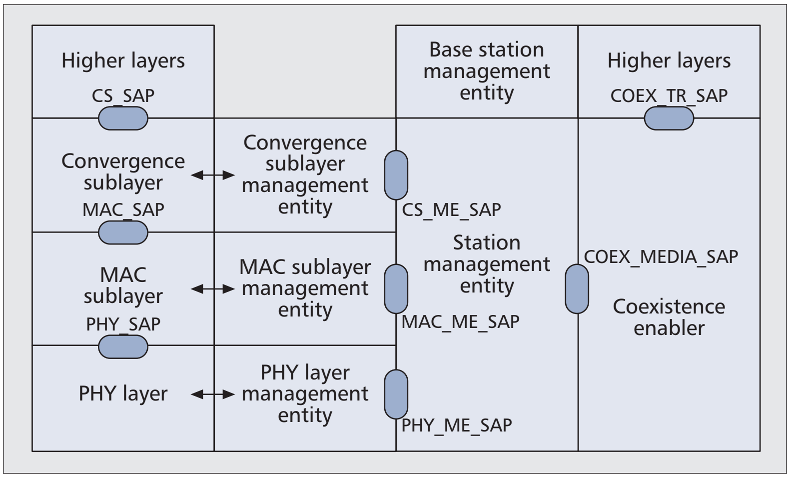


Figure 4. *Example reference model showing the CE within a base station protocol stack.*

REFERENCES

[1] P. Marshall, "XG Communications Program Information Briefing," Apr 2005, www.daml.org/meetings/2005/04/pi/DARPA_XG.pdf

[2] FCC, "Second Memorandum Opinion and Order In the Matter of Unlicensed Operation in the TV Broadcast Bands, Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band," docket 10-174, Sept. 2010.

[3] FCC, "Second Report and Order and Memorandum Opinion and Order In the Matter of Unlicensed Operation in the TV Broadcast Bands, Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band," docket 08-260, Nov. 2008.

[4] Ofcom, "Digital Dividend: Cognitive Access Statement on License Exempting Cognitive Devices Using Interleaved Spectrum," July 2009.

[5] Ofcom, "Geolocation for Cognitive access: A Discussion on Using Geolocation to Enable Licence-Exempt Access to the Interleaved Spectrum," Nov. 2009.

[6] Ofcom, "Implementing Geolocation," Nov. 2010.

[7] Ofcom, "Implementing Geolocation, Summary of Consultation Responses and Next Steps," Sept. 2011

[8] Industry Canada, "SMSE-012-11: Consultation on a Policy and Technical Framework for the Use of Non-Broadcasting Applications in the Television Broadcasting Bands Below 698 MHz," Aug. 2011.

[9] IEEE 802.18 Radio Regulatory Technical Advisory Group, "Response to the Industry Canada Consultation on a Policy and Technical Framework for the Use of Non-Broadcasting Applications in the Television Broadcasting Bands Below 698 MHz," Oct 2011, available: https://mentor.ieee.org/802.18/dcn/11/18-11-0075-04-0000-ieee-802-response-to-canadian-tvws-consultation.doc

[10] ECC, "Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the "White Spaces" of the Frequency Band 470–790 MHz," Jan. 2011.

[11] iDA, "Trial of White Space Technology Accessing VHF and UHF Bands in Singapore," July 2010.

[12] FCC, "Notice of Inquiry, Promoting More Efficient Use of Spectrum Through Dynamic Spectrum Use Technologies," (et docket 10-237)," Dec. 2010.

[13] IEEE Std 802.22-2011, "IEEE Standard for Information technology Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks Specific Requirements — Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands," July 2011, pp. 1–680.

[14] A. Moody and G. Chouinard, "IEEE 802.22 Overview and Core Technologies," June 2010; https://mentor.ieee.org/802.22/dcn/10/22-10-0073-02-0000-ieee-802-22-overview-and-core-technologies.pdf.

[15] IEEE Std 802.11-2007, "IEEE Standard for Information Technology Telecommunications and information Exchange Between Systems Local and metropolitan Area Networks Specific Requirements — Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," June 2007.

[16] "Project Authorization Request for IEEE Standard for Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements — Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment: TV White Spaces Operation," Dec. 2009.

[17] Std ECMA-392, "MAC and PHY for Operation in TV White Space," Dec. 2009.

[18] European Commission Information Society and Media Directorate, "Radio Spectrum Policy Group — Opinion on Cognitive Technologies," Feb. 2011.

[19] IEEE Std. 802.22.1, "IEEE Standard for Information Technology Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks Specific Requirements Part 22.1: Standard to Enhance Harmful Interference Protection for Low Power Licensed Devices Operating in TV Broadcast Bands," 2009.

[20] "Project Authorization Request for IEEE Standard for Local and Metropolitan Area Networks Part 15.4: Low Rate Wireless Personal Area Networks (LR-WPANs) Amendment: TV White Space Between 54 MHz and 862 MHz Physical Layer" July 2011.

[21] "Project Authorization Request for P1900.7 Radio Interface for White Space Dynamic Spectrum Access Radio Systems Supporting Fixed and Mobile Operation," June 2011.

[22] C. S. Sum *et al.*, "WS Radio Usage Models (IEEE doc. Scc41-ws-radio-10/5r0)," Apr. 2010.

[23] K. Harrison, S. M. Mishra, and A. Sahai, "How Much White Space Capacity is There?," *Proc. 4th IEEE Int'l. Symp. New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2010)*, Singapore, May 010

[24] M. Nekovee, "Quantifying the Availability of TV White Spaces for Cognitive Radio Operation in the UK," *Proc. IEEE Int'l. Conf. Commun. Wksps. (ICC'09)*, Dresden, Germany, June 2009.

[25] C. Ghosh, *et al.*, "Coexistence Challenges for Heterogeneous Cognitive Wireless Networks in TV White Spaces," *IEEE Wireless Comm. Mag.*, vol. 18, no. 4, Aug. 201, pp. 22–31.

[26] J. Huang *et al.*, "Beyond Co-existence: Exploiting WiFi White Space for ZigBee Performance Assurance," *Proc. Int'l. Conf. Network Protocol (ICNP'10)*, Kyoto, Japan, Oct. 2010.

[27] N. Golmie, *Coexistence in Wireless Networks: Challenges and System-Level Solutions in the Unlicensed Bands*, Cambridge U. Press, 2006.

[28] B. A. Fette, *Cognitive Radio Technology*, Elsevier Inc, 2006.

[29] IEEE Std 802.16h-2010, "IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Broadband Wireless Access Systems Amendment 2: Improved Coexistence Mechanisms for License-Exempt Operation," Apr. 2010.

[30] T. Baykas, M. Kasslin, and S. Shellhammer, "System Design Document," Mar. 2010, available: https://mentor.ieee.org/802.19/dcn/10/19-10-0055-03-0001-system-design-document.pdf.

Biographies

Tuncer Baykas [S'02, M'08] (tuncerbaykas@nict.go.jp) received his B.A.Sc. degree in electrical engineering from Bogazici University, Istanbul, Turkey, in 2000. He received his M.A.Sc. and Ph.D. degrees, both in electrical engineering, from the University of Ottawa, Ontario, Canada in 2002 and 2007, respectively. In 2007 he joined NICT as an expert researcher. He served as secretary and subeditor for the IEEE 802.15 WPAN Task Group 3c (802.15.3c) Millimeter Wave Alternative PHY group. Currently, he is the chair of IEEE 802.19 Task Group 1, Wireless Coexistence in the TV White Space. He served as TPC Vice Chair of PIMRC 2009 and TPC Chair of Cogcloud 2010. His research interests include receiver design, interference mitigation and cognitive radio systems.

Mark Cummings holds a Ph.D. from Tohoku Imperial University in Japan, and an M.B.A. from the Wharton School. He is special assistant to the vice president for research and dean of the Graduate College, and research professor of computer and information sciences, Kennesaw State University, Atlanta, Georgia; CTO of Orchestral Networks; managing partner, enVia Technology Partners, Inc.; and special member, Board of Directors, SVC Wireless (Silicon Valley China Wireless Technology Association). He currently participates in IEEE 802 and 3GPP SA5. Previously he was a member of the TV White Space Data Base Group. He is the principal inventor on the first patent granted for Software Defined Radio (SDR). Earlier in his career, he founded three wireless venture backed startups, and held technical, marketing, finance, and management positions in communications common carriers and large end users. He founded the Pocket Intelligence Program at SRI International (Stanford Research Institute). He has over 200 publications, three granted patents, and three in process.

Hyunduk Kang (henry@etri.re.kr) received his B.Eng. degree from the Department of Electronics Engineering of Dong-A University, Busan, South Korea, in 1997, and his M.S. and Ph.D. degrees from Gwangju Institute of Science and Technology (GIST), Gwang-Ju, South Korea, in 1999 and 2006, respectively. In 2006, he joined the Electronics and Telecommunications Research Institute (ETRI) as a senior member of engineering staff in the radio technology research department. He has been involved in several projects regarding radio resource management and performance evaluation of cognitive radio systems. He is currently participating in IEEE 802.19.1 on wireless coexistence in the TV white space.

Mika Kasslin (mika.kasslin@nokia.com) is a principal engineer at Nokia, currently doing research and development in the area of cognitive radio systems. Since joining Nokia in 1992, he has been involved in numerous projects covering digital broadcasting systems, short-range radio communications, multiradio access, and wireless mesh networking. He received an M.Sc. in technical physics from Helsinki University of Technology.

Joe Kwak (joekwak@sbcglobal.net) has been a consultant to the wireless industry for twenty years. His primary area of interest are standards development for 3G/4G cellular and wireless networking in PAN, LAN and WAN systems. He has been an active contributor in standards projects in IEEE, ETSI, and CTIA. His client list includes InterDigital Communications, Motorola, Lucent, Golden Bridge Technology, Pacific Communications Sciences, Titan Corporation, Epsilon Lambda, and DelCan. Prior to his consulting career, he was employed doing design and R&D for government and Department of Defense communication system projects at General Dynamics, Logicon, Linkabit, and M/A-COM Government Systems. He earned his B.S.E.E. Summa Cum Laude from Illinois Institute of Technology and his M.S. in biomedical engineering Cum Laude from Northwestern University. He is a California licensed Professional Electrical Engineer, and has been awarded a reasonable number of U.S. and international patents for wireless innovations.

Alex Reznik [SM] (Alex.Reznik@interdigital.com) is a senior principal engineer at InterDigital, currently leading the company's research and system design activities in the area of IP mobility and heterogeneous networks. Since joining InterDigital in 1999, he has been involved in a wide range of projects, including leadership of 3G modem ASIC architecture, design of advanced wireless security systems, and coordination of standards strategy in the cognitive networks space. He earned his B.S.E.E. Summa Cum Laude from The Cooper Union, S.M. in electrical engineering and computer science from the Massachusetts Institute of Technology, and Ph.D. in electrical engineering from Princeton University. He holds a visiting faculty appointment at WINLAB, Rutgers University, where he collaborates on research in cognitive radio, wireless security, and future mobile Internet. He is an inventor of over 50 granted U.S. patents, and has been awarded several President's and CTO awards for Innovation at InterDigital.

Rashid A. Saeed [SM] (eng_rashid@ieee.org) received his B.Sc. in electronics from Sudan University of Science and Technology (SUST); his MSc. from KU, Sudan; and his Ph.D. in wireless communications from UPM, Malaysia. He served as senior researcher in MIMOS Berhad and TMR&D, in 2007 and 2010, respectively. He has been awarded the "platinum badge" as one of the best researchers in MIMOS. Recently, he returned to SUST. He has published over 100 research papers in the areas of UWB, cognitive radio, and radio resources management. He has also been awarded two U.S. and 10 Malaysia patents. He is a certified WiMAX engineer (RF and core network). He is also a Six Sigma™ certified Black Belt based on DMAIC++ from Motorola University. He is a member of IEM Malaysia and Sigma Xi.

Stephen J. Shellhammer [SM] (sshellha@qualcomm.com) is a member of the Qualcomm corporate research and development department. He is currently the chair of the IEEE 802.19 working group on wireless coexistence, leading a project on TV white space coexistence. He is currently a member of the IEEE 802 Executive Committee. He was the chair of the IEEE 802.15.2 task group on wireless coexistence between WiFi and Bluetooth. Before joining Qualcomm he was a wireless architect in Intel's wireless local area network division. Previously he was the director of the Advanced Development Department at Symbol Technologies. He was an adjunct professor at the State University of New York at Stony Brook, where he taught graduate courses in electrical engineering. He has a Ph.D. in electrical engineering from University of California Santa Barbara, an M.S.E.E. from San Jose State University, and a B.S. in physics from the University of California San Diego. He has over 20 issued patents.