Ad Hoc Networks 27 (2015) 195–218

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Survey Paper

A survey of MAC issues for TV white space access

You Han [a,*], Eylem Ekici [a], Haris Kremo [b], Onur Altintas [b]

[a] Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43210, USA
[b] Toyota InfoTechnology Center Co., Ltd, Tokyo, Japan

ARTICLE INFO

Article history:
Received 5 July 2014
Received in revised form 1 November 2014
Accepted 4 November 2014
Available online 10 December 2014

Keywords:
TV white space
Cognitive radio
Medium access control
Survey
Open research issues

ABSTRACT

The opening of TV white space (TVWS) bands for cognitive access is one of the first tangible steps to solve spectrum scarcity problem in current wireless networks. However, this has also raised many new challenges to efficiently use the TVWS spectrum. One of the primary challenges is the design of efficient Medium Access Control (MAC) protocols that conform to various rules imposed to protect primary users as well as accommodate spatio-temporal variations of the TVWS spectrum. This article presents MAC-related challenges related to cognitive access to TVWS, discusses potential approaches to overcoming these challenges, and investigates open research issues. It also reviews regulatory activities in several countries and worldwide standardization efforts for TVWS access.

1. Introduction

The spectrum scarcity problem is becoming more and more challenging in current wireless networks due to exponential growth of wireless traffic. The Cognitive Radio (CR) paradigm has emerged as an efficient method to improve spectrum usage and help to address the spectrum scarcity problem. The idea of CR is to allow unlicensed devices to access underutilized licensed spectrum without causing harmful interference to incumbent communication services. The U.S. Federal Communications Commission (FCC) has published its final regulations to allow unlicensed radio devices to operate in the broadcast television spectrum at locations where that spectrum is not being used by licensed services. The spectrum is termed "TV white space" (or "TVWS"). TVWS access is a promising method to address spectrum scarcity problem due to large amount of TVWS spectrum resources and better propagation properties of TVWS channels.

One of the primary challenges of TVWS access is the design of efficient Medium Access Control (MAC) protocols. The cognitive MAC protocol is required to not only protect primary users (PUs) (e.g., TV stations and wireless microphones) from harmful interference caused by secondary users (SUs), but also deal with spatial–temporal variations of TVWS. Additionally, a cognitive MAC protocol must enable the coexistence of heterogeneous TV band devices (TVBDs) to operate in TVWS, which is very challenging due to significant differences of these TVBDs in terms of signal characteristics (such as bandwidth, modulation and power spectral density), transmit power levels, PHY/MAC techniques and mobility characteristics. Furthermore, increased mutual interference in TVWS makes the design of cognitive MAC protocols more difficult. More specifically, mutual interference in TV bands is significantly increased due to better propagation properties of TVWS channels, such as higher aperture gain, lower diffraction losses, less scattering, excellent RF penetration depth.

In this article, we survey MAC related issues for TVWS access, discuss potential approaches to addressing these issues and investigate open research issues. In Section 2, we discuss discovery of spectrum opportunities in TVWS. In Section 3, coexistence related issues are discussed in

* Corresponding author.
E-mail addresses: han.639@osu.edu (Y. Han), ekici.2@osu.edu (E. Ekici), hkremo@jp.toyota-itc.com (H. Kremo), onur@jp.toyota-itc.com (O. Altintas).

http://dx.doi.org/10.1016/j.adhoc.2014.11.009
1570-8705/

detail, including classification of coexistence issues and approaches, coexistence of homogeneous and heterogeneous secondary networks in TVWS. Section 4 focuses on operational issues on TVWS access, i.e., dealing with fragmentation of TVWS, diverse transmit power levels of TVBDs, design of efficient channel assignment mechanisms, seamless migration from SUs' licensed spectrum to TVWS, cognitive spectrum handoff in TVWS, quality of service provisioning and support of broadcast in TVWS. Then we review regulatory activities in several countries and worldwide standardization efforts on TVWS access in Sections 5 and 6, respectively. Finally, we conclude the article in Section 7.

MAC issues in CR networks have been widely explored, and many survey papers have been published to investigate these issues in both general CR networks (e.g., [1–4]) and CR networks operating in TVWS (e.g., [5–7]). Compared with these works, the contributions of this survey can be summarized as follows:

1. Provide a more comprehensive summary of MAC issues and corresponding methods on TVWS access. First, we include numerous MAC issues that were not widely explored in existing surveys on CR MAC protocols (e.g., [1,2]). For example, various coexistence issues in CR networks discussed in this paper have been rarely investigated in existing surveys. Second, compared with previous surveys on TVWS access (e.g., [5,6]), we consider more novel issues, e.g., fragmentation of TVWS spectrum, quality of service provisioning and migration from SUs' licensed spectrum to TVWS.
2. Extend existing analysis on many existing MAC issues. Even though many MAC issues in this paper have been discussed in previous surveys, we extend these works and provide more insights on these issues. For example, geo-location/database access for the discovery of spectrum opportunities was discussed in [5,6], but the authors only introduced basic concepts on this method. In contrast, in this paper, we provide a comprehensive analysis on this issue by investigating many related issues, such as bootstrapping problem, localization error and database access delay.
3. Explore open research problems on every specific MAC issue and propose potential solutions. Most existing surveys focus on summarizing previous works on CR MAC protocols or MAC issues on TVWS access. Hence many of them did not provide sufficient insights on open issues and potentially new research problems in this area. In contrast, in this paper, we explore open research problems related to every MAC issue in detail, and provide potential approaches to dealing with these issues. For example, in the discussion of spectrum handoff in TVWS, we propose four open research problems: spectrum handoff with known PU activities, spectrum handoff due to channel quality deterioration, modeling of handoff performance and impact of mobility on spectrum handoff.
4. Provide more comprehensive information on worldwide regulatory and standardization activities. In addition to research progress in the academia, we also survey state-of-the-art TVWS related regulatory activities in different countries as well as standardization activities in the industry. All these efforts are supposed to motivate more research efforts in TVWS access.

2. Discovery of spectrum opportunities in TVWS

There are generally two requirements on the efficient discovery of spectrum opportunities in TVWS. The first requirement is reliable protection of PUs, i.e., TVBDs can only access TVWS channels not used by PUs. The second requirement is to make the most use of TVWS spectrum resources subject to the first requirement. Two methods are available for the discovery of available TVWS channels: geo-location/database access and spectrum sensing. Geo-location/database has been regarded as the primary method to discover available TVWS channels by both FCC and Ofcom [8,9]. In page 24 of [8], FCC even eliminates the spectrum sensing requirement for TVBDs relying on geo-location/database access to obtain availability information of TVWS channels, because "the geo-location/database access method and other provisions of the rules will provide adequate and reliable protection for television and low power broadcast auxiliary services". For sensing-only TVBDs, FCC has changed the minimum required detection threshold for wireless microphones from −114 dBm to −107 dBm [8]. Before we proceed to discuss the two methods for the discovery of available TVWS channels, we first give a brief introduction to the classification of TVBDs proposed by FCC.

As shown in Table 1, FCC classifies TVBDs into two categories: fixed devices and personal/portable devices [10]. Fixed devices are required to register with a database and determine their geographic locations through incorporated geo-location capability and obtain TVWS availability information through database access. Personal/portable devices are further classified into three types: Mode 1 (client mode), Mode 2 (independent mode) and sensing-only devices. Portable devices operating in Mode 1 obtain the list of available channels from a fixed device or a portable device operating in Mode 2, and Mode 2 portable devices determine available channels through geo-location/database access. Sensing-only portable devices obtain availability information merely through spectrum sensing. Fixed devices are allowed to operate at up to 1 Watt output power and to achieve 4 Watts equivalent isotropically radiated power (EIRP) with a gain antenna. In contrast, transmit power of portable devices must be less than 100 mW EIRP, with no antenna gain. When portable devices operate on a channel adjacent to the operating channel of a TV station or other licensed station/service and within the protected coverage area of that service, their transmit power is limited to 40 mW. Moreover, for sensing-only portable devices, the detection threshold becomes −107 dBm for low power auxiliary signals.

2.1. Geo-location/database access

TV band databases aim to provide TVBDs, upon request, available TVWS channels at the TVBD's location. The availability of a TVWS channel is determined based on PUs' location information stored in the databases and

Table 1
Classification of TVBDs [8,10].

TV band devices	Determine channel availability	Maximum transmit power (EIRP)	Detection threshold	In service monitoring
Fixed device	Geo-location/database access	1 W/6 MHz	−114 dBm	At least once a day (database access)
Portable device (Mode 1)	From a fixed device or Mode 2 portable device	100 mW/6 MHz	−114 dBm	At least once every 60 s
Portable device (Mode 2)	Geo-location/database access	100 mW/6 MHz	−114 dBm	At least once a day and once for every 100 m move
Portable device (sensing only)	Spectrum sensing	50 mW/6 MHz	−114 dBm	At least once every 60 s

regulator's requirements on the protection of PUs (e.g., Section 15.1712 in [10]). For example, FCC requires that location information of PUs must be stored in databases. Protected PUs include digital television stations, private land mobile radio service stations, and protected areas include sites where low power auxiliary stations (including wireless microphones and wireless assist video devices) and television translator station receive sites [10]. Before accessing TV band databases, both fixed and Mode II TVBDs must register with the databases. Then TVBDs determine their location information and send channel access requests to the database in their region. After receiving the channel request from a TVBD, the database checks availability contour of each TVWS channel and notifies the TVBD available channels at its location. According to FCC's rules [8,10], portable TVBDs are required to access the database again when they move 100 m away from the location of their previous access.

Open research issues:

- Bootstrapping problem: For TVBDs merely relying on geo-location/database access to obtain TVWS availability information, the bootstrapping problem is that a new TVBD cannot send its location and channel request to any database, since it does not know available TVWS channels at its location. This problem can be easily solved in infrastructure-based networks like those designed for Internet access in rural areas. In that case, the base station (BS) already has access to the Internet through which it is able to query the database. Each BS can periodically broadcast messages containing channel availability information in its coverage region [11]. Additionally, the BS can periodically switch to each available channel and listen to clients who want to join. However, this method only applies to infrastructure-based networks and it is still an open issue to solve the bootstrapping problem in ad-hoc networks. If, in an ad-hoc network, nodes have additional radio like 3G, they are able to access the database through this radio. If not, an intuitive solution would be to incorporate spectrum sensing capability in such TVBDs. However, this method does not work for TVBDs without sensing capability.
- Localization error: According to FCC's rules [10], TVBDs are required to determine their location with an accuracy of 50 m, which is very challenging in practice. Actually, having a GPS receiver does not always guarantee satisfying geo-location accuracy for TVBDs. The geo-location accuracy depends on the signal strength which deteriorates due to many factors, such as water vapor in the atmosphere, path loss, multipath fading and shadowing caused by blocking objects (e.g., trees and buildings, etc.). For example, experiment results in [12] show that localization error can exceed 50 m by almost 100% in rainy days even with six satellites. In addition, according to the measurements in [11], location errors can result in significant loss of available TVWS spectrum opportunities. In [13], a sensing enabled localization and tracking system is proposed which is shown to achieve a localization accuracy less than 50 m. The system localizes TVBDs based on their measurements of PU signals in TVWS. However, this method also requires the incorporation of sensing capability for TVBDs and thus does not work for TVBDs without sensing capability.
- Database access congestion: Two factors may lead to the congestion of database access: high density and mobility of TVBDs. According to FCC's rules [8,10], a portable TVBD must access the database again whenever it moves 100 m away from the location of its previous access. Given this rule, it is shown in [12] that mobile TVBDs' frequent access of a database would cause congestion at the database. To address this issue, FCC allows a region-based database access procedure to reduce the number of channel availability requests [14]. However, the number of available channels decreases with the expansion of the region, since the availability of a channel requires that it is not being used by all PUs in the region. Since performance of the region-based database access procedure depends on size of the region as well as PU activities in the region, it is still unclear whether it would solve the database congestion problem without loss of TVWS spectrum opportunities. In [15], a white space vector scheme is presented to represent complex geographical white space information in a much simpler way. The scheme allows TVBDs to reduce the amount of downloaded data from databases. However, the simplification of the geographical white space information would sacrifice the accuracy of the availability information.
- Geo-location/database access delay: Bounding geo-location/database access latency within a certain threshold is very important for both a mobile cognitive network and a cognitive network supporting delay-sensitive applications. For example, in the vehicular environment, vehicles cannot obtain real time TVWS availability

information if the geo-location/database access delay is too long, which either causes harmful interference to PUs or missed spectrum opportunities. In [16], it is shown that existing methods incur much latency by checking overlapping areas of protected contours and SU's operation area for the protection of PUs. The authors propose to submit SU's preferred channels to the database to reduce computation time and access delay. However, this method does not apply to mobile networks since available channels of each mobile TVBD keep changing. A possible solution is that the database determines available TVWS channels at all locations of a region offline for a mobile TVBD based on the TVBD's route. Thus the TVBD does not need to access the database until it leaves the region. However, this method would fail if available TVWS channels change too quickly, such that some of the available channels at a certain location become unavailable when the vehicle arrives at the location.

- Propagation modeling accuracy: According to FCC's current rules [8,10], each database determines the availability of a TVWS channel solely depending on a propagation model. However, the accuracy of these databases can be low due to sophisticated propagation and showing properties of the TVWS spectrum as well as variable communication environments (e.g., interference, noise and obstacles like trees and buildings). For example, experiment results in [17] show that the databases tend to over-predict the coverage of certain TV broadcasts, and thus unnecessarily blocks the usage of TVWS spectrum in a large area (up to 42% measured locations). To solve this problem, one option is to improve the propagation model. For example, in [18], a combination of an up-to-date database of incumbents, sophisticated signal propagation modeling, and an efficient content dissemination mechanism is proposed to ensure efficient, scalable and safe TVWS network operation. An alternative method is to replace the propagation model with actual measurement of radio signals. In other words, the databases determine the availability of channels based on measured radio signals. For example, spectrum sensors can be mounted on vehicles to periodically collect channel usage information, and report the results to databases [17,19]. However, there are still many system and networking issues regarding this method that remain unexplored. For example, this method can be constrained by the vehicle density in a certain region. The measurement accuracy may decrease with the decreasing of vehicle density. In addition, it is also a challenging networking problem for vehicles to cooperatively sense and report channel availability information.

2.2. Spectrum sensing

FCC requires that a sensing-only TVBD must keep sensing a TVWS channel for at least 30 s at bootstrap to determine availability of the channel [8,10]. Spectrum sensing is defined according to FCC's rules with other very challenging requirements. For example, the detection threshold is -107 dBm for both TV and microphone signals [8]. The performance of spectrum sensing is largely affected by the fundamental characteristics of wireless channels, such as path loss, noise uncertainty, multipath fading, and shadowing. For example, significant fading of a PU's signals in a direction makes it very difficult for SUs in that direction to detect the PU. Therefore, cooperative spectrum sensing has been extensively utilized to improve sensing performance in the literature [20,21], which will be discussed later.

General spectrum sensing technologies include energy detection [22], cyclostationary feature detection [23], compressed sensing [20], pilot sensing and detection for ATSC DTV signals [24], interference temperature measurement based detection [22], waveform based detection [3], matched filtering detection [22] and radio identification based detection [3]. Furthermore, there are several sensing technologies dedicated to the detection of wireless microphone signals, such as pattern recognition based sensing [5], sensing technique based on the correlations between RF signals and acoustic information [25], compressive sensing techniques based on fast Fourier sampling [26] and autocorrelation based spectrum sensing [27].

In addition to the aforementioned physical layer sensing techniques, scheduling of sensing is also crucial to the performance of spectrum sensing. Sensing scheduling usually aims to discover the most spectrum opportunities with the least time, by adjusting sensing parameters, such as set of channels to sense, sensing sequence, time to start sensing, sensing duration and period of re-sensing the operating channel. Since TVBDs have to interrupt their ongoing session to sense TVWS channels, the sensing scheduling should also consider the impact of spectrum sensing on the transmission efficiency of the TVBDs. For example, in [28], a sensing-period optimization scheme and an optimal channel-sequencing mechanism are developed to maximize spectrum opportunities that an SU can obtain and minimize the time of finding an available channel. In [29], the authors propose a stationary optimal spectrum sensing and access policy by viewing the sensing problem as a partially observable Markov decision problem. However, both of the two works fail to consider the scheduling of spectrum sensing of multiple SUs, which is more challenging and may need the cooperation of SUs.

Cooperative sensing has been extensively studied to maximize performance of spectrum sensing for multiple SUs. Existing cooperative sensing mechanisms can be classified into two categories: centralized [30–32] and distributed sensing [33–36]. For example, in [32], a centralized Bayesian decision rule based algorithm is proposed to maximize throughput of SUs by cooperative sensing. In [35], a distributed cooperative sensing mechanism is proposed to efficiently detect PUs. In this mechanism, each cognitive device observes and analyzes available channels, and shares its sensing results with other cognitive devices, such that the global performance of air interface detection is improved. A multidimensional-correlation-based sensing algorithm is proposed in [36] to minimize energy consumption. Based on the observation that, spectrum sensing information at a given space and time can represent spectrum information at a different point in space and time, the authors defined a new quality metric to evaluate the correctness of spectrum availability information. The proposed cooperative sensing algorithm is proved to achieve a distributed and near-optimal sensing scheme under certain easily satisfied assumptions.

Sensing PUs in mobile wireless networks is another important issue for spectrum sensing. However, most of the aforementioned sensing techniques and scheduling mechanisms fail to evaluate the impact of mobility on sensing performance. The performance of spectrum sensing is mainly affected by two characteristics of signals: multipath fading and shadowing fading. Hence the impact of mobility on spectrum sensing can be evaluated from the two perspectives. Multipath fading occurs because multiple replicas of a signal arrive at the sensor with different delays [12]. Rayleigh fading is usually used to model the effect of multipath fading. Shadowing fading is caused by blocking objects between the transmitter and the sensor, such as buildings and trees. The log-normal shadowing is mostly used to model the shadowing effect [37]. In [12], the authors estimated the effect of mobility on sensing by considering multipath fading. More specifically, given the Doppler spread effect caused by mobility of vehicles, it is shown that at low frequencies (e.g., TV band frequency) the channel coherence time is large and the channel appears as approximately time invariant for long time intervals. The impact of mobility on spectrum sensing is theoretically studied in [37] considering shadowing fading. It is proved that sensor mobility can yield a significant performance gain achieved by using spatial–temporal variations of received signals. The reason is that mobility of sensors helps decrease shadowing fading correlation of received signal strength and thus increases the performance gain of cooperative sensing.

Open research issues:

- Differentiate PU signals and SU signals: The fundamental challenge of spectrum sensing is that many sensing techniques (e.g., energy detection) are blind to distinguish PU signals from SU signals [8]. Since the availability of a TVWS channel only depends on PU activities, mistakenly regarding SU signals as PU signals would result in loss of spectrum opportunities. "Quiet period" is proposed to address this problem in IEEE 802.22 protocol, during which both 802.22 base stations and users must stop transmitting and sense their operating channel. However, other TVBDs (e.g., IEEE 802.11af devices or vehicular devices) may be transmitting during the "quiet period", which can be regarded as PU activities by 802.22 devices if blind methods are used. Instead, if feature detection (e.g., matched filter) is used, one might be able to discriminate different radios depending on SIR. However, it is probably inefficient to have matched filter for every possible radio/modulation sharing the band. A signal processing based method is proposed in [38] to distinguish different packet-based radio signals. However, the method is too computationally complex, and thus is not suitable for real time spectrum sensing. Therefore, new techniques or methods must be developed for spectrum sensing to differentiate PU and SU signals.
- Accurate detection of wireless microphone signals: The spectrum sensing problem is not a binary distinction between pure noise and wireless microphone signal in noise, because the "pure noise" indeed contains narrowband interference with strengths probably similar to microphone signal strengths, such as leakages from adjacent TV channels, quantization noise from analog-to-digital conversion (ADC), spurious emissions and unintentional transmissions from all types of electronic devices [5]. In [39], a spectrum sensing mechanism is proposed to enable the coexistence of SUs and wireless microphones, in which a new device called microphone protector is used to measure the interference level at a microphone receiver. In addition, a signaling protocol is proposed to notify TVBDs to optimize their transmissions (e.g., through subcarrier suppression technique) without causing harmful interference to microphones [39]. However, the approach only applies to the coexistence between wideband TVBDs and wideband microphones. Therefore more work needs to be done to address the coexistence issue between TVBDs and narrowband microphones. Besides, this approach requires an external sensing device, which may not be practical.
- Open issues on cooperative sensing mechanisms: The first open issue is the support of information exchange among SUs. The most common approach to addressing this issue is to use a separate control channel [40,41]. However, there may not exist such a common TVWS control channel which is available to all neighboring SUs due to spatial–temporal variations of TVWS. Another open issue is to reduce shadowing fading correlation of sensed data. It is proved in [42,43] that the performance of cooperative sensing would degrade when the shadowing fading correlation of sensed data increases. In [42,44], the performance degradation caused by correlated shadowing fading is studied in terms of loss of spectrum opportunities. Beam-forming and directional antennas have been proposed to address the shadowing fading correlation issue [45]. However, this method is not practical when SUs do not know the location of PUs (e.g., microphone users). In contrast, the problem may be better solved through optimal scheduling of spectrum sensing, i.e., optimally choosing TVBDs for cooperative sensing [46].
- Modeling of PU activities: A precise PU model is fundamental to the design of efficient spectrum sensing mechanisms. However, most existing spectrum sensing mechanisms are developed by simply assuming that PU activity on a channel follows with an ON–OFF Markov chain, which cannot capture the diverse characteristics of PUs in TVWS [47]. Moreover, inaccurate modeling of PU activities would result in either loss of spectrum opportunities or higher interference to PUs. Although there exist some empirical models on PU activities [48,49], they are not practical due to high computational complexity [47]. In addition, several other models have been proposed to model PU activities, such as Bernoulli random process, multidimensional Markov chain and M/G/1 queuing model [50]. However, they only

apply to activities of specific PUs and thus cannot be used to model all PU activities. Hence more precise and tractable models of PUs must be developed such that more practical and efficient spectrum sensing mechanisms can be further developed.

3. Coexistence issues

FCC's final regulations on TVWS access only include requirements on the coexistence of SUs (TVBDs) and PUs (i.e., requirements on the protection of PUs), and leave the coexistence of different TVBDs an important open issue. In this paper, "coexistence" means that multiple TVBDs in a certain area share the same TVWS band and are allowed to access the same band simultaneously. "Coexistence" is also interchangeable with "spectrum sharing" in this paper. In contrast, "coexistence" of PUs and TVBDs requires that TVBDs must not access the TVWS channels being used by PUs. The coexistence of diverse TVBDs is of great importance to the efficient use of TVWS. The reason is that TVWS is a public spectrum resource which can be used by all secondary wireless networks, and thus congestion and mutual interference among these networks can occur easily without effective coexistence mechanisms. However, it is very challenging to enable the coexistence of heterogeneous TVBDs in TVWS due to the following reasons.

1. Increased interference in TVWS: Mutual interference in TV bands is significantly increased due to better propagation properties of TVWS channels, as discussed in the introduction part of this article.
2. Scarcity of TVWS in urban areas: The number of available TVWS channels in a region depends on the amount of PU activities within the region. In urban areas, demand for spectrum is large while the amount of available TVWS spectrum is expected to be very small for the existence of large number of TV stations and microphones. Interference and congestion can be inevitable due to the significant imbalance between demand and supply of TVWS channels.
3. Diversity of TVBDs: TVBDs may be heterogeneous with respect to signal characteristics (such as bandwidth, modulation and power spectral density), transmit power levels, PHY/MAC techniques and mobility characteristics (e.g., static IEEE 802.22 networks and vehicular networks).
4. Asynchronous and uncoordinated TVBDs: TVBDs in heterogeneous secondary networks may not be coordinated for two reasons. The first reason is that a TVBD may be selfish and tend to maximize its own utility by competing with other TVBDs. The other reason is that heterogeneous TVBDs may not be able to coordinate with each other due to the lack of a common control channel. In addition, TVBDs in heterogeneous secondary networks may not be synchronized due to extreme difficulty to realize synchronization among heterogeneous networks [51].

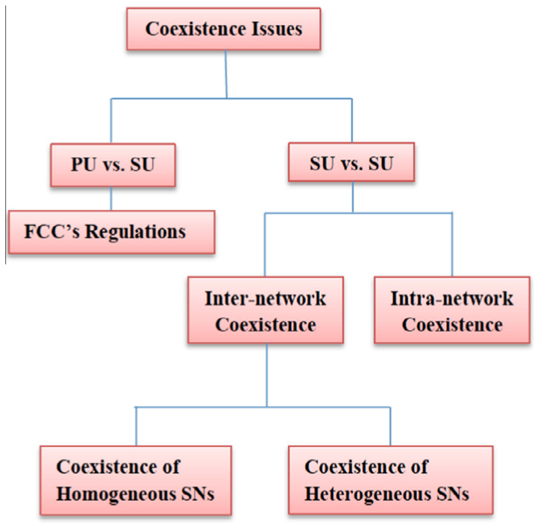


Fig. 1. Classification of coexistence issues.

3.1. Classification of coexistence issues and approaches

As shown in Fig. 1, coexistence issues on TVWS access can be generally classified into two categories: intra-network and inter-network coexistence issues. In this paper, "intra-network coexistence" denotes spectrum sharing of SUs within a single secondary network. In contrast, "inter-network coexistence" represents spectrum sharing among different secondary networks. Intra-network issues in CR networks have been extensively studied while inter-network coexistence issues are largely unexplored. Hence, in this paper, we only give a brief introduction to intra-network coexistence issues, and concentrate on inter-network coexistence issues. Inter-network coexistence issues in TVWS are further divided into two subcategories: coexistence of homogeneous secondary networks (SNs) and coexistence of heterogeneous SNs.

According to [22], approaches to intra-network coexistence issues can be classified from three perspectives: architecture assumption, spectrum allocation behavior, and spectrum access techniques. First, from the perspective of architecture assumption, intra-network coexistence approaches are classified into two categories: centralized and distributed approaches. In centralized approaches, a central entity is responsible for the coordination of all TVBDs within the secondary network [52]. In contrast, distributed approaches are often used in secondary networks where central entities are unavailable, such as CR ad-hoc networks [53]. Second, from the perspective of spectrum allocation behavior, intra-network coexistence approaches are also classified into two categories: cooperative [54] and non-cooperative [55] approaches. Third, from the perspective of spectrum access techniques, intra-network coexistence approaches are classified into overlay and underlay coexistence approaches. In overlay approaches, only channels not being used by other TVBDs can be accessed by a certain TVBD [56]. In contrast, underlay approaches allow multiple TVBDs to access the same channel simultaneously, on condition that they would not cause unacceptable interference to each other [56].

Although many ideas, terminologies and approaches for intra-network coexistence are also applicable for inter-network coexistence issues (e.g., cooperative coexistence, listen-before-talk), the two types of coexistence issues have significant differences. First, the goal of inter-network coexistence is to minimize mutual interference among multiple SNs, while intra-network coexistence approaches aim to maximize spectrum usage efficiency within a network. Second, inter-network coexistence issues are more challenging due to limited information exchange among SNs, sophisticated interference scenarios (e.g., varying overlapping users of multiple SNs), and heterogeneous characteristics of SNs.

Given the classification of inter-network coexistence issues, approaches to those issues are classified into two categories: approaches to the coexistence of homogeneous SNs and coexistence of heterogeneous SNs. From the perspective of coexistence architecture, those approaches can be divided into centralized and distributed approaches. In centralized approaches, a central entity (e.g., TVWS database [57]) manages available TVWS channels and controls the coordination of diverse SNs operating in TVWS. In distributed approaches, the steps of enabling coexistence for a SN in TVWS are enumerated as follows.

- Discovery of neighboring SNs: Since TVWS is an open spectrum resource, many diverse SNs would coexist in the same TVWS spectrum, such as 802.22 (WRAN), 802.11, LTE, cellular and vehicular networks. It's non-trivial for a SN to identify neighboring SNs because SNs not necessarily register with TVWS databases like PUs, especially for mobile SNs. A straightforward solution is spectrum sensing. However, spectrum sensing is insufficient for a SN to discover neighboring SNs since the neighboring SNs may be idle during the SN's sensing time. Future research can follow two directions to design mechanisms for the discovery of neighboring SNs: proactive and reactive mechanisms. In proactive mechanisms, an SN identifies all neighboring SNs even though it is not using TVWS channels or no interference has emerged in TVWS. An example is the Coexistence Discovery and Information Server (CDIS) used in IEEE 802.19.1. More specifically, the CDIS stores information (e.g., location and PHY/MAC techniques) of all neighboring SNs. Hence a SN can acquire the information by sending request to the CDIS. In contrast, in reactive mechanisms, a SN only discovers neighboring operating SNs when it intends to access TVWS channels or interference from other SNs is detected. Given the insufficiency of individual spectrum sensing, cooperative sensing can be used to discover neighboring SNs more reliably. For example, two methods are proposed in IEEE 802.22 for the discovery of neighboring 802.22 networks: network discovery at network initialization and at normal operation. In both ways, a SN must scan TVWS channels to detect self-coexistence beacons sent by other SNs.
- Detection of interference from other SNs: When a SN is operating on a TVWS channel, it has to periodically detect possible interference from other SNs and identify source of the interference. Existing detection approaches can be classified into two categories: spectrum sensing and infrastructure-based mechanisms. For example, periodical signaling and spectrum sensing are used in IEEE 802.22. More specifically, base stations schedule customer premise equipment (CPEs) to listen to certain TVWS channels, in order to receive self-coexistence beacons sent by neighboring 802.22 networks. Spectrum sensing can also be used to detect heterogeneous SNs. For example, a cyclo-stationary feature based sensing algorithm is proposed in [58] to detect heterogeneous CR networks in TVWS. The algorithm differentiates SNs (e.g., IEEE 802.11af and IEEE 802.22 networks) based on their OFDM parameters such as ratio of cyclic prefix. However, the sensing algorithm is not able to differentiate heterogeneous SNs with the same cyclo-stationary features. Hence PHY/MAC independent approaches are preferable for the detection and identification of heterogeneous SNs. For example, detection of SNs in IEEE 802.16 h is based on the use of coexistence databases which store information regarding the spectrum usage for certain local areas [59]. Similarly, in IEEE 802.19.1, CDIS provides coexistence information to coexistence managers and facilitates discovery of coexistence enablers. The CDIS also supports discovery and communication among coexistence managers [60].
- Mitigation of the interference: Generally, a SN can mitigate the interference by coordinating with the conflicting SNs or by adjusting its own transmission parameters (e.g., increasing transmitting power or switching to other channels). Instead of discussing diverse approaches to the mitigation of inter-network interference here, we delve into this issue in the following two paragraphs by discussing coexistence approaches to homogeneous and heterogeneous SNs, respectively.

3.2. Coexistence of homogeneous SNs in TVWS

Coexistence of homogeneous SNs in TVWS is also termed "self-coexistence" (e.g., in IEEE 802.22). Coexistence issues of homogeneous SNs are more challenging than the coexistence issues in traditional wireless networks due to spatial–temporal variations of TVWS and better propagation properties of TVWS channels. Furthermore, a SN to operate in TVWS may have its own licensed frequency band (e.g., cellular networks to offload part of their traffics to TVWS spectrum [61]), which makes its coexistence with other homogeneous SNs more difficult, since coexistence on both the SNs' licensed frequency and TVWS frequency must be guaranteed. This issue will be discussed later in detail in part *D* of this section.

3.2.1. General coexistence mechanisms

Existing coexistence mechanisms can be generally classified into two categories: non-cooperative and cooperative coexistence mechanisms. Non-cooperative coexistence mechanisms include transmit power control (TPC) [62], dynamic channel selection (DCS) [55] and listen-before-talk (LBT) [63]. Non-cooperative mechanisms are generally sufficient to enable coexistence in systems with adequate spectrum resources such that SNs can access different set of channels. However, such mechanisms may not work well in networks with large spectrum demand and much less spectrum resources, in which case cooperative mechanisms are preferable. Cooperative mechanisms include inter-network time-division multiple access (TDMA), frequency-division multiple access (FDMA), code-division multiple access (CDMA) and hybrid mechanisms [63]. A more detailed summary of existing coexistence solutions can be seen in Table 2.

The DCS mechanism has been widely used in enabling intra-network coexistence in CR networks [64]. The core idea of DCS is to enable SUs to select the best available channel (e.g., with the lowest interference level) based on their local observations of spectrum usage. This idea can also be used to address inter-network coexistence issues. More specifically, each SN keeps scanning available TVWS channels and chooses the best one by evaluating interference level of those channels. The LBT mechanism has been utilized for spectrum sharing among multiple IEEE 802.11 networks. The idea of LBT is that a transmitter decides whether a channel is available through a clear channel assessment (CCA) check before transmitting on the channel. Furthermore, the maximum contiguous transmission time is limited by a threshold such that a transmitter leaves reasonable opportunities for other transmitters [63].

A TDMA based coexistence mechanism is proposed in IEEE 802.22 to enable inter-network coexistence. The IEEE 802.22 WRAN system includes two operational modes: normal mode and self-coexistence mode [65]. In normal mode, an 802.22 network operates on one TVWS channel; while in the self-coexistence mode, multiple 802.22 networks share the same TVWS channel based on a TDMA mechanism. More specifically, when operating in self-coexistence mode, base stations (BSs) of several neighboring networks access the channel on a per frame basis, i.e., each BS is allocated a subset of frames of an 802.22 super-frame. The frame allocation is determined through negotiation of the neighboring BSs. In [66], a standard-independent framework is proposed to enable coexistence of homogeneous SNs through cooperative mechanisms. A cluster head equipment with multiple radios is used to acquire coexistence information, identify coexistence opportunities, and make coexistence decisions.

3.2.2. Game based coexistence mechanisms

Game-theoretic models have been used to address the issues of both intra-network coexistence [62,67] and inter-network coexistence [57,54], the goal of which is usually to find Nash Equilibrium (NE). Coexistence approaches can be implemented in both cooperative and non-cooperative mechanisms. In the inter-network coexistence game, multiple homogeneous SNs operating in TVWS are players. A player's actions include channel selection and power control. Utility functions can be many performance metrics, such as throughput and delay. Strategic form games, repeated games, asynchronous myopic repeated games and mixed strategy games can all be used to address coexistence issues [47].

A dynamic spectrum sharing scheme is proposed in [68] based on truthful mechanisms and virtual currency. In this work, the authors consider the case where every SU (player) estimates capacity of a free channel according to its local information, and sends the valuation (i.e., estimated capacity) to the spectrum manager. Then the spectrum manager determines a conflict-free allocation by implementing a truthful mechanism. Each SU pays for the allocation an amount which depends on the set of valuations. In addition, a virtual currency is defined to facilitate spectrum sharing. It is shown that these mechanisms can be modified to achieve different sharing objectives which are trade-offs between efficiency and fairness. Another spectrum selection game is proposed in [69] to enhance spectrum utilization in CR networks. In this work, a game theoretic model is proposed to evaluate spectrum management mechanisms. The spectrum selection process is treated as a non-cooperative game among SUs who are able to dynamically select the "optimal" spectrum opportunity, without causing harmful interference to

Table 2
Summary of existing coexitence methods in TVWS.

Coexistence methods	Homogeneous or heterogeneous	Cooperation type	Centralized or distributed	Key feature
Transmit power control [63]	Both	Non-cooperative	Both	Every SN decreases its interference to other SNs by adjusting transmit power
Dynamic channel selection [64]	Both	Non-cooperative	Distributed	Every SN selects the best available channels based on its local observations of spectrum usage
Listen before talk [82]	Both	Non-cooperative	Distributed	A transmitter does a clear channel assessment check before using the channel
TDMA [65]	Homogeneous	Cooperative	Distributed	Homogeneous SNs share available spectrum on a TDMA basis
Clustering-based solution [56]	Both	Cooperative	Centralized	Cluster head is responsible for coordinating inter-network communication and spectrum sharing
Game-based solutions [57]	Both	Both	Distributed	View each SN as a player and deal with the coexistence problem by formulating various games
IEEE 802.19.1 [60]	Heterogeneous	Cooperative	Centralized	Standard independent coexistence solution by using external coordination entities
Common control channel [79]	Both	Cooperative	Distributed	SNs coordinate with each other on a common control channel

PUs. Various quality measures for the spectrum opportunities are investigated and evaluated, including the spectrum bandwidth, and the spectrum opportunity holding time. Cost of spectrum mobility is also accounted in the model.

In [57], an auctioning based mechanism is proposed to enable coexistence of multiple home networks operating in TVWS. More specifically, the authors develop an online multi-unit, iterative auction mechanism by considering spectrum availability in multiple home networks and characteristics of TVWS. In this mechanism, a centralized spectrum manager plays the role of auctioneer and controls TVWS spectrum sharing among multiple home networks (bidders) through short-term auctions. One auction interval consists of one or more rounds involving interaction between the auctioneer and bidders. The auctioneer aims to meet the bidders' spectrum demands subject to their valuations, spectrum availability at different bidders and mutual interference relationships. In [70], another auction-based solution is proposed for spectrum sharing among multiple SUs, in which the bandwidth and power requirements of the SUs determine the bids. However, both of the two coexistence mechanisms can only be implemented in a centralized way. In addition, although algorithms proposed for game-theoretic coexistence models are usually proved to converge to a NE, the NE is generally not Pareto-optimal and may be quite inefficient in terms of system utility [71].

3.3. Coexistence of heterogeneous SNs in TVWS

Given that TVWS is an open spectrum resource, it can be expected that heterogeneous SNs would coexist in the same TVWS spectrum, such as IEEE 802.22, 8022.11af, LTE, cellular and vehicular networks. Those SNs may be of significant difference in terms of signal characteristics (e.g., bandwidth, modulation and power spectral density), transmit power levels, PHY/MAC techniques and mobility characteristics.

3.3.1. Coexistence of heterogeneous networks in the ISM band

Actually, coexistence of multiple heterogeneous wireless networks in the same spectrum band is not a unique issue of TVWS access, and it has long been a challenging problem for the ISM band access. The industrial, scientific and medical (ISM) frequency band is a license-free band, in which all related field wireless networks are allowed to operate, and thus neither resource planning nor bandwidth allocation can be guaranteed [72]. Typical wireless systems operating in the ISM band include IEEE 802.11, Bluetooth, Zigbee and IEEE 802.15.4. The coexistence of these heterogeneous networks is also a critical requirement for the efficient use of the ISM band, which is similar to the coexistence issue in TVWS. Hence many existing coexistence ideas and approaches for the ISM band can be used in TVWS coexistence issues (e.g., [72–76]).

However, there are still several significant differences between coexistence issues on the two bands, which requires us to develop new coexistence approaches for the TVWS band. First, all ISM networks have equal access priority while heterogeneous networks in TVWS can only operate as SUs. Hence in the inter-network coexistence issue on TVWS access, there is an additional concern for the protection of PUs. For example, ISM channels are always available while the availability of TVWS channels varies spatially and temporally due to uncertain PU activities. Second, mutual interference in TVWS is increased as discussed in the introduction part of this article. Therefore the inter-network coexistence of heterogeneous SNs in TVWS is more challenging and new coexistence mechanisms must be developed for the efficient use of the TVWS band. In next part, inter-network coexistence mechanisms dedicated to TVWS access are discussed.

3.3.2. Coexistence mechanisms for heterogeneous SNs in TVWS

The critical idea to enable inter-network coexistence of heterogeneous SNs is underlay spectrum sharing. More specifically, multiple SNs are allowed to access the same TVWS spectrum simultaneously on condition that each SN would not incur unacceptable interference to other SNs. In contrast, coexistence of SNs and PUs requires overlay spectrum sharing mechanisms, i.e., SNs are prohibited to access TVWS channels when PUs are operating on the channels. Existing coexistence mechanisms can be classified into two categories: centralized and distributed mechanisms.

In centralized mechanisms, a central spectrum manager controls spectrum allocation and transmit power control. For example, an inter-cell spectrum sharing framework is proposed in [56] for infrastructure-based CR networks. In this framework, base station (BS) of each cell is allowed to exploit both exclusive and common use mechanisms. In the exclusive spectrum usage mechanism, the BS selects the best channel among channels not being used by other cells. If all channels are being used by other cells, the framework switches to common use mechanism, in which a channel is used by neighboring cells simultaneously. The channel selection is based on interference and PU activities of all channels in neighboring cells. The proposed framework is shown to be able to maximize capacity of a cell while causing less interference to neighboring cells. However, the approach does not apply to ad-hoc networks without centralized controllers, especially to mobile SNs.

IEEE 802.19.1 is a standard-independent coexistence framework for the coexistence of heterogeneous SNs in TVWS. Here "standard-independent" means the coexistence mechanism is not affected by the standards that SNs follow (e.g., PHY/MAC techniques). Fig. 2 shows the framework of 802.19 coexistence enabling system. In this framework, coexistence manager (CM), coexistence discovery and information server (CDIS), and coexistence enabler (CE) are three basic entities [60]. The CM makes coexistence related decisions, including generating and providing corresponding coexistence requests/commands and control information to the CE. The CE facilitates communications between the CM and TVBDs. The CDIS provides coexistence related information to the CM and is responsible for discovering CEs. The advantage of this framework is guarantee of reliable and efficient coexistence of heterogeneous SNs. However, it is very expensive to implement since it requires the construction of too many entities.

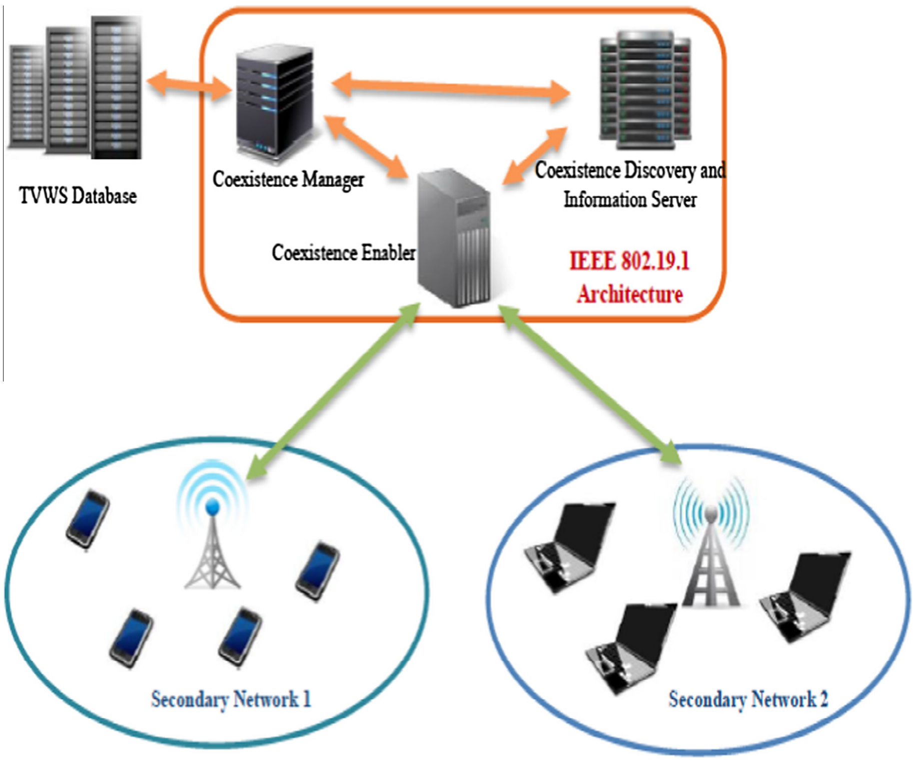


Fig. 2. IEEE 802.19.1 coexistence enabling system [60].

Hence it may not be practical in rural areas where density of TVBDs is very low.

Distributed inter-network coexistence approaches can be implemented in both cooperative and non-cooperative ways. All the non-cooperative coexistence mechanisms for homogeneous SNs in part *B* of this section also apply to inter-network coexistence of heterogeneous SNs since the mechanisms are standard-independent. Another category of existing coexistence mechanisms is cooperative mechanism which is usually game-theoretic mechanisms. For example, the inter-network spectrum sharing problem in CR networks is formulated as a stochastic bandit problem in [54]. The critical issue of the problem is that each agent tries to balance reward acquired by obtaining new knowledge and optimizing its decision based on already known knowledge. In the proposed stochastic bandit problem, there are several SNs and each SN has a finite state space. At each time slot, only one SN is active who will earn an active reward. Other passive SNs do not change states and earn passive rewards. The cooperative scheduling aims to maximize the aggregate expected discounted reward earned over an infinite horizon by choosing the optimal policy, i.e., determining which SN should become active at each slot. A hierarchy of increasingly stronger linear programming relaxations is proposed to solve the stochastic bandit problem which is based on the result of LP formulations of Markov decision chains [54]. However, the authors fail to consider many implementation issues under their solution, e.g., SNs may be asynchronous and have different signal characteristics as well as PHY/MAC techniques. In particular, the proposed mechanism only applies to SNs using OFDM technique. In addition, the utility function of each SN is not well defined since the authors neither give closed formula nor explain the explicit meaning of the "price" that each SN would pay for renting the spectrum band.

The inter-network coexistence problem is also studied in [77] on a game-theoretic basis. The authors take into account asymmetries and selfish behaviors of heterogeneous networks operating in the same unlicensed band. First, distributed self-enforcing spectrum sharing rules are proposed to improve spectrum efficiency and fairness of SNs. Then both a one shot game and a repeated game are formulated to model the interactions of the heterogeneous networks. In particular, it is shown that the repeated games can result in many self-enforcing outcomes, since a network is able to build reputation and apply punishment to other networks. It is further illustrated that performance loss due to selfish behaviors is small in many cases. However, this work is dedicated to coexistence problem in license-free band (e.g., ISM) and does not include CR functionality. In addition, the proposed work only applies to inter-network coexistence in single-channel scenarios. Hence the approach needs to be extended into multi-channel scenarios in order to be used in TVWS access. Another game-based model is proposed in [78] for the distributed spectrum sharing among heterogeneous wireless cognitive networks. QoS requirements of heterogeneous SNs are incorporated in the model and the proposed solution is proved to maximize overall spectrum utilization. However, the authors also fail to consider implementation issues under their solution, e.g., SNs may be asynchronous and have different signal characteristics as well as PHY/MAC techniques.

In addition to those game-theoretic models, there are many other inter-network coexistence ideas and approaches, such as the common spectrum coordination channel etiquette protocol [79], distributed QoS-based dynamic channel reservation scheme [80], adaptive frequency hopping [81] and cooperative busy tone [73]. However, most of them are dedicated to coexistence issues on ISM access, and thus should be incorporated CR functionality to be used in TVWS access.

3.4. Open research issues

Given existing coexistence ideas and approaches investigated above, reliable coexistence of multiple SNs in TVWS is still a largely unexplored issue, especially coexistence of heterogeneous SNs. In this part, we detail the open research issues for coexistence of multiple SNs in TVWS along with some possible solutions.

- Modeling and comparison of existing coexistence mechanisms: Although many ideas and approaches have been proposed to enable coexistence of multiple SNs in TVWS, most of them are lack of theoretical analysis. Hence it is still unclear to what extent these algorithms would solve the coexistence problem. For example, TPC, DCS and LBT are all non-cooperative inter-network coexistence mechanisms, but none of them have been theoretically analyzed and compared. In addition, although algorithms proposed for game-theoretic coexistence models are usually proved to converge to a NE, the NE is generally not Pareto-optimal and may be quite inefficient in terms of system utility [71]. Therefore it is critical to evaluate performance gap between the NE and Pareto optimum (e.g., the work in [62]), and compare the performance of game-based algorithms with other utility-optimal algorithms.
- Impact of mobility on coexistence issues: So far, few works have considered the impact of mobility on the coexistence of SNs in TVWS access. Actually, the coexistence problem would become much more challenging when mobility is taken into account for the following reasons. First, mobility of a SN would further increase spatial–temporal variations of TVWS availability. Second, it becomes more difficult for a SN to coordinate with other SNs when it moves constantly. Third, high mobility of a SN requires almost real time coexistence mechanisms. In other words, latency of the coexistence process (discovering neighboring SNs, detecting interference from other SNs and coordination with the SNs) must be very low in order to meet the delay requirements. Most existing coexistence mechanisms aim to optimize the throughput performance of a single SN or several cooperative SNs. However, few works have considered delay requirements of multiple SNs and delay-sensitive applications in TVWS (e.g., broadcast of safety related messages in vehicular networks).
- Design of cross-band coexistence mechanisms: Many SNs have their own licensed frequency band and only use TVWS channels on a "per need" basis, such as 802.11, cellular, LTE and vehicular networks. Hence it is possible to design cross-band coexistence mechanisms for these networks, where a SN decides to either share a TVWS channel with other SNs or access its own licensed channel when TVWS channels are congested. It makes the coexistence problem more challenging since a SN has to compare channel quality of its licensed band with the TVWS band. Although it seems that cross-band approaches are more efficient, many works are required to design cross-band mechanisms and compare them with single-band mechanisms. For example, in [61], the authors present two findings by analyzing TVWS access in cellular networks. First, cellular users achieve higher capacity by accessing their own licensed channels instead of TVWS channels when the inter-cell interference is generated by the same sources (i.e., neighboring cells). Second, TVWS channels can be assigned to cellular users far away from their base stations, whereas the licensed channels can be allocated to cellular users close to the base stations. The reason is that TVWS channels usually suffer less path loss than the cellular channels. Although this work is not dedicated to the coexistence of multiple SNs in TVWS, it presents the idea of "cross-band" channel access which matches cross-band coexistence in TVWS.
- Common control channel and inter-network synchronization: Most coexistence mechanisms require information exchange among multiple SNs. Hence common control channel (CCC) and inter-network synchronization are both required. However, it is still regarded as an open question that whether a CCC is available in TVWS [83]. One reason is that SNs may have different sets of available channels and no TVWS channels are available to all neighboring SNs. The other reason is that a pre-selected TVWS CCC can become unavailable due to the return of PUs or movement of SNs. Synchronization of heterogeneous SNs in TVWS is also a very challenging problem due to diverse PHY/MAC techniques used by heterogeneous SNs [51]. A potential solution is to use an out-of-band channel as the CCC. If a SN does not support out-of-band CCCs, multiple guard bands between digital TV signals can be aggregated to form a CCC [84]. Another method is to utilize Cognitive Pilot Channels (CPCs). A CPC is a channel which conveys necessary information facilitating the operations of CR systems [85]. For example, in [86], available band is divided into many sub-bands and the first two sub-bands are used as CPCs. So far, few works have been presented to address the inter-network synchronization issue in TVWS.

4. Operational issues

In addition to the coexistence issues, there are several operational issues on TVWS access (see Fig. 3), i.e., dealing with fragmentation of TVWS, dealing with diverse transmit power levels of TVBDs, design of efficient channel

Fig. 3. Operational issues on TVWS access.

allocation algorithms, seamless migration from SUs' licensed spectrum to the TVWS spectrum, cognitive spectrum handoff in TVWS, quality of service and broadcast related issues. These issues are of significant importance to the efficient use of TVWS since they are resulted from properties of TVWS (e.g., fragmentation, spatial–temporal variations), regulations on the protection of PUs (e.g., diverse transmit power levels of TVBDs) and special communication requirements of different TVBDs (e.g., QoS provisioning and support of broadcast).

4.1. Fragmentation of TVWS

Available TVWS spectrum is usually fragmented due to uncertain distribution of PU activities in the TVWS spectrum. The size of each spectrum fragment ranges from one channel to several channels. In fact, channel aggregation requirement is not unique for TVWS access. One of the key requirements for International Mobile Telecommunications Advanced (IMT-ADV) technologies (e.g., LTE-Advanced) is to enable transmission with variable and non-contiguous bandwidth [87]. Hence both 3GPP LTE and WiMAX (IEEE 802.16m) standards evolution have regarded carrier aggregation technologies as one of their major features in the future to meet the IMT-ADV requirements on the deployments of the fourth-generation wireless network. An overview of carrier aggregation framework and usage cases is presented in [87]. Although some carrier aggregation ideas and methods for IMT-ADV technologies also apply to TVWS access technologies, there are significant differences between operations in the two bands. The most important difference is that distribution of available spectrum fragments is fixed in IMT-ADV while it is variable in TVWS. In addition, carrier aggregation in IMT-ADV usually aims to obtain aggregated channels with constant bandwidth (e.g., 20 MHz for LTE), while the bandwidth requirement is more flexible in TVWS access. Therefore, new spectrum aggregation techniques are required for TVWS access.

Both PHY and MAC layer channel aggregation techniques have been proposed to address the fragmentation issue on TVWS access. For example, agile modulation and spectrum pooling techniques are PHY layer transmission techniques being able to aggregate fragmented TVWS spectrum [6]. One of these techniques is a variant of orthogonal frequency division multiplexing (OFDM), namely Non-Contiguous OFDM (NC-OFDM) [88]. Other techniques have been proposed to facilitate agile wave forming over fragmented spectrum, such as the use of filter bank multi-carrier techniques for CR applications [89].

A MAC layer spectrum aggregation mechanism is proposed in [90] to dynamically aggregate TVWS channels in a small area (e.g., a house or an office). The authors consider a wireless communication system consisting of a dynamic spectrum management (DSM) engine and multiple clients. The DSM engine manages interface to the TVWS database and dynamically allocates TVWS channels to DSM clients. Available TVWS spectrum fragments are termed "PHY chains" that are divided to different aggregation sets (or aggregate channels) by the DSM engine. A wide-band DSM agent is required to simultaneously operate on all PHY chains in an aggregation set. Receivers collect data from all the PHY chains of the aggregation set and obtain the transmitted packets. However, no algorithms are presented in this work to optimize the partition of PHY chains into disjoint aggregation sets. Actually, different partition algorithms would result in significantly different system performance.

Open research issues:

- Underlay sharing of fragmented spectrum: Almost all existing spectrum aggregation mechanisms only support overlay spectrum sharing. More specifically, in these mechanisms, a certain set of non-continuous TVWS channels are only allowed to be used by at most one TVBD. However, even though the availability of TVWS may vary at different TVBDs, it is possible that two TVBDs have some overlapping available TVWS spectrum fragments. Hence spectrum efficiency of TVWS would be improved if the two TVBDs are allowed to use the overlapping spectrum simultaneously, on condition that they would not cause unacceptable interference to each other. For example, transmit power control can be used at each TVBD to limit its interference to neighboring TVBDs. However, each TVBD has to also control its transmitting power in its remaining operating spectrum fragments since the transmit power must be constant in all its operating spectrum fragments. Intuitively, the transmit power is determined by the spectrum fragment with the minimum allowed transmit power. In other words, incorporating additional spectrum fragments may decrease a TVBD's transmitting power. Hence it is nontrivial to obtain a good trade-off between the number of operating TVWS fragments and transmitting power.

- MAC layer spectrum aggregation mechanisms: Although there are a few works on MAC layer spectrum aggregation, most existing aggregation mechanisms concentrate on designing PHY methods given the specific PHY technique of a certain SN. However, such PHY mechanisms may not be able to be extended to multiple SNs with heterogeneous PHY techniques. Considering the fact that heterogeneous SNs would coexist in TVWS, PHY-independent spectrum algorithms are preferable. Furthermore, future MAC layer spectrum aggregation algorithms can be associated with certain intra-network or inter-network coexistence mechanisms (e.g., [52,60]).

4.2. Diverse transmit power levels of TVBDs

According to FCC's regulations on TVWS access [8,10], fixed and portable TVBDs have different transmit power levels. More specifically, fixed devices are allowed to transmit with up to 4 Watts EIRP power, while the transmit power of portable devices is limited to 100 mW. Given the fact that fixed and portable devices have the same priority to access TVWS, the power asymmetry rule raises serious coexistence problem between fixed and portable TVBDs, i.e., fixed TVBDs can easily starve portable TVBDs.

A distributed and state-less protocol is proposed in [91] to solve the power asymmetry problem in TVWS, which is based on the idea of cross-layer coexistence between high and low power devices. In the PHY layer, a novel adaptive preamble detector is included in the existing OFDM PHY design of a high power device as an add-on. The detector allows high power devices to detect the presence of low power devices at very low SNR (lower than −15 dB). Furthermore, two types of preambles are designed to significantly decrease error probability of detection. In the MAC layer, a distributed reservation mechanism is developed for low power devices based on adaptive preamble signaling. In each reservation period, all low power devices contend to transmit packets whenever possible. High power and low power traffics are balanced by prioritizing the access of high power devices in between low power reservation periods. Moreover, a novel algorithm is proposed for low power devices to adapt their preamble size to maximize the spatial reuse of TVWS. The proposed coexistence protocol is shown to prevent starvation of low power devices in almost all existing scenarios and improve the date rates of low power devices. However, one problem of this protocol is that it requires external detection device in high power devices, which may be expensive and difficult to implement. Another problem is that the protocol only applies to high power devices using OFDM technique.

Table 3
Users of different TVWS channels [10].

TVWS channel numbers	Frequency (MHz)	Users
2	54–60	Fixed TVBD only
3–4	60–72	No TVWS
5–20	76–512	Fixed TVBD only
21–35	512–602	Fixed and portable TVBDs
36	602–608	Wireless microphones
37	608–614	No TVWS
38	614–620	Wireless microphones
39–51	620–698	Fixed and portable TVBDs
52	698–704	No TVWS

Open research issues: The power asymmetry problem can be solved from three perspectives: channel allocation, operation of high power devices and operation of low power devices. We discuss related issues on these approaches.

- From the perspective of channel allocation: Here the general idea is to allocate disjoint set of channels to high and low power devices. For example, according to FCC's regulations [10], TVWS bands 54–60 MHz and 76–512 MHz can only be accessed by high power (fixed) devices (see Table 3). In fact, as shown in Fig. 4, only fixed-to-fixed (F2F) communications (i.e., communication between fixed devices) are allowed to use bidirectional high power. Given this observation, TV bands for the access of both fixed and portable devices (i.e., 512–602 MHz and 620–698 MHz) can be further divided into two parts: fixed-only and portable-only bands. However, this division may result in low spectrum efficiency since spectrum opportunities would be largely wasted when either fixed devices or portable devices become less active in their allocated bands. This problem can be solved within the IEEE 802.19.1 framework, in which the coexistence manager dynamically allocate disjoint set of channels to both fixed and portable devices [60].
- From the perspective of the operation of low power devices: One future research direction is that low power devices signal high power devices their presence such that high power devices leave spectrum opportunities to them. An example is the work presented in [91] as discussed in the second paragraph of this part. However, future coexistence mechanisms should try to avoid the use of external add-on and solve the power asymmetry problem with MAC layer methods. Another future research direction is that low power devices spatially reuse the operating spectrum of high power devices. Although fixed devices are allowed to use very high transmit power, they may not necessarily use the maximum power all the time due to energy or PU protection concerns. Instead, they would only use the maximum power when necessary (e.g., the receiver is too far or interference from other devices is too high). For example, IEEE 802.22 supports transmit power control on a link-by-link basis to minimize transmit power of fixed devices while still maintaining reliable connection [65]. Hence low power devices can spatially reuse the operating channel of the 802.22 network when the transmit power of 802.22 devices is low.
- From the perspective of the operation of high power devices: Fixed devices can adjust their behaviors to improve the coexistence with portable devices. First, transmit power control can be utilized by fixed devices as discussed in the previous paragraph. Second, directional antennas can be used to reduce interference to low power devices. For example, a novel multi-channel

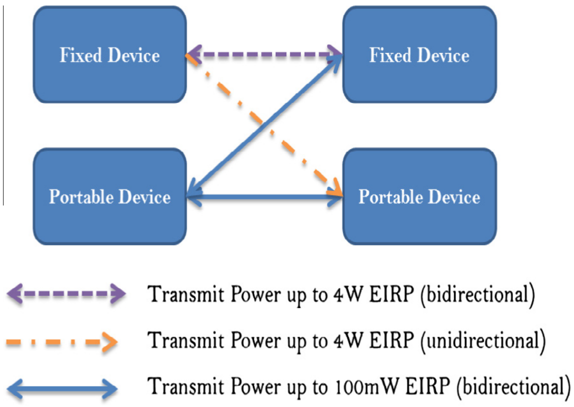


Fig. 4. Diverse transmit power levels of different links.

MAC protocol with directional antenna is proposed in [92] to enhance spatial reuse and bandwidth utilization in WLANs. However, the protocol does not incorporate CR functionality and fails to consider significant difference of diverse networks.

4.3. Efficient spectrum allocation algorithms

Design of spectrum allocation algorithms is already a challenging issue in traditional CR networks since many factors must be taken into account, such as PU activities, QoS requirements of SUs, quality of channels (e.g., interference level, path loss, link error, MAC layer delay and holding time, etc. [22]). The holding time is defined as the expected time duration that an SU can occupy a channel before PUs return. However, spectrum allocation is even more challenging in TVWS access for the following reasons: (1) mutual interference is increased due to better propagation properties of TVWS channels; (2) coexistence of heterogeneous TVBDs; (3) possible high mobility of TVBDs (e.g., vehicular TVBDs); (4) TVBDs may have their own licensed channels, such as Wi-Fi, LTE and vehicular communication devices; (5) requirements of both intra-network and inter-network spectrum allocation. The objective of spectrum allocation can be to optimize performance metrics such as system throughput, delay and fairness.

In [56], a joint spectrum and power allocation algorithm is proposed for inter-cell spectrum sharing in infrastructure-based CR networks. Both exclusive allocation and common use models are studied in this work. In the exclusive allocation model, a CR user accesses a channel only when the channel is not being used by other users. On the contrary, the common use model allows multiple users to access the same channel simultaneously. The proposed algorithms are shown to be able to maximize capacity of a cell, minimize the interference to its neighboring cells and reliably protect PUs. However, the approach does not apply to ad-hoc networks without centralized controller, especially for mobile SNs. Moreover, the proposed model simply assumes PU activities to be a two state birth–death process without evaluating quality of each available channel.

A network model is proposed in [61] to incorporate a centralized CR network (e.g., IEEE 802.22 network) in an existing cellular system. Two findings are presented in the analysis of TVWS access in cellular networks. First, TVBDs achieve higher capacity by accessing their own licensed channels instead of TVWS channels, when the inter-cell interference is generated by the same sources (i.e., neighboring cells). Second, TVWS channels should be assigned to TVBDs far away from their base stations, whereas the licensed channels should be allocated to TVBDs close to the base stations. The difference in channel allocation strategies results from better propagation properties of TVWS, i.e., TVWS channels usually suffer less path loss than the cellular channels. However, this model is only applicable for centralized networks with a central control entity. In addition, delay requirements are not considered in the model. In [93], the TVWS spectrum is used on an overflow basis, i.e., TVWS is only used as a temporary spectrum when traffic exceeds the capacity of available Wi-Fi spectrum. A good indicator of spectrum congestion is degradation of network performance, e.g., dropping of system throughput or increase of collision rate. A priority-based segmentation mechanism is also proposed in [93], in which TVWS is used based on the urgency of the data. More specifically, less urgent data can be transmitted in TVWS, while more urgent messages are transmitted in Wi-Fi bands. However, no theoretical analysis is given in this work.

Open research issues:

- Complete modeling of the TVWS spectrum: Most spectrum allocation algorithms only focus on channel capacity in the evaluation of channel quality. However, many other channel characteristics also have significant impact on the spectrum usage efficiency, such as delay, link error rate and holding time [22]. Two methods are available to evaluate quality of TVWS channels: spectrum sensing and centralized spectrum management. First, TVBDs can either individually or cooperatively sense TVWS channels to evaluate their quality. However, TVBDs have to interrupt their ongoing session to sense the channels, which degrades their transmission performance. Hence it's important to properly schedule spectrum sensing and data transmission to achieve a good trade-off between channel quality evaluation and spectrum usage efficiency. Another method is to manage all channels in a centralized way. More specifically, a spectrum manager is responsible for monitoring quality of all TVWS channels and allocating those channels to TVBDs. However, such infrastructure-based methods may not work in ad-hoc networks such as mobile wireless sensor networks.
- Determine usage pattern of TVWS: As discussed in the third paragraph of this part, TVWS channels can be used either as backup channels or low priority channels. In the first pattern, TVWS channels are only used when the TVBDs' licensed spectrum is overloaded. In the second pattern, TVWS channels are always used to carry low priority packets. However, it is nontrivial to compare the two usage patterns. In the overflow pattern,

it is still an open issue to determine whether current traffic load has outstripped the capacity of SUs' licensed spectrum. Actually, the degradation of network performance can be caused by other factors instead of spectrum spillover, such as interference from neighboring TVBDs. In the second pattern, it is possible that the throughput of low priority packets would be higher if they are transmitted in their licensed spectrum instead of TVWS. Although an SU's throughput on its licensed channel can be degraded due to congestion, the SU's throughput on a TVWS channel can also be degraded due to return of PUs, interference from other heterogeneous SUs and spatial variations of the TVWS channel. In fact, the usage pattern should be based on the complete modeling of both the TVBDs' licensed spectrum and TVWS.

- Impact of mobility on spectrum allocation: Most existing channel allocation algorithms only focus on static or low-speed CR networks with fixed set of available channels. However, high mobility of TVBDs (e.g., vehicular TVBDs) would raise more new challenges on the design of spectrum allocation. First, it would become extremely hard to evaluate the quality of available channels through spectrum sensing given very short allowed time for evaluation. Hence an infrastructure-based evaluation mechanism is preferable. Second, the availability of TVWS channels can change more quickly due to spatial–temporal variations of TVWS, especially in urban areas. Third, the time complexity of the spectrum allocation algorithms must be very low to meet delay requirements of mobile TVBDs.

4.4. Migration from SUs' licensed spectrum to TVWS

As discussed in the previous part, TVBDs may have their own licensed spectrum and use TVWS as backup or low priority spectrum. Once a TVWS channel is allocated to a transmitter–receiver pair, they must switch from their licensed channel to TVWS channel seamlessly. Given possibly different properties of TVBDs' licensed spectrum and TVWS, the channel migration (or switch) must be seamless, i.e., with low control overhead and short delay. This issue is trivial in infrastructure-based networks, where a central controller monitors both spectrum usage and status (either busy or idle) of each TVBD. More specifically, a transmitter simply sends its request to the central controller including the ID of its target receiver. Then the controller determines channel allocation and channel migration time based on channel usage information and status of the receiver. In contrast, the channel migration issue becomes very challenging in ad-hoc networks for the following reasons: (1) the transmitter may not know the status of its target receiver; (2) the transmitter and the receiver must negotiate to determine their operating channel since they may have different set of available TVWS channels, which makes the channel selection problem more difficult; (3) both the transmitter and the receiver may keep moving. Hence efficient transmitter–receiver rendezvous and negotiation mechanisms must be developed to enable their seamless migration to TVWS.

Channel migration mechanisms are usually associated with multi-channel MAC protocols. Existing multi-channel MAC protocols can be classified into four categories based on their principles of operation: Dedicated Control Channel (DCC), Parallel Rendezvous (PR), Common Hopping (CH) and Split Phase (SP) protocols [94]. In the DCC protocols, each TVBD is assumed to have two transceivers, one of which is used to exchange control information with other TVBDs on a dedicated control channel. During control intervals, all TVBDs contend to broadcast control messages on the control channel. However, these protocols do not apply to TVBDs with only one radio. PR protocols are extension of DCC protocols in which multiple channels are used as control channels. Both DCC and PR protocols may not work in TVWS access since there may not exist a common control channel as discussed in part *D* of Section 3.

In the CH protocols, each TVBD has only one transceiver and keeps hopping among available channels until it makes an agreement with another TVBD. However, it is very challenging to design optimal hopping sequence to minimize the time for transmitter–receiver rendezvous. In SP protocols, time is partitioned into alternating sequences of control information and data exchange phases. However, such protocols can largely degrade system throughput since TVBDs must interrupt their ongoing transmissions in control intervals, even though they do not have control information to send. In addition, it is also very difficult to determine the optimal ratio between the duration of control and data exchange intervals.

In addition to the MAC protocols above, cluster-based and cooperative multi-channel MAC protocols can both be used to enable channel migration in TVWS. In the cluster-based MAC protocol, a cluster head is responsible for channel allocation and migration within its cluster. Furthermore, cluster heads coordinate to support inter-cluster communications. In other words, cluster heads work in the similar way to "network bridge" in wired networks. In cooperative MAC protocols, idle neighboring TVBDs of a transmitter help the transmitter establish connection with its receiver as follows. The transmitter broadcasts a pre-RTS message to its neighbors and receiver including its available TVWS channels. Once its neighbors overhear the message, they would reply the transmitter with unavailable channels at their locations and forward the message to the receiver. If the receiver receives the pre-RTS from either the transmitter or its neighbors, it would reply the transmitter by sending a pre-CTS message including its preference on channel selection. In this way, the transmitter is able to know the status of its receiver as well as available channels. Then the transmitter determines the operating channel and sends a RTS message including channel selection and migration information. After receiving a CTS message from the receiver, the transmitter starts migrating to the operating channel and transmitting packets on the channel.

Open research issues:

- Inter-spectrum channel migration: Almost all the multi-channel MAC protocols discussed above are dedicated to channels within a single licensed spectrum.

However, in TVWS access, TVBDs must deal with the channel migration problem from their licensed spectrum to TVWS. Moreover, the channel migration problem becomes even more complicated since CR functionality must be incorporated into the channel migration algorithms to protect PUs. So far, few works have been presented to enable seamless inter-spectrum channel migration in TVWS. The channel migration problem in TVWS can be divided to two sub-problems: transmitter–receiver rendezvous and negotiation. Since the receiver can alternatively operate in its licensed spectrum or TVWS, it is very difficult for the transmitter to rendezvous with the receiver. An algorithm is proposed in [95] to design common hopping sequence for a multi-channel network to maximize rendezvous probability for any transmitter–receiver pair. A remarkable advantage of the algorithm is that it achieves high system throughput without the need for global synchronization or a dedicated control channel/interval. However, all transmitter–receiver pairs are required to use the same hopping sequence, which is not practical in TVWS access, since TVBDs may have different set of available TVWS channels. The transmitter–receiver negotiation problem is also nontrivial due to spatial–temporal variations of TVWS.

- Theoretical evaluation of delay performance: Short delay is almost the most important requirement for seamless migration from TVBDs' licensed spectrum to TVWS. However, the migration delay performance is merely evaluated through simulations in most multi-channel MAC protocols [94]. Actually, the modeling of migration delay is extremely difficult since it is affected by many factors, such as status of receivers, PU activities, channel quality in both the licensed spectrum and TVWS, transmitter–receiver rendezvous and negotiation algorithms.

4.5. Spectrum handoff in TVWS

In CR networks, spectrum handoff is defined as the process in which an SU switches from its operating channel to a new channel. As shown in Fig. 5, two events can trigger the spectrum handoff: return of PUs on the operating channel or the quality of the operating channel deteriorates significantly such that the SU has to switch to a better channel to meet its quality of service requirements. In the first scenario, SUs are usually required to periodically sense the operating channel and vacate the channel if PU activities are detected. For example, FCC requires every sensing-only TVBD to perform in-service monitoring of its operating channel for at least once every 60 s [8]. However, this requirement does not apply to TVBDs determining available TVWS channels through geo-location/database access. In the second scenario, it is nontrivial to determine whether to switch to a new channel due to the cost of spectrum handoff. More specifically, the cost consists of many parts such as interruption of ongoing communication and spectrum latency (including spectrum sensing time, handshaking time, channel switching time, waiting time and contention time with other SUs on the new channel).

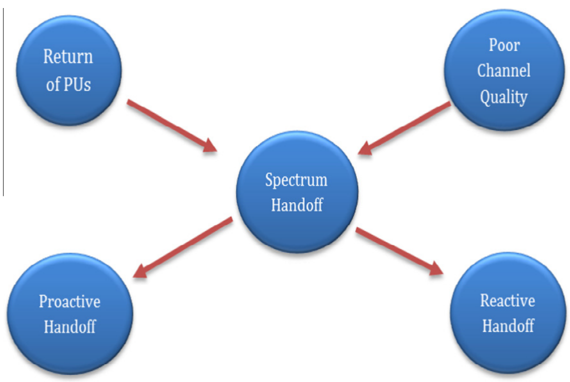


Fig. 5. Triggering events and classification of spectrum handoff.

The objective of spectrum handoff is to ensure the channel switch is made smoothly and as quickly as possible, such that the applications running on SUs suffer from the minimum performance degradation during the spectrum handoff period [22]. Hence performance metrics of spectrum handoff can be spectrum usage efficiency, the number of handoffs, switching latency, link maintenance probability, non-completion probability [96], among which switching latency is the most important one. Existing spectrum handoff mechanisms can be classified into two categories: proactive and reactive handoffs. Proactive handoff happens before a triggering event occurs (e.g., return of PUs or significant deterioration of channel quality) while reactive handoff happens after a triggering event occurs.

In the proactive handoff, target channel is pre-determined based on the prediction of short-term PU activities and evaluation of available channels. Hence the switching latency can be very low. However, one problem with this handoff mechanism is channel obsolescent, i.e., the pre-determined channel may become unavailable when spectrum handoff occurs. Furthermore, spectrum sensing must be done periodically to predict the pattern of PU activities and evaluate channel quality, which also incurs some latency. Another equivalent problem is channel waste, i.e., leaving the operating channel before PU triggering events happen can result in waste of spectrum opportunities on the operating channel due to prediction inaccuracy. A proactive spectrum handoff mechanism is proposed in [97] based on the prediction of PU activities. More specifically, reliable residual channel lifetime is estimated by assuming PU activity follows with an ON/OFF Markov chain. A similar mechanism is proposed in [98] in which a proactive spectrum handoff framework for CR ad-hoc networks is developed without common control channel. Furthermore, several other functionalities are incorporated in the framework, such as channel switching policies, a proactive spectrum handoff coordination scheme and a distributed channel selection scheme. In particular, the distributed channel selection scheme is proved to eliminate collisions among SUs and achieve short spectrum handoff delay. However, both the channel obsolescent and waste issues are not attacked in the proposed framework.

In contrast to proactive mechanisms, the switching latency of reactive spectrum handoff is much higher since spectrum sensing, hand-shaking, contention with other

SUs on the new channel must be done before the SU switches to the new channel. A special type of reactive spectrum handoff is backup channel based handoff. More specifically, SUs pre-determine a set of backup channels and switch to one of the backup channels when triggering events happen on their operating channels. It's easy to see channel obsolescent problem also exists in such spectrum handoff mechanisms. For example, each IEEE 802.22 WRAN has one operating channel, several backup channels and a couple of candidate channels. When PUs are sensed on the current operating channel, one of the backup channels will be selected as the new operating channel. Candidate channels can be promoted to be backup channels if PUs do not appear in these channels for a long time. In [99], an opportunistic spectrum access mechanism with backup channels is proposed to reduce the number of spectrum handoffs. However, the work fails to deal with the channel obsolescent issue.

Game-theoretic models have also been used to address the issues of spectrum handoff [100,101]. In a spectrum handoff game, each SU aims to maximize the amount of its spectrum opportunities by making handoff decisions on when and how to switch its channels. Meanwhile, each SU must take into account the PU activities, handoff cost and possible contention with other SUs on the new channel. Singleton Bayesian spectrum mobility games are proposed in [101] to model the interaction of SUs in spectrum handoff. The games are based on Singleton Congestion Games and are attacked both in complete-information scenario and incomplete-information scenario. The authors provide a polynomial-time algorithm to find the socially optimal equilibrium among all equilibriums, which optimizes the overall performance of all SUs in terms of average SINR. However, the proposed work fails to evaluate the spectrum handoff performance in terms of handoff latency, which is one of the most important performance metrics of spectrum handoff.

Open research issues:

- Spectrum handoff with known PU activities: Almost all existing spectrum handoff mechanisms assume that PU activities are unknown and thus make handoff decisions based on the prediction of short-term PU activities. However, this assumption should be loosened in TVWS access because availability of channels changes at a large time scale [100]. In other words, PU activities can be assumed to be known and constant in a large time scale, which requires new handoff policies. However, it is still very challenging to make optimal spectrum handoff decisions, since both cost of handoff and contention with other SUs must be taken into account. Given the knowledge of channel availability information, a spectrum mobility game is proposed in [100] to determine when and how each TVBD should switch channel. The game is proved to be equivalent to a symmetric network congestion game and a distributed protocol is proposed to organize TVBDs into Nash equilibria without negotiating with each other. However, the authors fail to evaluate the handoff performance in terms of latency.
- Spectrum handoff due to channel quality deterioration: As discussed at the beginning of this part, two events can trigger spectrum handoff: return of PUs on the operating channel or quality deterioration of the operating channel. However, almost all existing spectrum handoff mechanisms only focus on the first triggering event. Actually, the second triggering event could happen much more frequently than the first event in TVWS, especially for fixed and Mode 2 portable devices. The reason is that, according to FCC's regulations (page 46 of [8]), fixed and Mode 2 portable devices are required to check the database at least once per day to obtain channel availability information. In other words, the channel availability information can be assumed to be constant in one day unless they move. In contrast, heterogeneous TVBDs would coexist on the same TVWS channels, which can often deteriorate the channel quality significantly. Therefore, future research should pay more attention to the design of spectrum handoff mechanisms considering channel quality deterioration. Furthermore, such mechanisms need to be associated with coexistence protocols of heterogeneous SNs.
- Modeling of handoff performance: As discussed above, the performance of spectrum handoff can be modeled from the perspectives of spectrum efficiency, handoff latency, the number of handoffs, link maintenance probability and non-completion probability. The modeling of handoff performance in TVWS is very complicated since both spatial–temporal variations of TVWS and contention among heterogeneous TVBDs must be considered. Although there are already a few models on handoff performance in terms of handoff latency [50] and the number of handoffs [99], the modeling in terms of other metrics and overall performance is largely unexplored. Queuing-theoretic models are good candidates for future modeling of spectrum handoff as studied in [50].
- Impact of mobility on spectrum handoff: The mobility of TVBDs (e.g., vehicular devices and cell phone users) would make the spectrum handoff problem more difficult due to both spectrum mobility and user mobility. More specifically, the mobility of TVBDs raises several new challenges for the spectrum handoff as follows: (1) quality of TVWS channels varies with the mobility of TVBDs, hence it is more difficult to design proactive and backup channel based handoff mechanisms; (2) it becomes more difficult to predict PU activities since neighboring PUs keep changing with the mobility of TVBDs; (3) handoff latency must be even lower to meet the quality of service requirements of mobile TVBDs; (4) it is more difficult to model the contention between the mobile TVBD with neighboring static or mobile TVBDs on new TVWS channels, especially for heterogeneous TVBDs. Future research should model the spectrum handoff process by jointly considering spectrum mobility and user mobility. For example, a unified mobility management framework is proposed in [102] to model diverse mobility events in CR networks, which consists of spectrum mobility management, user mobility management and inter-cell resource allocation. However, the framework is dedicated to CR

cellular networks with centralized base stations. In addition, PU activities are simply modeled as ON/OFF Markov chains. Hence future works should address the mobility issue in spectrum handoff for more general CR networks.

4.6. Quality of service provisioning

As an important component, quality of service (QoS) provisioning is required in many wireless networks, such as the IEEE 802.11e and the IEEE 802.11p networks. In non-CR (or regular) networks, wireless traffic is usually classified to four types based on the QoS requirements: constant bit rate traffic, video-conference, VoIP sessions and simple best effort communications [103]. However, CR networks can only support services with strictly lower QoS requirements than regular networks due to protection of PUs and coexistence of contention among SUs. Hence, in addition to traditional QoS metrics such as throughput [103], delay [104], SINR [105], data distortion rate [106], bandwidth [107] and bit error rate [105], some other QoS metrics have been proposed for CR networks, such as blocking probability [108], dropping probability [109] and fairness [103] among SUs. In CR networks, an SU must switch to a new channel when PUs appear on its operating channel. However, the session of the SU may be dropped due to unavailability of new channels. Furthermore, incoming sessions can be even blocked when many PUs are active on the licensed channels. Both dropping and blocking would significantly deteriorate the SU's QoS performance, and thus dropping and blocking probabilities are important QoS metrics in CR networks.

QoS provisioning is already very challenging in regular wireless networks. However, today's networks require QoS measures going beyond the availability of bandwidth. Furthermore, it is more difficult to provide QoS guarantees in TVWS due to channel fragmentation, spatial–temporal variations of TVWS and coexistence of heterogeneous TVBDs. Moreover, since it is extremely difficult to provide deterministic QoS guarantees in CR networks, most existing works focus on realizing statistical QoS provisioning [110]. Existing approaches to supporting QoS provisioning can be classified into the following categories: MAC layer resource allocation [105,111,112], call admission control [103,108,113], bandwidth adaption [107,108] and cross-layer QoS provisioning mechanisms [114,115]. To protect PUs, all these approaches are associated with certain spectrum sensing, access and mobility policies.

In addition, an application layer method is proposed in [106] to support QoS provisioning, which is defined as the multimedia distortion rate. Given source coding rate and packet loss rate, the authors aim to minimize the multimedia distortion rate by choosing the optimal spectrum sensing policy, spectrum access decision, data intra-refreshing date. The QoS optimization problem is modeled as a partially observable Markov decision process, and the optimal policy is obtained. However, the contention among different SUs is not considered in the model. In addition, the multimedia distortion rate metric does not apply to many types of wireless networks such as delay-sensitive and throughput-sensitive networks.

Open research issues:

- Fairness among heterogeneous SNs in TVWS: Multiple diverse SNs are supposed to coexist in the same TVWS spectrum with equal priority and they may have significantly different QoS requirements (e.g., throughput, delay, and dropping/blocking probability). However, the operation of a SN may dominant the operation of other SNs on the same channel. For example, IEEE 802.22 high-power networks can starve IEEE 802.11af low-power networks without proper coordination. Hence it is nontrivial to achieve fairness of multiple heterogeneous SNs in terms of their QoS requirements. Few works have been proposed to solve the fair QoS provisioning problem among diverse SNs in TVWS. Intuitively, possible solutions can be classified into centralized and distributed fair inter-network QoS provisioning mechanisms. Centralized mechanisms can be based on the IEEE 802.19.1 coexistence framework in which the coexistence manager is responsible for achieving fairness among diverse SNs. In distributed mechanisms, neighboring SNs can cooperate to realize joint QoS provisioning.
- Impact of mobility on QoS provisioning: Many mobile wireless networks have QoS requirements. For example, in vehicular networks, safety related messages are required to be transmitted with certain delay requirements. Hence it is necessary to incorporate QoS provisioning in such mobile CR networks operating in TVWS. However, mobility of SUs would make the QoS provisioning more difficult in TVWS for the following reasons: (1) more frequent spatial–temporal variations of TVWS; (2) more complicated contention of an SU with neighboring static or mobile TVBDs, especially heterogeneous TVBDs. Few works have been proposed to deal with the QoS provisioning problem in mobile CR networks.

4.7. Support of broadcast

In regular wireless networks, a separate common control channel (CCC) is usually used to broadcast control information or emergency information during broadcasting periods in both infrastructure-based and ad-hoc networks. However, it is still deemed to be an open question whether the use of a CCC is feasible in TVWS access [83]. One reason is that TVBDs may have different sets of available channels, and thus there may not exist a CCC available to all neighboring TVBDs. The other reason is that a pre-selected CCC can become unavailable due to return of PUs or mobility of TVBDs. Hence it is nontrivial to support broadcast in TVWS. In contrast to unicast issues in CR networks, the support of broadcast is largely an unexplored issue.

Below are several potential methods to enable reliable broadcast in TVWS access. The first method is that TVBDs use one of their own licensed channels as the broadcasting channel. This method is practical since many wireless networks to operate in TVWS spectrum have their own licensed channels, such as vehicular and cellular networks. Another method is to utilize a separate Cognitive Pilot

Channel (CPC) as the broadcasting channel. A CPC is an open channel to all CR users which conveys necessary information facilitating the operations of CR systems [85]. For example, in [86], available band is divided into many sub-bands and the first two sub-bands are used as CPCs.

Additionally, multiple TVWS channels can be used as broadcast channels. A "selective broadcasting" mechanism is proposed in [116] in which a small subset of channels covering all SUs are selected for exchanging control information. To reduce the number of broadcast messages, the minimum number of channels is chosen through which an SU can reach all its neighboring SUs [116]. A similar broadcast mechanism is proposed for multi-hop CR ad-hoc networks without a common control channel in [117]. The mechanism is shown to provide very high successful broadcast ratio by downsizing original available channel set and designing optimal broadcasting sequences and scheduling schemes. However, the end-to-end delay between the broadcaster and some receivers can be very high since the broadcast is implemented in a multi-hop way. In addition, system performance may be degraded since more users are involved in relaying packets for a single broadcaster.

Open research issues:

- Multi-hop broadcast: Since there may not exist a common control channel available to all TVBDs, it is reasonable to realize the one-hop broadcast task in a multi-hop way as proposed in [116,117]. However, as discussed above, this method may incur more latency and result in the degradation of system performance. Hence more efficient scheduling mechanisms should be developed to support multi-hop broadcast in TVWS.
- Broadcast among multiple heterogeneous networks: Most of existing broadcast mechanisms only apply to broadcast within a cognitive network, and it is still an open research issue to enable reliable broadcast among multiple heterogeneous networks in TVWS. A potential method is to use an out-of-band channel as the broadcast channel available to all heterogeneous TVBDs. When a SN is broadcasting on the channel, all other TVBDs are required to listen to the channel at the same time. However, it can be extremely hard to realize synchronization of heterogeneous TVBDs in TVWS [51]. Additionally, the out-of-band broadcast channel would be easy to get congested since all heterogeneous TVBDs try to broadcast messages on the channel.

5. Worldwide regulatory activities

USA: FCC proposed to allow cognitive access of TVWS for the first time in 2004 [118]. In 2008, the Second Report and Order [10] was issued with specific rules on the protection of PUs (e.g., TV stations and wireless microphones) to allow license-exempt access of TVWS. Further regulation works were completed in 2010 and the Second Memorandum Opinion and Order [8] was published at the same time, which finalized FCC's general rules on the use of TVWS. In addition, FCC NPR 13–22 added more regulations about future use of the DSRC band.

The UK: In the UK, the first document regarding the license-exempt use of interleaved spectrum (i.e., TVWS) called Digital Divided Review was released by Ofcome in 2007. Afterwards, in 2009, Ofcom proposed to allow the use of spectrum sensing and geo-location/database access to detect incumbent communication services [119]. Furthermore, another Statement [120] was published to specify the rules on the implementation of geo-location/database access in 2011. Ofcome has also created a TVWS working group to establish the UK-specific framework for TVBDs operating with geo-location/database access.

Europe: The European Conference of Postal and Telecommunications Administrations (CEPT) has also started working on the regulations on the use of TVWS [121]. The regulation works are tackled by the CEPT Group SE43, created in June 2009. SE43 is currently considering TVWS usage modeling and defining technical/operational TVBD requirements in the 470 MHz to 790 MHz band.

Japan: The Japanese Ministry of Internal Affairs and Communications (MIC) is following the same path and considering TVWS utilization. With the creation of an Evaluation Committee (EvC) 2009, it evaluated the usage models and technical issues toward TVWS utilization. More recent information can be found in [122].

Singapore: In 2010, the chief information officer of the Singapore government (iDA) announced its White Space Technology Information Package and Test Plan, and requested organizations to indicate their interests to participate in white-space trials. Such trials provided real-world measurements, which would facilitate the development of TVBDs and assist iDA in constructing a regulatory framework to enable access to TVWS. The latest development can be found in [123].

6. Worldwide standardization efforts

ECMA-392: The first standard regarding cognitive access of TVWS was from ECMA International. Standard ECMA-392 (i.e., MAC and PHY for Operation in TV White Space) was published in December 2009 [124]. This standard was mainly designed for communication between personal/portable devices.

IEEE 802.22: In July 2011, the IEEE 802.22-2011standard was published [65]. The 802.22 standard is dedicated to Wireless Regional Area Networks (WRANs). The primary target application of the standard is licensed-exempt broadband wireless access of TVWS in rural areas. The network architecture including MAC and PHY was derived from the IEEE 802.16 WiMAX.

IEEE 802.11af: The 802.11af task group is working on an amendment to the IEEE 802.11 standard, including MAC/PHY modifications and enhancements to satisfy legal requirements for channel access and coexistence in TVWS [125]. The completed IEEE 802.11af standard will likely use the OFDM PHY proposed in IEEE 802.11ac. The 802.11af task group plans to enable the use of multiple contiguous and non-contiguous channels in TVWS.

IEEE 802.19: The IEEE 802.19 Working Group has been working on TVWS coexistence issue, and a task group, 802.19 TG1, is dedicated to developing a standard to improve coexistence in TVWS. In December 2009, the IEEE 802.19.1 TG was formed to develop radio technology independent standard methods for coexistence of heterogeneous TVBDs in TVWS. The IEEE 802.19.1 task group has proposed a high-level approach, i.e., new PHY and/or MAC design is not considered. In August 2011, the task group released its first draft standard [60], providing the framework towards the development of coexistence schemes for efficient spectrum sharing in TVWS.

ETSI-RSS (European Telecommunications Standard Institute Technical Committee for Reconfigurable Radio Systems)**:** Four working groups were established by ETSI-RRS in 2008 to propose technical solutions beyond the scope of other standardization bodies including system aspects, radio equipment architecture, cognitive management and control, and public safety [126]. Two cases are considered by ETSI RRS for TVWS access: middle and long range wireless access over TVWS and access to UHF TVWS in a centralized mode. In the first case, Internet access is provided by a base station to end users by utilizing TVWS over ranges similar to cellular networks, e.g., from 0 to 10 km. In the second case, a central control node (logical node) is responsible for managing the access of the macro radio systems (e.g., TD-LTE) to the UHF TVWS.

IEEE 1900.7: The IEEE DySPAN Standards Committee (DySPAN-SC) is dedicated to addressing CR and dynamic spectrum access problems. A new 1900.7 task group was formed to create another MAC/PHY standard for TVWS in 2011 [127]. According to its project authorization request, the new MAC/PHY will enable fixed and mobile operation in TVWS, while avoiding harmful interference to PUs.

IEEE 802.16 h: The IEEE 802.16 h [59] was published as an amendment for license-exempt WiMAX in 2010. In the IEEE 802.16 h, various coordinated and uncoordinated coexistence mechanisms are proposed, which are applicable for the coexistence of metropolitan area networks in TVWS.

IEEE 1900.4a (Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands)**:** Based on the existing IEEE standard 1900.4, the IEEE 1900.4a defines additional interfaces and entities to realize mobile wireless access services in TVWS without requirements on radio interface (physical and media access control layers, carrier frequency, etc.) [128].

IEEE 802.15.4m (low rate (LR) wireless personal area networks (WPANs) operating in the TV white space): IEEE 802.15.4m or Task Group 4m was established in 2011. The IEEE 802.15.4m group is formed under the IEEE 802.15 LR-WPAN Working Group and is dedicated to enabling LR-WPAN in the TVWS bands [129].

7. Conclusion

The release of large TV spectrum resources by FCC for cognitive access provides a promising approach to solving spectrum scarcity problem in current wireless networks. However, many new challenges are also raised to efficiently use TVWS under requirements on the protection of PUs. This article summarizes cognitive MAC issues on TVWS access, discusses potential solutions to deal with the issues and investigates open research issues. All the mentioned issues must be carefully addressed to realize the efficient use of TVWS in current wireless networks.

References

[1] C. Cormio, K.R. Chowdhury, A survey on {MAC} protocols for cognitive radio networks, Ad Hoc Netw. 7 (7) (2009) 1315–1329, http://dx.doi.org/10.1016/j.adhoc.2009.01.002. <http://www.sciencedirect.com/science/article/pii/S1570870509000043>.

[2] I. Akyildiz, W.-Y. Lee, M.C. Vuran, S. Mohanty, A survey on spectrum management in cognitive radio networks, IEEE Commun. Mag. 46 (4) (2008) 40–48, http://dx.doi.org/10.1109/MCOM.2008.4481339.

[3] T. Yucek, H. Arslan, A survey of spectrum sensing algorithms for cognitive radio applications, IEEE Commun. Surv. Tutorials 11 (1) (2009) 116–130, http://dx.doi.org/10.1109/SURV.2009.090109.

[4] C. Ghosh, S. Roy, D. Cavalcanti, Coexistence challenges for heterogeneous cognitive wireless networks in TV white spaces, IEEE Wireless Commun. 18 (4) (2011) 22–31, http://dx.doi.org/10.1109/MWC.2011.5999761.

[5] S. Shellhammer, A. Sadek, W. Zhang, Technical challenges for cognitive radio in the tv white space spectrum, in: Information Theory and Applications Workshop, 2009, 2009, pp. 323–333. doi:http://dx.doi.org/10.1109/ITA.2009.5044964.

[6] M. Nekovee, A survey of cognitive radio access to TV white spaces, Int. J. Digital Multimedia Broadcast. (2010) 1–11. doi:http://dx.doi.org/10.1155/2010/236568.

[7] M. Nekovee, Cognitive radio access to tv white spaces: Spectrum opportunities, commercial applications and remaining technology challenges, in: 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum, 2010, pp. 1–10. doi:http://dx.doi.org/10.1109/DYSPAN.2010.5457902.

[8] Federal Communications Commission, Second Memorandum Opinion and Order in ET Docket No. 04-186 (FCC order modifying the TVBD rules, FCC-10-174), 2010.

[9] TV white spaces: approach to coexistence, 2013. <http://stakeholders.ofcom.org.uk/binaries/consultations/white-space-coexistence/summary/white-spaces.pdf> (accessed 04.09.13).

[10] Federal Communications Commission, Second Report and Order and Memorandum Opinion and Order in ET Docket No. 04-186 (FCC order adopting the TVBD rules, FCC-08-260), 2008.

[11] R. Murty, R. Chandra, T. Moscibroda, P. Bahl, Senseless: a database-driven white spaces network, IEEE Trans. Mobile Comput. 11 (2) (2012) 189–203, http://dx.doi.org/10.1109/TMC.2011.241.

[12] H. Kremo, O. Altintas, On detecting spectrum opportunities for cognitive vehicular networks in the TV white space, J. Signal Process. Syst. (2013) 1–12, http://dx.doi.org/10.1007/s11265-013-0765-z. http://dx.doi.org/10.1007/s11265-013-0765-z.

[13] L. Chen, T. Zhang, D. Tsang, Salt: Sensing enabled localization and tracking for geolocation database in TV white space, in: 2013 9th International Wireless Communications and Mobile Computing Conference (IWCMC), 2013, pp. 712–717. doi:http://dx.doi.org/10.1109/IWCMC.2013.6583644.

[14] J. Heo, G. Noh, S. Park, S. Lim, E. Kim, D. Hong, Mobile TV white space with multi-region based mobility procedure, IEEE Wireless Commun. Lett. 1 (6) (2012) 569–572, http://dx.doi.org/10.1109/WCL.2012.081312.120314.

[15] K. Inage, S. Lee, T. Fujii, O. Altintas, White space vectors for channel selection in vehicular cognitive networks, in: 2011 IEEE Vehicular Networking Conference (VNC), 2011, pp. 55–61. doi: http://dx.doi.org/10.1109/VNC.2011.6117124.

[16] H.N. Tran, Y. Alemseged, C. Sun, H. Harada, Reducing load of geo-location database by querying with secondary user's preferred channels, in: 2012 IEEE 75th Vehicular Technology Conference (VTC Spring), 2012, pp. 1–5. doi: http://dx.doi.org/10.1109/VETECS.2012.6240246.

[17] T. Zhang, S. Banerjee, V-scope: an opportunistic wardriving approach to augmenting TV whitespace databases, in: Proceedings of the 19th Annual International Conference on Mobile Computing &, Networking, MobiCom '13, ACM, New York, NY, USA, 2013, pp. 251–254. doi:http://dx.doi.org/10.1145/2500423.2504588 URL http://doi.acm.org/10.1145/2500423.2504588.

[18] R. Murty, R. Chandra, T. Moscibroda, P. Bahl, Senseless: a database-driven white spaces network, IEEE Trans. Mobile Comput. 11 (2) (2012) 189–203, http://dx.doi.org/10.1109/TMC.2011.241.

[19] T. Fujii, K. Inage, M. Kitamura, O. Altintas, H. Kremo, H. Tanaka, Short paper: probing the spectrum with vehicles: towards an

advanced spectrum database, in: 2013 IEEE Vehicular Networking Conference (VNC), 2013, pp. 226–229. doi:http://dx.doi.org/10.1109/VNC.2013.6737619.
[20] I.F. Akyildiz, B.F. Lo, R. Balakrishnan, Cooperative spectrum sensing in cognitive radio networks: a survey, Phys. Commun. 4 (1) (2011) 40–62, http://dx.doi.org/10.1016/j.phycom.2010.12.003. <http://www.sciencedirect.com/science/article/pii/S187449071000039X>.
[21] W. Zhang, R. Mallik, K. Letaief, Cooperative spectrum sensing optimization in cognitive radio networks, in: IEEE International Conference on Communications, 2008 (ICC '08), 2008, pp. 3411–3415. doi:http://dx.doi.org/10.1109/ICC.2008.641.
[22] I.F. Akyildiz, W.-Y. Lee, M.C. Vuran, S. Mohanty, Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey, Comput. Netw. 50 (13) (2006) 2127–2159, http://dx.doi.org/10.1016/j.comnet.2006.05.001. <http://www.sciencedirect.com/science/article/pii/S1389128606001009>.
[23] L. Lu, X. Zhou, U. Onunkwo, G. Li, Ten years of research in spectrum sensing and sharing in cognitive radio, EURASIP J. Wireless Commun. Netw. 2012 (1) (2012) 1–16, http://dx.doi.org/10.1186/1687-1499-2012-28. http://dx.doi.org/10.1186/1687-1499-2012-28.
[24] S.J. Kim, E.C. Kim, J.S. Park, Y.C. Oh, J.-S. Lee, J.Y. Kim, Performance of primary user detection based on fft for dtv signals, in: 2010 The 12th International Conference on Advanced Communication Technology (ICACT), vol. 2, 2010, pp. 1073–1075.
[25] S. Chen, K. Zeng, P. Mohapatra, Hearing is believing: detecting mobile primary user emulation attack in white space, in: 2011 Proceedings IEEE INFOCOM, 2011, pp. 36–40. doi: http://dx.doi.org/10.1109/INFCOM.2011.5935184.
[26] Y. Tachwali, W. Barnes, F. Basma, H. Refai, The feasibility of a fast fourier sampling technique for wireless microphone detection in ieee 802.22 air interface, in: INFOCOM IEEE Conference on Computer Communications Workshops, 2010, 2010, pp. 1–5. doi: http://dx.doi.org/10.1109/INFCOMW.2010.5466621.
[27] H.-S. Chen, W. Gao, Spectrum sensing for TV white space in north america, IEEE J. Select. Areas Commun. 29 (2) (2011) 316–326, http://dx.doi.org/10.1109/JSAC.2011.110205.
[28] H. Kim, K. Shin, Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks, IEEE Trans. Mobile Comput. 7 (5) (2008) 533–545, http://dx.doi.org/10.1109/TMC.2007.70751.
[29] Y. Chen, Q. Zhao, A. Swami, Distributed spectrum sensing and access in cognitive radio networks with energy constraint, IEEE Trans. Signal Process. 57 (2) (2009) 783–797, http://dx.doi.org/10.1109/TSP.2008.2007928.
[30] C. Sun, W. Zhang, K. Letaief, Cooperative spectrum sensing for cognitive radios under bandwidth constraints, in: Wireless Communications and Networking Conference, 2007 (WCNC 2007), IEEE, 2007, pp. 1–5. doi:http://dx.doi.org/10.1109/WCNC.2007.6.
[31] J. Shen, T. Jiang, S. Liu, Z. Zhang, Maximum channel throughput via cooperative spectrum sensing in cognitive radio networks, IEEE Trans. Wireless Commun. 8 (10) (2009) 5166–5175, http://dx.doi.org/10.1109/TWC.2009.081110.
[32] S. Li, Z. Zheng, E. Ekici, N. Shroff, Maximizing system throughput by cooperative sensing in cognitive radio networks, in: 2012 Proceedings IEEE INFOCOM, 2012, pp. 1575–1583. doi:http://dx.doi.org/10.1109/INFCOM.2012.6195526.
[33] W. Ejaz, N. ul Hasan, H.S. Kim, M. Azam, Fully distributed cooperative spectrum sensing for cognitive radio ad hoc networks, in: Frontiers of Information Technology (FIT), 2011, 2011, pp. 9–13. doi:http://dx.doi.org/10.1109/FIT.2011.10.
[34] F. Yu, H. Tang, M. Huang, P. Mason, Z. Li, Distributed consensus-based cooperative spectrum sensing in cognitive radio mobile ad hoc networks, in: F.R. Yu (Ed.), Cognitive Radio Mobile Ad Hoc Networks, Springer, New York, 2011, pp. 3–35. doi:http://dx.doi.org/10.1007/978-1-4419-6172-3_1, URL http://dx.doi.org/10.1007/978-1-4419-6172-3_1.
[35] M. Gandetto, C. Regazzoni, Spectrum sensing: a distributed approach for cognitive terminals, IEEE J. Select. Areas Commun. 25 (3) (2007) 546–557, http://dx.doi.org/10.1109/JSAC.2007.070405.
[36] D. Xue, E. Ekici, M.C. Vuran, Cooperative spectrum sensing in cognitive radio networks using multidimensional correlations, IEEE Trans. Wireless Commun. 13 (4) (2014) 1832–1843, http://dx.doi.org/10.1109/TWC.2014.022714.130351.
[37] A.W. Min, K.G. Shin, Impact of mobility on spectrum sensing in cognitive radio networks, in: Proceedings of the 2009 ACM Workshop on Cognitive Radio Networks, CoRoNet '09, ACM, New York, NY, USA, 2009, pp. 13–18. doi:http://dx.doi.org/10.1145/1614235.1614239, URL http://doi.acm.org/10.1145/1614235.1614239.
[38] G. Ivkovic, P. Spasojevic, I. Seskar, Single sensor radio scene analysis for packet based radio signals, in: Information Theory and Applications Workshop (ITA), 2010, 2010, pp. 1–10. doi:http://dx.doi.org/10.1109/ITA.2010.5454082.
[39] G. Nychis, R. Chandra, T. Moscibroda, I. Tashev, P. Steenkiste, Reclaiming the white spaces: spectrum efficient coexistence with primary users, in: Proceedings of the Seventh COnference on emerging Networking EXperiments and Technologies, CoNEXT '11, ACM, New York, NY, USA, 2011, pp. 1:1–1:12. doi:http://dx.doi.org/10.1145/2079296.2079297, URL http://doi.acm.org/10.1145/2079296.2079297.
[40] P. Paweczak, C. Guo, R.V. Prasad, R. Hekmat, Clusterbased spectrum sensing architecture for opportunistic spectrum access networks, Tech. rep., IEEE Vehicular Technology Conference VTC2007, 2006.
[41] J. Perez-Romero, O. Salient, R. Agusti, L. Giupponi, A novel on-demand cognitive pilot channel enabling dynamic spectrum allocation, in: 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2007 (DySPAN 2007), 2007, pp. 46–54. doi:http://dx.doi.org/10.1109/DYSPAN.2007.14.
[42] A. Ghasemi, E. Sousa, Asymptotic performance of collaborative spectrum sensing under correlated log-normal shadowing, IEEE Commun. Lett. 11 (1) (2007) 34–36, http://dx.doi.org/10.1109/LCOMM.2007.060662.
[43] S. Mishra, A. Sahai, R. Brodersen, Cooperative sensing among cognitive radios, in: IEEE International Conference on Communications, 2006 (ICC '06), vol. 4, 2006, pp. 1658–1663. doi:http://dx.doi.org/10.1109/ICC.2006.254957.
[44] P. Pawelczak, G.J.M. Janssen, R. Venkatesha Prasad, Wlc10-4: performance measures of dynamic spectrum access networks, in: Global Telecommunications Conference, 2006, GLOBECOM '06, IEEE, 2006, pp. 1–6. doi:http://dx.doi.org/10.1109/GLOCOM.2006.671.
[45] D. Cabric, A. Tkachenko, R. Brodersen, Spectrum sensing measurements of pilot, energy, and collaborative detection, in: Military Communications Conference, 2006, MILCOM 2006, IEEE, 2006, pp. 1–7. doi:http://dx.doi.org/10.1109/MILCOM.2006.301994.
[46] E. Peh, Y.-C. Liang, Optimization for cooperative sensing in cognitive radio networks, in: Wireless Communications and Networking Conference, 2007, WCNC 2007, IEEE, 2007, pp. 27–32. doi:http://dx.doi.org/10.1109/WCNC.2007.11.
[47] I.F. Akyildiz, W.-Y. Lee, K.R. Chowdhury, Crahns: cognitive radio ad hoc networks, Ad Hoc Netw. 7 (5) (2009) 810–836, http://dx.doi.org/10.1016/j.adhoc.2009.01.001. <http://www.sciencedirect.com/science/article/pii/S157087050900002X>.
[48] S. Geirhofer, L. Tong, B. Sadler, Cognitive radios for dynamic spectrum access – dynamic spectrum access in the time domain: modeling and exploiting white space, IEEE Commun. Mag. 45 (5) (2007) 66–72, http://dx.doi.org/10.1109/MCOM.2007.358851.
[49] D. Willkomm, S. Machiraju, J. Bolot, A. Wolisz, Primary users in cellular networks: a large-scale measurement study, in: 3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2008 (DySPAN 2008), 2008, pp. 1–11. doi:http://dx.doi.org/10.1109/DYSPAN.2008.48.
[50] L.-C. Wang, C.-W. Wang, C.-J. Chang, Modeling and analysis for spectrum handoffs in cognitive radio networks, IEEE Trans. Mobile Comput. 11 (9) (2012) 1499–1513, http://dx.doi.org/10.1109/TMC.2011.155.
[51] B. Gao, J.-M. Park, Y. Yang, S. Roy, A taxonomy of coexistence mechanisms for heterogeneous cognitive radio networks operating in TV white spaces, IEEE Wireless Commun. 19 (4) (2012) 41–48, http://dx.doi.org/10.1109/MWC.2012.6272422.
[52] Y. Yuan, P. Bahl, R. Chandra, P. Chou, J. Ferrell, T. Moscibroda, S. Narlanka, Y. Wu, Knows: cognitive radio networks over white spaces, in: 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2007 (DySPAN 2007), 2007, pp. 416–427. doi:http://dx.doi.org/10.1109/DYSPAN.2007.61.
[53] L. Cao, H. Zheng, Distributed rule-regulated spectrum sharing, IEEE J. Select. Areas Commun. 26 (1) (2008) 130–145, http://dx.doi.org/10.1109/JSAC.2008.080112.
[54] P. Si, H. Ji, F. Yu, V. Leung, Optimal cooperative internetwork spectrum sharing for cognitive radio systems with spectrum pooling, IEEE Trans. Vehicular Technol. 59 (4) (2010) 1760–1768, http://dx.doi.org/10.1109/TVT.2010.2041941.
[55] H.-P. Shiang, M. van der Schaar, Queuing-based dynamic channel selection for heterogeneous multimedia applications over cognitive

radio networks, IEEE Trans. Multimedia 10 (5) (2008) 896–909, http://dx.doi.org/10.1109/TMM.2008.922851.

[56] W.-Y. Lee, I. Akyildiz, Joint spectrum and power allocation for inter-cell spectrum sharing in cognitive radio networks, in: 3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2008 (DySPAN 2008), 2008, pp. 1–12. doi:http://dx.doi.org/10.1109/DYSPAN.2008.36.

[57] S. Manickam, M.K. Marina, S. Pediaditaki, M. Nekovee, Auctioning based coordinated TV white space spectrum sharing for home networks, CoRR abs/1307.0962.

[58] S. Lim, H. Jung, S. won Kim, B.-J. Jeong, Novel cr signal detection algorithms for coexistence in tv white space, in: 2011 International Conference on ICT Convergence (ICTC), 2011, pp. 465–469. doi:http://dx.doi.org/10.1109/ICTC.2011.6082639.

[59] 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, 2010.

[60] Tv white space coexistence methods (draft standard), August 2011.

[61] Y.-J. Choi, K. Shin, Opportunistic access of TV spectrum using cognitive-radio-enabled cellular networks, IEEE Trans. Vehicular Technol. 60 (8) (2011) 3853–3864, http://dx.doi.org/10.1109/TVT.2011.2164426.

[62] F. Wang, M. Krunz, S. Cui, Spectrum sharing in cognitive radio networks, in: The 27th Conference on Computer Communications (INFOCOM 2008), IEEE, 2008, http://dx.doi.org/10.1109/INFOCOM.2008.252.

[63] T. Baykas, M. Kasslin, M. Cummings, H. Kang, J. Kwak, R. Paine, A. Reznik, R. Saeed, S. Shellhammer, Developing a standard for TV white space coexistence: technical challenges and solution approaches, IEEE Wireless Commun. 19 (1) (2012) 10–22, http://dx.doi.org/10.1109/MWC.2012.6155872.

[64] K.-L. Yau, P. Komisarczuk, P. Teal, A context-aware and intelligent dynamic channel selection scheme for cognitive radio networks, in: 4th International Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2009 (CROWNCOM '09), 2009, pp. 1–6. doi:http://dx.doi.org/10.1109/CROWNCOM.2009.5189427.

[65] 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.

[66] G. Villardi, Y. Alemseged, C. Sun, C.-S. Sum, T.H. Nguyen, T. Baykas, H. Harada, Enabling coexistence of multiple cognitive networks in TV white space, IEEE Wireless Commun. 18 (4) (2011) 32–40, http://dx.doi.org/10.1109/MWC.2011.5999762.

[67] N. Nie, C. Comaniciu, Adaptive channel allocation spectrum etiquette for cognitive radio networks, in: 2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005 (DySPAN 2005), 2005, pp. 269–278. doi:http://dx.doi.org/10.1109/DYSPAN.2005.1542643.

[68] J.R. Vidal, V. Pla, L. Guijarro, J. Martinez-Bauset, Dynamic spectrum sharing in cognitive radio networks using truthful mechanisms and virtual currency, Ad Hoc Netw. 11 (6) (2013) 1858–1873, http://dx.doi.org/10.1016/j.adhoc.2013.04.010. <http://www.sciencedirect.com/science/article/pii/S1570870513000942>.

[69] I. Malanchini, M. Cesana, N. Gatti, On spectrum selection games in cognitive radio networks, in: Global Telecommunications Conference, 2009, GLOBECOM 2009, IEEE, 2009, pp. 1–7. doi:http://dx.doi.org/10.1109/GLOCOM.2009.5425335.

[70] M. Parzy, H. Bogucka, Non-identical objects auction for spectrum sharing in tv white spaces 2014; the perspective of service providers as secondary users, in: 2011 IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011, pp. 389–398. doi:http://dx.doi.org/10.1109/DYSPAN.2011.5936228.

[71] R. Cendrillon, M. Moonen, J. Verliden, T. Bostoen, W. Yu, Optimal multi-user spectrum management for digital subscriber lines, IEEE Trans. Commun. 1 (2004) 1–5.

[72] A. Sikora, V. Groza, Coexistence of ieee802.15.4 with other systems in the 2.4 ghz-ism-band, in: Proceedings of the IEEE Instrumentation and Measurement Technology Conference, 2005 (IMTC 2005), vol. 3, 2005, pp. 1786–1791. doi:http://dx.doi.org/10.1109/IMTC.2005.1604479.

[73] X. Zhang, K.G. Shin, Enabling coexistence of heterogeneous wireless systems: case for ZIGBEE and WIFI, in: Proceedings of the Twelfth ACM International Symposium on Mobile Ad Hoc Networking and Computing, MobiHoc '11, ACM, New York, NY, USA, 2011, pp. 6:1–6:11. doi:http://dx.doi.org/10.1145/2107502.2107510, URL http://doi.acm.org/10.1145/2107502.2107510.

[74] J. Huang, G. Xing, G. Zhou, R. Zhou, Beyond co-existence: exploiting wifi white space for zigbee performance assurance, in: 2010 18th IEEE International Conference on Network Protocols (ICNP), 2010, pp. 305–314. doi:http://dx.doi.org/10.1109/ICNP.2010.5762779.

[75] C. Chiasserini, R. Rao, Coexistence mechanisms for interference mitigation in the 2.4-GHz ISM band, IEEE Trans. Wireless Commun. 2 (5) (2003) 964–975, http://dx.doi.org/10.1109/TWC.2003.817417.

[76] C.F. Chiasserini, R. Rao, A comparison between collaborative and non-collaborative coexistence mechanisms for interference mitigation in ism bands, in: IEEE VTS 53rd Vehicular Technology Conference, 2001 (VTC 2001 Spring), vol. 3, 2001, pp. 2187–2191. doi:http://dx.doi.org/10.1109/VETECS.2001.945084.

[77] R. Etkin, A. Parekh, D. Tse, Spectrum sharing for unlicensed bands, IEEE J. Select. Areas Commun. 25 (3) (2007) 517–528, http://dx.doi.org/10.1109/JSAC.2007.070402.

[78] C. Zou, T. Jin, C. Chigan, Z. Tian, QOS-aware distributed spectrum sharing for heterogeneous wireless cognitive networks, Comput. Netw. 52 (4) (2008) 864–878, http://dx.doi.org/10.1016/j.comnet.2007.11.008. http://dx.doi.org/10.1016/j.comnet.2007.11.008.

[79] X. Jing, D. Raychaudhuri, Spectrum co-existence of ieee 802.11b and 802.16a networks using the cscc etiquette protocol, in: 2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005 (DySPAN 2005), 2005, pp. 243–250. doi:http://dx.doi.org/10.1109/DYSPAN.2005.1542640.

[80] G. Marias, Spectrum scheduling and brokering based on qos demands of competing wisps, in: 2005 First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005 (DySPAN 2005), 2005, pp. 684–687. doi:http://dx.doi.org/10.1109/DYSPAN.2005.1542696.

[81] Coexistence of wireless personal area networks with other wireless devices operating in unlicensed frequency bands, July 2003.

[82] Q. Zhao, W. Ren, A. Swami, Spectrum opportunity detection: how good is listen-before-talk? in: Conference Record of the Forty-First Asilomar Conference on Signals, Systems and Computers, 2007 (ACSSC 2007), 2007, pp. 767–771. doi:http://dx.doi.org/10.1109/ACSSC.2007.4487320.

[83] Y.-C. Liang, K.-C. Chen, G. Li, P. Mahonen, Cognitive radio networking and communications: an overview, IEEE Trans. Vehicular Technol. 60 (7) (2011) 3386–3407, http://dx.doi.org/10.1109/TVT.2011.2158673.

[84] N. Yaginuma, M. Umehira, R. Funada, H. Harada, A guard band aggregation scheme for cognitive radio using TV white space, in: 2012 IEEE International Conference on Communication Systems (ICCS), 2012, pp. 428–432. doi:http://dx.doi.org/10.1109/ICCS.2012.6406184.

[85] J. Gebert, M. Mueck, P. Muller, P. Ruuska, Etsi reconfigurable radio system – system aspects and control channels for cognitive radio, in: 2012 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), 2012, pp. 410–414. doi: http://dx.doi.org/10.1109/WCNCW.2012.6215532.

[86] N. Bolivar, J.-L. Marzo, E. Rodriguez-Colina, Distributed control using cognitive pilot channels in a centralized cognitive radio network, in: 2010 Sixth Advanced International Conference on Telecommunications (AICT), 2010, pp. 30–34. doi:http://dx.doi.org/10.1109/AICT.2010.72.

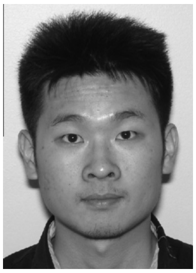
[87] M. Iwamura, K. Etemad, M.-H. Fong, R. Nory, R. Love, Carrier aggregation framework in 3GPP LTE-advanced [WIMAX/LTE update], IEEE Commun. Mag. 48 (8) (2010) 60–67, http://dx.doi.org/10.1109/MCOM.2010.5534588.

[88] R. Rajbanshi, A.M. Wyglinski, G. Minden, An efficient implementation of nc-ofdm transceivers for cognitive radios, in: 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2006, 2006, pp. 1–5. doi:http://dx.doi.org/10.1109/CROWNCOM.2006.363452.

[89] W. Rhee, J. Chuang, L. Cimini, Performance comparison of ofdm and multitone with polyphase filter bank for wireless communications, in: 48th IEEE Vehicular Technology Conference, 1998 (VTC 98), vol. 2, 1998, pp. 768–772. doi: http://dx.doi.org/10.1109/VETEC.1998.683685.

[90] Y. Dai, A. Cuffaro, J. Gauvreau, R. Di Girolamo, A. Touag, A. Demir, Dynamic spectrum management system aggregating non-contiguous spectrum over TVWS, in: 2012 7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2012, pp. 303–308.

[91] B. Radunović, R. Chandra, D. Gunawardena, WEEBLE: enabling low-power nodes to coexist with high-power nodes in white space networks, in: Proceedings of the 8th International Conference on Emerging Networking Experiments and Technologies, CoNEXT '12, ACM, New York, NY, USA, 2012, pp. 205–216. doi:http://dx.doi.org/10.1145/2413176.2413201. URL http://doi.acm.org/10.1145/2413176.2413201.
[92] C.-Y. Chang, Y.-C. Chen, L.-L. Hung, S.-W. Chang, A novel multi-channel {MAC} protocol with directional antenna for enhancing spatial reuse and bandwidth utilization in {WLANs}, J. Parallel Distrib. Comput. 69 (10) (2009) 824–837, http://dx.doi.org/10.1016/j.jpdc.2009.07.006. <http://www.sciencedirect.com/science/article/pii/S0743731509001415>.
[93] G. Villardi, C.-S. Sum, C. Sun, Y. Alemseged, Z. Lan, H. Harada, Efficiency of dynamic frequency selection based coexistence mechanisms for TV white space enabled cognitive wireless access points, IEEE Wireless Commun. 19 (6) (2012) 69–75, http://dx.doi.org/10.1109/MWC.2012.6393520.
[94] J. Mo, H.-S. So, J. Walrand, Comparison of multichannel mac protocols, IEEE Trans. Mobile Comput. 7 (1) (2008) 50–65, http://dx.doi.org/10.1109/TMC.2007.1075.
[95] F. Hou, L. Cai, X. Shen, J. Huang, Asynchronous multichannel MAC design with difference-set-based hopping sequences, IEEE Trans. Vehicular Technol. 60 (4) (2011) 1728–1739, http://dx.doi.org/10.1109/TVT.2011.2119384.
[96] Y. Zhang, Spectrum handoff in cognitive radio networks: Opportunistic and negotiated situations, in: IEEE International Conference on Communications, 2009 (ICC '09), 2009, pp. 1–6. doi:http://dx.doi.org/10.1109/ICC.2009.5199479.
[97] S.-U. Yoon, E. Ekici, Voluntary spectrum handoff: a novel approach to spectrum management in CRNS, in: 2010 IEEE International Conference on Communications (ICC), 2010, pp. 1–5. doi:http://dx.doi.org/10.1109/ICC.2010.5502725.
[98] Y. Song, J. Xie, Prospect: a proactive spectrum handoff framework for cognitive radio ad hoc networks without common control channel, IEEE Trans. Mobile Comput. 11 (7) (2012) 1127–1139, http://dx.doi.org/10.1109/TMC.2011.140.
[99] M. Kalil, H. Al-mahdi, A. Mitschele-Thiel, Spectrum handoff reduction for cognitive radio ad hoc networks, in: 2010 7th International Symposium on Wireless Communication Systems (ISWCS), 2010, pp. 1036–1040. doi:http://dx.doi.org/10.1109/ISWCS.2010.5624253.
[100] R. Southwell, J. Huang, X. Liu, Spectrum mobility games, in: 2012 Proceedings IEEE INFOCOM, 2012, pp. 37–45. doi:http://dx.doi.org/10.1109/INFCOM.2012.6195776.
[101] Q. Liang, X. Wang, Z. Feng, Singleton spectrum mobility games with incomplete information, in: 2012 IEEE Global Communications Conference (GLOBECOM), 2012, pp. 5608–5613. doi:http://dx.doi.org/10.1109/GLOCOM.2012.6504014.
[102] W.-Y. Lee, I. Akyildiz, Spectrum-aware mobility management in cognitive radio cellular networks, IEEE Trans. Mobile Comput. 11 (4) (2012) 529–542, http://dx.doi.org/10.1109/TMC.2011.69.
[103] B. Canberk, I. Akyildiz, S. Oktug, A QOS-aware framework for available spectrum characterization and decision in cognitive radio networks, in: 2010 IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), 2010, pp. 1533–1538. doi:http://dx.doi.org/10.1109/PIMRC.2010.5671959.
[104] H. Su, X. Zhang, Cross-layer based opportunistic mac protocols for QOS provisionings over cognitive radio wireless networks, IEEE J. Select. Areas Commun. 26 (1) (2008) 118–129, http://dx.doi.org/10.1109/JSAC.2008.080111.
[105] L. Akter, B. Natarajan, QOS constrained resource allocation to secondary users in cognitive radio networks, Comput. Commun. 32 (18) (2009) 1923–1930, http://dx.doi.org/10.1016/j.comcom.2009.06.009. <http://www.sciencedirect.com/science/article/pii/S0140366409001492>, Cognitive Radio and Dynamic Spectrum Sharing Systems.
[106] S. Ali, F. Yu, Cross-layer QOS provisioning for multimedia transmissions in cognitive radio networks, in: Wireless Communications and Networking Conference, 2009 (WCNC 2009), IEEE, 2009, pp. 1–5. doi:http://dx.doi.org/10.1109/WCNC.2009.4917655.
[107] D. Willkomm, A. Wolisz, Efficient QOS support for secondary users in cognitive radio systems [dynamic spectrum management], IEEE Wireless Commun. 17 (4) (2010) 16–23, http://dx.doi.org/10.1109/MWC.2010.5547917.
[108] T. Guo, K. Moessner, Optimal strategy for qos provision under spectrum mobility in cognitive radio networks, in: 2012 IEEE Vehicular Technology Conference (VTC Fall), 2012, pp. 1–5. doi:http://dx.doi.org/10.1109/VTCFall.2012.6399317.
[109] B. Ishibashi, N. Bouabdallah, R. Boutaba, QOS performance analysis of cognitive radio-based virtual wireless networks, in: The 27th Conference on Computer Communications, INFOCOM 2008, IEEE, 2008. doi:http://dx.doi.org/10.1109/INFOCOM.2008.312.
[110] S.-C. Lin, L. Gu, K.-C. Chen, Providing statistical QOS guarantees in large cognitive machine-to-machine networks, in: 2012 IEEE Globecom Workshops (GC Wkshps), 2012, pp. 1700–1705. doi:http://dx.doi.org/10.1109/GLOCOMW.2012.6477841.
[111] A. Al-Fuqaha, B. Khan, A. Rayes, M. Guizani, O. Awwad, G. Ben Brahim, Opportunistic channel selection strategy for better QOS in cooperative networks with cognitive radio capabilities, IEEE J. Select. Areas Commun. 26 (1) (2008) 156–167, http://dx.doi.org/10.1109/JSAC.2008.080114.
[112] K. Hamdi, W. Zhang, K. Letaief, Uplink scheduling with QOS provisioning for cognitive radio systems, in: Wireless Communications and Networking Conference, 2007 (WCNC 2007), IEEE, 2007, pp. 2592–2596. doi: http://dx.doi.org/10.1109/WCNC.2007.482.
[113] A. Alshamrani, X. Shen, L.-L. Xie, QOS provisioning for heterogeneous services in cooperative cognitive radio networks, IEEE J. Select. Areas Commun. 29 (4) (2011) 819–830, http://dx.doi.org/10.1109/JSAC.2011.110413.
[114] L.B. Le, E. Hossain, Resource allocation for spectrum underlay in cognitive radio networks, IEEE Trans. Wireless Commun. 7 (12) (2008) 5306–5315, http://dx.doi.org/10.1109/T-WC.2008.070890.
[115] A. Kumar, J. Wang, K. Challapali, K. Shin, Analysis of QOS provisioning in cognitive radio networks: a case study, Wireless Personal Commun. 57 (1) (2011) 53–71, http://dx.doi.org/10.1007/s11277-010-0006-8. http://dx.doi.org/10.1007/s11277-010-0006-8.
[116] Y. Kondareddy, P. Agrawal, Selective broadcasting in multi-hop cognitive radio networks, in: 2008 IEEE Sarnoff Symposium, 2008, pp. 1–5. doi:http://dx.doi.org/10.1109/SARNOF.2008.4520042.
[117] Y. Song, J. Xie, A distributed broadcast protocol in multi-hop cognitive radio ad hoc networks without a common control channel, in: 2012 Proceedings IEEE INFOCOM, 2012, pp. 2273–2281. doi:http://dx.doi.org/10.1109/INFCOM.2012.6195614.
[118] Federal Communications Commission, Spectrum Policy Task Force, Report of the Spectrum Efficiency Working Group, 2004.
[119] Statement on cognitive access to interleaved spectrum. <http://stakeholders.ofcom.org.uk/consultations/cognitive/statement/>.
[120] Ofcom, Implementing Geolocation, 2011.
[121] European Conference of Postal and Telecommunications Administrations (CEPT), Electronic Communications Committee (ECC), ECC Report 159: technical and operational requirements for the possible operation of CR systems in the white spaces of frequency band 470–790 MHz, (ECC-159), 2011.
[122] Wireless communication in tv white space succeeded, 2012. <http://www.nict.go.jp/en/press/2012/06/07en-1.html>.
[123] Singapore white space pilot group, 2012. <http://whitespace.i2r.a-star.edu.sg/swspg/index.php>.
[124] MAC and PHY for operation in TV white space, December 2009.
[125] 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, December 2009.
[126] C.M.P. Delahaye, M. Ariyoshi, White space standardization activities at etsi technical committee for reconfigurable radio systems, Tech. Rep., European Telecommunications Standard Institute Technical Committee for Reconfigurable Radio Systems, vol. 60, no. 7, April 2011, pp. 38–44.
[127] Project authorization request for p1900.7 radio interface for white space dynamic spectrum access radio systems supporting fixed and mobile operation, June 2011.
[128] Ieee standard for architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks amendment 1: architecture and interfaces for dynamic spectrum access networks in white space frequency bands, September 2011.
[129] C.-S. Sum, M.-T. Zhou, L. Lu, R. Funada, F. Kojima, H. Harada, Ieee 802.15.4m: the first low rate wireless personal area networks operating in tv white space, in: 2012 18th IEEE International Conference on Networks (ICON), 2012, pp. 326–332. doi:http://dx.doi.org/10.1109/ICON.2012.6506578.



You Han received the B.E. degree in electrical engineering and automation from Zhejiang University, Hangzhou, China, in 2012, and is currently pursing his Ph.D. degree in electrical and computer engineering at The Ohio State University, Columbus, USA. His research interests include scheduling in wireless networks, dynamic spectrum access and resource allocation in cognitive vehicular networks.

Eylem Ekici received his B.S. and M.S. degrees in Computer Engineering from Bogazici University, Istanbul, Turkey, in 1997 and 1998, respectively, and the Ph.D. degree in Electrical and Computer Engineering from the Georgia Institute of Technology, Atlanta, GA, in 2002. Currently, he is an Associate Professor with the Department of Electrical and Computer Engineering, The Ohio State University. His current research interests include wireless networks, vehicular communication systems, cognitive radio networks, nano communication systems, with an emphasis on resource management, and analysis of network architectures and protocols. He is an Associate Editor of IEEE/ACM Transactions on Networking, Computer Networks Journal (Elsevier) and ACM Mobile Computing and Communications Review.

Haris Kremo received the Dipl.Ing. degree from the School of Electrical Engineering, University of Sarajevo, Bosnia and Herzegovina in 2000. He received M.S. and Ph.D. degrees from Rutgers, The State University of New Jersey in 2005 and 2010, respectively. From 2000 to 2002 he was a Research Engineer with ENERGOINVEST dd, Sarajevo. From 2003 to 2010 he was a Graduate Assistant with the Wireless Information Networks Laboratory (WINLAB), where he was one of the engineers responsible for design and maintenance of the ORBIT wireless testbed. In 2010 he was with the EDGE Lab, Princeton University as a Postdoctoral Research Associate. Currently he is a Postdoctoral Researcher with Toyota InfoTechnology Center, Tokyo. His research interests include cognitive radio, experimental characterization and modeling of vehicular radio channels, and MAC layer protocols evaluation and design.

Onur Altintas is a principle research at the R&D Group of Toyota InfoTechnology Center, Co. Ltd, in Tokyo. From 1999 to 2001 he was with Toyota Motor Corporation and was also a visiting research at Telcordia Technologies. From 2001 to 2004 he was with Toyota InfoTechnology Center USA. Before joining Toyota Motor Corporation in 1999, he was a research scientist at Ultra High Speed Network and Computer Technology Labs (UNCL), Tokyo. He received his B.S. (1987) and M.S. (1990) degrees from Orta Dogu Teknik Universitesi, Ankara, Turkey, and his Ph.D. (1995) degree from the University of Tokyo, Japan; all in electrical engineering. He served as the Co-Chair for Vehicle-to-Vehicle Communications Workshops (V2VCOM 2005 and V2VCOM 2006) co-located with ACM MobiQuitous, and V2VCOM 2007 and V2VCOM 2008 co-located with IEEE Intelligent Vehicles Symposium. He also served as the Co-Chair for the IEEE Workshop on Automotive Networking and Applications (AutoNet 2006, AutoNet 2007 and AutoNet 2008) co-located with IEEE Globecom. He is the co-founder and general co-chair of the IEEE Vehicular Networking Conference (IEEE VNC) held in Tokyo in 2009, in New Jersey in 2010, in Amsterdam in 2011, and in Seoul in 2012. He is an IEEE VTS Distinguished Lecturer.