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Research Article

A Survey on Coexistence in Heterogeneous Wireless Networks in TV White Spaces

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With the advent of analog to digital transition in TV broadcasting, a substantial amount of spectrum has become available in TV bands. To take advantage of this, the idea for cognitive radios was introduced for two major reasons: better utilization of spectrum in urban areas and facilitation of wireless connectivity in rural areas. To achieve these two goals, however, many challenges have to be addressed first. Considering that these frequencies are commonly licensed, besides primary user detection, a serious challenge remains the detection and identification of other secondary devices and networks. The problems arising from this issue concern the coexistence problems happening from having several primary and secondary networks of different technologies cohabiting the same licensed spectrum simultaneously and from many secondary systems/users coexisting at the same place while using identical or different technologies. In this survey we provide a review of existing works and outline new challenges regarding coexistence and self-coexistence in heterogeneous wireless networks in TV White Spaces including a comparative analysis between selected coexistence mechanisms.

1. Introduction

With the rapid development of technology, the need for access to wireless Internet has become a daily necessity. This has created severe congestion in the frequency spectrum, especially in urban areas where the number of users is consistently high. This exponential increase in broadband traffic has underscored the need for a more efficient and opportunistic use of the available spectrum. Researchers have highlighted the underutilization of licensed portions of the spectrum as a potential opportunity in addressing the spectrum congestion problem. The use of already licensed portions of the spectrum would be enabled by cognitive radios, which behave as secondary users and use the spectrum whenever the primary users, i.e., the license owners, are not using it. A cognitive radio (CR) is a radio that can change its transmission parameters based on interaction with the environment in which it operates [1].

The use of such radios has been approved both by US and UK regulatory bodies, in 2009 and 2012 respectively [2]. The move was motivated by the digital transition in TV broadcasting, which made large swathes of TV spectrum accessible for opportunistic use. This portion of the spectrum is referred to as TV White Space (TVWS) and its capacity is quite high. According to Ofcom research, there is more than 150 MHz of interleaved spectrum in over 50% of locations in UK and 100 MHZ of interleaved spectrum in 90% of locations [3]. However, the availability of TVWS spectrum varies from country to country and depends largely on the channels chosen for TV broadcasting. Most available (unused or vacant) channels can be found in less densely populated areas, such as in developing countries or rural areas [4, 5].

Frequency bands corresponding to TVWS spectrum are: VHF 30-300 MHz and UHF 300-1000 MHz except for the channels reserved for emergency transmissions. In Europe a challenging aspect of TVWS use is that TV spectrum is not only occupied by fixed TV broadcasting signals but also by licensed Programme Making Special Event (PMSE) devices, e.g., wireless microphones used in small events, concerts or security agencies. PMSE can operate in licensed or unlicensed basis. The detection of such equipment is the subject of research project [6]. Furthermore their protection should be guaranteed based on legislative regulations [7].

While it is not expected that TVWS based broadband access will completely substitute the WiFi technology, such bands may be used to augment spectrum resources when needed [8]. The TVWS are convenient for two main reasons: their superior propagation characteristics for wireless communication which enable larger coverage and the minimal infrastructure requirements which makes them ideal for rural and undeveloped areas which are difficult to reach or connect through optical fiber. This is especially convenient for developing countries such as those in Western Balkans, where broadband penetration rates are increasing rapidly as comparing ITU reports on the state of broadband show [9, 10]. In Albania alone, the number of active mobile broadband subscribers has shot up from 8.8 to 52.6 per 100 inhabitants in the last five years. Furthermore, providing fiber optic connection may not be cost-efficient for service providers, due to the high cost, thus access through wireless broadband networks through TVWS could be preferred [11].

This being said, the successful implementation of this technology largely depends on the ability to effectively manage and avoid the possible interference caused to the primary users. To enable this, the cognitive radios will have to continuously sense the channel to detect primary user transmissions and ensure that primary users are protected at all times. In case that secondary user is using the spectrum and primary user starts operating, than secondary user has to immediately vacate the channel in order to avoid causing interference to primary user. To ensure this, the UK regulator, Ofcom and Federal Communication Commission (FCC) in the United States, have proposed three methods to be used by secondary users: (i) beacons, (ii) sensing and (iii) geolocation with database.

When beacons are used as a controlling method, secondary users will only start transmitting if they have already received a beacon signal implying the vacant channel. The drawback of this method is that it requires the infrastructure of beacons to be implemented and maintained [12].

With sensing, the secondary users will sense the spectrum and try to detect the presence of primary users based on the amount of energy received. Secondary users may operate when they do not detect any primary signals. However, in the case of cognitive devices, this is not a straightforward task as it involves detecting other signal characteristics such as modulation and bandwidth, thus increasing device complexity and cost [13].

The third technique uses geolocation and databases. Secondary users have to send a query to a database that contains information regarding the spectrum usage in the vicinity during the specific time period. The database will respond with the list of available frequencies including all transmission parameters that need to be followed for secondary transmission to start. This implies that secondary users must have geolocation capability, while the database must be kept updated at all times, which incurs additional overhead. An additional challenge on using geolocation and database access is when secondary users are indoors where GPS connectivity may not be available due to the signal disruption from buildings, walls, etc., [14]. Although GPS is one of the most widely used localization techniques, alternative techniques for outdoor and indoor localization using cellular network and wireless local network signals are also possible [15].

Techniques involving both spectrum sensing and information coming from geolocation databases have also been proposed and tested [16]. Ofcom, has performed a series of trials, as part of the TVWS pilot project, to test a number of aspects of white space technology, including the white space device and geolocation database interactions, the validity of the channel availability/powers calculations by the database and associated interference aspects on primary services [17].

Following the decision by US and UK to allow opportunistic use of TVWS several standards were developed to facilitate its practical implementation. The first international standard to be developed for TVWS cognitive devices was ECMA-392, introduced in 2009. But with the introduction of the idea of WiFi communications in TVWS, a task group to develop a new IEEE 802.11af standard was developed in the same year. The IEEE 802.11af standard was approved in February 2014. In July 2010, the IEEE 802.16h standard was published for WiMAX. Following this, in July 2011, a new standard for cognitive radios that will be used in rural areas and enable spectrum sharing, IEEE 802.22, was introduced [18]. 802.22 wireless access technology is envisioned for rural communications because the coverage is large up to 100 km and there is no need for fixed spectrum which makes it very profitable for operators. Because cognitive radios might be used for different purposes and may operate with different technologies, coexistence and self-coexistence problems arise. We use the term *coexistence* to describe the situation that arises when primary users and cognitive radio devices (secondary users) exists/operate in the same time and location, whereas *self-coexistence* describes the cohabitation, in time and space, in the same frequency, of several cognitive radio users or networks which can be of the same or different type. Challenges surface because the different networks tend to selfishly occupy the spectrum to satisfy their own needs without any regards for other network cohabiting in the same spectrum, and the problem is further exacerbated when the various systems using the same spectrum have different operating parameters (transmit power, bandwidth, MAC/PHY layer, etc.).

2. The Cognitive Radio (CR) Network

The cognitive radio network is composed of secondary devices that communicate among themselves; however the configuration and organization of the network will depend on the technology and standard applied. In general, cognitive devices for use in TVWS are divided into four groups: fixed devices, Mode I personal/portable devices, Mode II personal/portable devices and sensing only devices, as defined by FCC specifications and standards [19] and summarized in Table 1.

Fixed devices can transmit up to 4W EIRP (Effective Isotropic Radiated Power). Due to the high transmission power level these devices are not allowed to operate on adjacent channels of the TV channels that are in use and they must have access to database and geolocation capability.

Table 1: Classification of TVWS cognitive devices and the FCC requirements.

Type of device	Position	Geo-location and Database access requirement	Max transmission power allowance	Operation allowance on adjacent channels
Fixed	Fixed	Yes	P_t=4W	No
Portable Mode I Device	Fixed or flexible	No	P_t=100mW	Yes, if P_t=40mW
Portable Mode II Device	Fixed or flexible	Yes	P_t=100mW	P_t=40mW
Sensing Device	Fixed or flexible	No	P_t=50mW	P_t=40mW

Personal/portable devices, also known as low-power devices, are allowed transmission power of 100mW if they are operating in the channels that are not adjacent to the TV channel in use. Otherwise, if operating in adjacent channels their maximum transmit power is reduced to 40mW. These devices are divided in two groups: Mode I and Mode II. Mode I devices are not required to have geolocation and database access, while Mode II are required to have access in order to get the list with available channels in that location. Both these devices, however, are intended to operate using the geolocation principle, which implies that Mode I devices operate only when under the coverage of a Mode II device [12].

The TVWS database is a central database, managed by reliable authority that contains information on all primary user's operation characteristics, such as: transmission power, allocated channels and usage patterns, location, etc. Secondary networks/users must send a query to this database to ask for available channels in their location. It can be noted that location is usually determined based on GPS connection, which may be available for certain types of secondary devices. Therefore, it is most likely that fixed devices will be used in rural areas where the conditions will change slowly, whereas portable devices will be more appropriate for use in metropolitan areas [20].

Sensing only devices are devices that independently sense the radio spectrum in order to detect primary users and avoid harmful interference with them. Their maximum transmit power is 50mW. They are able to sense digital TV, analog TV and wireless microphone transmitted signals at -114dBm. Sensing is performed periodically to determine the availability of a channel, and afterwards, when the channel is allocated, sensing is performed repeatedly over a longer period. Once any kind of signal is detected, within the spectrum they are operating in, these devices stop transmitting within 2s [19, 21].

The cognitive radio devices (CRs) are allowed to operate in most of the channels except those that are reserved for public safety or commercial use. Related work shows that the number of available channels in indoor cases is also significant [22, 23].

It is envisioned that CR networks will be used for the following applications [2]:

(i) Wide area broadband provision to rural areas

(ii) Future home networks and smart grids

(iii) Cellular communications

(iv) Public Safety

As mentioned earlier, CR technology is being viewed as an effective solution for the provision of broadband services in rural areas. Based on a report published by the United Nations, more than 3 billion people live in rural areas [24]. Also in some developing countries such as China and India, around 70 percent of the population live in rural areas. Providing communication services to communities that live in these areas is an important factor towards the betterment of their social and educational development [25].

However, implementation issues present a big challenge considering the high cost versus the low demand. Due to this, different operators are leaning towards low cost solutions. Compared to the cost for wired networks, wireless technologies are more cost-efficient, and several approaches have already been proposed [26–28]. So far none of these initial proposals has produced feasible solutions to offering services in these areas considering the low demand and high cost. The implementation of CR networks, emerged as an optimal solution which takes advantage of better spectrum usage while coexisting with primary users [29]. It is expected that CR will also find an application in future smart grid systems [30, 31].

3. Coexistence Challenges for CR Networks in TVWS

Because existing wireless networks are generally designed to work with fixed frequency allocation, coexistence challenges between wireless networks arise when switching to a cognitive radio environment. In addition, because the available spectrum changes rapidly and there are many different QoS requirements for different applications, CR networks have to handle many additional challenges: interference avoidance with primary users, optimal spectrum band selection for QoS guarantee, seamless communications regardless of the appearance of primary users [32], to name a few. To tackle these challenges, a coexistence decision mechanism (CDM) of a CR network must have these four functionalities: spectrum sensing, spectrum decision, spectrum sharing strategy and spectrum mobility, described in detail in [33–36]. The cycle of cognitive radio functionalities is shown in Figure 1. To overcome the time delay introduced while performing

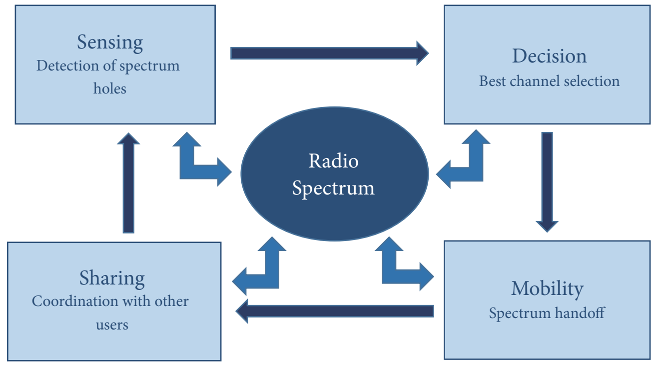

Figure 1: Functionalities for cognitive radio coexistence.

Table 2: Main PHY/MAC differences between IEEE 802.22 and 802.11af.

Systems	802.11af	802.22
Coverage	Up to few meters	Max up to 100 km
Channel bandwidth (MHz)	5, 10, 20, 40	6, 7, 8
Modulation	OFDM	OFDM
TX power (dBm)	20	36
RX (dBm) sensitivity	-97	-64
Multiple Method access	CSMA, TDMA	OFDMA

this complete cycle, solutions such as spectrum prediction for spectrum sensing was proposed [37].

Coexistence issues may arise between different services sharing adjacent portion of the spectrum, such as Digital Terrestrial Television (DTE) and cellular networks operating in the TVWS, as highlighted in [38]. In particular the potential interference caused by the LTE network to the DTT signal in the 700 MHz was studied in [39]. Both these papers conclude that the interference caused by the LTE network can be significant proposing the use of anti-LTE filters to improve the protection of DTT signals, and a case-by-case study of coexistence issues for DTT network planning. A similar study [40], proposes the application of suitable spectral emission masks on the LTE downlink transmission to mitigate the problem.

In particular, coexistence between IEEE 802.22 and 802.11af is challenging due to the differences in operating powers and sensitivity thresholds. The IEEE 802.22 system transmission power is 4W and sensitivity threshold -97 dBm whereas IEEE 802.11af has power transmission of 100 mW and sensitivity threshold -64 dBm [41]. The main differences between the two different IEEE standards are shown in Table 2.

The challenges to enable coexistence arise mainly because of two main reasons: (i) the reception threshold of 802.11af is higher than that of 802.22 receivers resulting on misdetection of 802.22 transmitter from 802.11af transmitter (the hidden terminal problem), and (ii) the transmission power of 802.22 is higher than 802.11af so 802.11af operation can be easily blocked if it is in proximity to the 802.22 transmitter. In the latter case 802.11af will have very little opportunity to transmit [42].

Therefore to enable a fair coexistence between heterogeneous wireless networks in TVWS, a coexistence mechanism must be implemented, that addresses these three main challenges: spectrum sharing, interference mitigation and spectrum detection [20], as further detailed in Table 3.

3.1. Spectrum Availability Detection. Spectrum availability detection or spectrum sensing is the process during which secondary networks while sensing the spectrum must identify available TV channels that can be used without causing harmful interference to primary users. Sensing can be performed in three domains: time, frequency and space. Sensing is used also to identify the types of signals that are occupying the spectrum by determining their: carrier frequency, modulation type, bandwidth etc. Spectrum sensing can be performed using several techniques: energy detection, matched filtering, cyclostationary feature-based sensing, radio-identification based sensing and waveform based sensing. However, due to its simple implementation, the energy detection technique is the one that is most commonly deployed. The signal detection with this technique is based on comparing the sensed signal with a defined SINR threshold [43]. The detection threshold is an important parameter that needs to be optimized to minimize the errors in detection, and adaptive techniques on setting this threshold have been investigated in [44]. Other techniques require *a priori* knowledge of regarding primary user transmitted signal, which is not always easy to get, and the implementation at the receiver end is a challenge. For example matched filtering technique is only appropriate to be used in the case that the secondary user knows all the information about the primary user transmitted signal. The computational time is very low but on the other hand the power consumption is high [45].

Moreover, the spectrum detection phase does not need to be performed in isolation. Indeed with the increasing number of interconnected sensors in the framework of the Internet of Things paradigm, some authors propose to take advantage of the readily available infrastructure to perform

Table 3: Coexistence challenges of cognitive users/networks in TVWS.

Challenges for cognitive devices/networks in TVWS					
Spectrum sharing		Interference mitigation		Spectrum availability detection	
Cooperative method	Non-cooperative method	Interference from/to primary users	Interference among cognitive wireless networks	Primary user detection	Secondary user/network detection

channel sensing and identification of TVWS [46]. A cloud-computing platform, which enables precisely this, and allows the Sensing-as-a-Service concept to be used in the context of spectrum availability detection is proposed in [47].

While detection of the primary users is crucial to enable self-coexistence, secondary networks must also be able to detect other secondary cognitive networks that operate in the same or neighboring channels. Failing to do so will lead to a decrease in network performance due to increased interference. To overcome this issue, one approach is to enable cooperation among secondary networks in order for them to be able to coordinate and synchronize spectrum usage.

3.2. Interference Mitigation and Spectrum Sharing. Interference mitigation is a very challenging issue especially in areas where availability of channels is limited or where there is overlapping between coverage areas of different networks. This is further accentuated considering the good propagation characteristics of TVWS signals.

In environments where heterogeneous networks coexist in TVWS, there are two types of interference that need to be addressed:

(i) Interference to and from primary users

(ii) Interference among secondary devices or networks

To ensure protection of primary users and measure the interference level, FCC Spectrum Policy Task Force has proposed a new metric named interference temperature [48]. Interference temperature is the level of RF power measured in receiving antenna per unit bandwidth [49].

$$T_I\left(f_C, B\right) = \frac{P_I\left(f_C, B\right)}{kB} \tag{1}$$

$P_I(f_C, B)$, is the interference power (in Watts) for frequency f_c and bandwidth B (in Hz), while k = 1.38 10 ^{23} Joules per degree Kelvin, is the Boltzmann constant.

For a specific location and frequency band, FCC has also established the interference temperature limit, which should not be exceeded by secondary users when allowed to operate simultaneously with the primary user [50]. The configuration of the interference temperature limit is further discussed in [51]. Interference from primary users to secondary ones, on the other hand, results from the high transmission power of primary users, e.g., TV stations. In addition to causing interference that will invariably degrade the performance of secondary users, it also may hinder secondary users from detecting the location of primary receivers.

To tackle primary/secondary interference there are two types of interference mitigation techniques: interference avoidance and interference control. With interference avoidance, primary and secondary users are not allowed to use the same channel in the same time or the same frequency, and in order to coexist they must detect spectrum gaps and then employ time or frequency separation, i.e., TDMA or FDMA. Using interference control, primary and secondary users can coexist in the same time or frequency if they follow specific coexisting requirements, such as set limits of allowed level of interference, which will guarantee QoS (Quality of Service) for both types of users.

While the interference to primary user has been widely investigated, the interference to the secondary user from the primary ones as well as the aggregated interference to secondary users among themselves has not gained as much attention. In most cases the secondary users are assumed to be idle or their degradation of performance is not accounted for.

Interference among secondary devices becomes a challenging issue as the number of secondary users/networks that will try to access the spectrum opportunistically increases. Such interference, may also affect primary signal detection as shown in [52]. The problem is worsened in areas with limited spectrum availability where many devices might choose the same channel or they will have to work on adjacent or cochannels. It was shown in [53] that cochannel interference is avoided by increasing the distance between primary and secondary users whereas adjacent channel interference is mitigated by avoiding the operating frequency between devices by at least three adjacent channels. To enable self-coexistence among secondary networks/devices, several parameters can be adjusted: power control due to the different transmits power levels from different devices, SINR (Signal to Noise Ratio) to estimate PER (Packet error rate), bandwidth and adaptive receiver threshold [54].

Self-coexistence is also ensured through spectrum sharing and management among different wireless technologies. Because they are generally expected to have different communications characteristics, this poses an important challenge for cognitive radio networks in TVWS. Based on access priorities, spectrum sharing among wireless heterogeneous systems is classified in two groups: open spectrum sharing and hierarchical spectrum sharing.

With open spectrum sharing every system, both primary and secondary have the same priority for accessing the spectrum [55–57]. Since in this type of spectrum sharing heterogeneous systems coexist without centralized coordination, spectrum access etiquette is proposed to mitigate the interference and give fairness among users [58]. By contrast hierarchical spectrum sharing is when primary users always have priority for spectrum access, while secondary users need to make sure that the interference caused to primary users is not harmful before accessing the spectrum. Based on the impact of interference, hierarchical spectrum sharing is divided into two groups: underlay and overlay spectrum sharing [59]. Underlay spectrum sharing is when the interference caused by a secondary user to a primary receiver is below a predefined threshold. Since the interference in this case is not harmful, the secondary user will be allowed to operate even if the primary user is active. To make this possible, the secondary user must have the channel gain information between its transmitter and the primary receiver [60]. Different interference measurement schemes have been proposed in [52, 61].

On the other hand, in overlay spectrum sharing, a secondary user may transmit only if the primary user is not active at that time, which is referred to as the idle period [62]. To detect this idle period, the secondary user needs to sense the spectrum. Sensing techniques are discussed later in the paper.

Based on their ability and willingness to collaborate or not, there are two possible ways for different networks to access the spectrum. There are schemes for coexistence that are based on cooperative or noncooperative method [63].

Cooperative method means that there has to be cooperation and communication between devices or networks that are sharing the spectrum and are within each other's' interference range. Cooperative methods are normally based on the ability to exchange information between networks of similar or different types. This method overcomes the hidden node problem as all the networks are aware of each other's' geographical positions. Using relays to pass the information among cognitive users that operate in the same band by using amplify and forward protocol was introduced as an idea in [64]. For this method there are different mechanisms that can be used, such as: TDMA (Time-Division Multiple Access), FDMA (Frequency-Division Multiple Access) and CDMA (Code-Division Multiple Access). However, considering that spectrum might be shared between heterogeneous networks that have different operational characteristics and requirements, such as: frame rate, guard bands, power allocation, etc., there are many challenges on implementing these techniques. Because of this, adopting a cooperative method for all secondary users may not be very useful as shown in [65].

The performance of cooperative spectrum sharing method in a more realistic propagation environment is investigated in [66]. Another major drawback in cooperative sensing method is the large amount of information that needs to be exchanged between secondary users inducing high overhead. To deal with the problem of overhead, the GUESS protocol was introduced in [67].

In***noncooperative methods***, different networks will make the decisions based on their own observations [68]. Different strategies are used for these methods such as: DFS (Dynamic Frequency Selection), DCS (Dynamic Channel Selection), power control, listen before talk, Energy Detection Threshold, etc. Even though this strategy is cheaper and easier to implement, it does not always give the best network performance in terms of throughput and fairness among networks and users.

4. Self-Coexistence Decision-Making Mechanisms for CR Networks in TVWS

Without the use of coexistence mechanisms, the utilization of TVWS spectrum will be significantly reduced. It was shown in [69] that without the use of coexistence mechanisms, 92% of available spectrum is overlapped by neighboring networks.

Based on the proposed architecture [70], the coexistence mechanisms are classified into three groups: centralized, coordinated and autonomous mechanisms. The difference among these coexistence mechanisms relies on where the coexistence decision is made.

(1) **Centralized mechanisms** - in order to mitigate the interference, these mechanisms use a database in which all coexistence information is collected and stored centrally. Then to pass the information to users, internetwork coordination channels are used [69]. However this solution is costly and also ineffective when there are many coexisting devices or even networks that do not want to be part of a centralized control system.

(2) **Distributed mechanisms** - an internetwork coordination channel is proposed so there is no need for central coexistence infrastructure. All the decisions regarding interference mitigation are made individually by each network or device and then the information is passed to others through control channels. This solution also incurs communication overhead, and depends on the willingness of the networks to exchange information. Furthermore, it relies on the existence of a common control channel and assumes that all coexisting networks use the same access technology in order to be able to decode each other's messages

(3) **Autonomous mechanisms** - there is no internetwork coordination channel or central infrastructure available. All the decisions for channel selection and interference mitigation are done only by individual observations. Possible techniques used for this case are: dynamic frequency/channel allocation technique and listen before talk. Even though these type of mechanisms are easy and cheap to implement they do not give a good network performance. Because each system aims at blindly maximizing their own performance, the internetwork interference severely degrades the overall network performance. The different coexistence mechanisms are presented in the Figure 2.

In general, a limited number of algorithms have been proposed in the relevant literature, that deal directly with the coexistence problem between heterogeneous cognitive radio networks. Most of such algorithms are centralized or assume some form of coordination between participating networks,

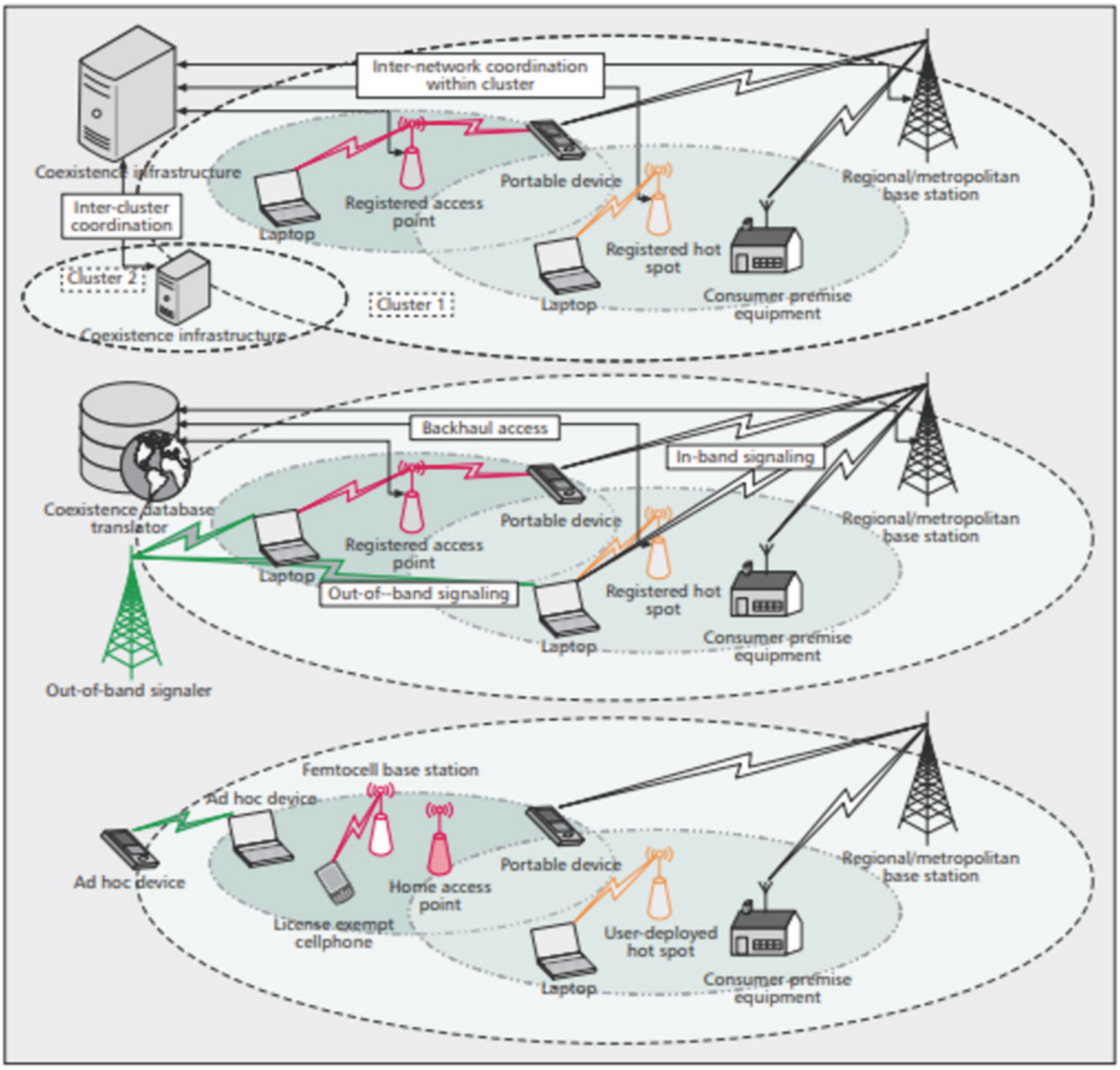

Figure 2: Types of coexistence mechanisms in heterogeneous cognitive networks [70].

with only a handful of autonomous approaches available. In the following subsections, we start by introducing the IEEE 802.19.1 standards, and then we list and compare some of the CDM solutions proposed in the literature.

4.1. The IEEE 802.19.1 Standard. The IEEE 802.19.1 standard, released in 2013, addresses the problem of self-coexistence in heterogeneous cognitive networks using a broadcast channel to send beacons to coexisting secondary networks. The purpose of the standard is to enable the family of IEEE 802 Wireless Standards to most effectively use TVWS by providing standard coexistence methods among dissimilar or independently operating secondary networks. This standard addresses coexistence for IEEE 802 networks and devices and may also be useful for non IEEE 802 networks [71].

In the architecture, shown in Figure 3, the main entities are: Coexistence Manager (CM), Coexistence Enabler (CE) and Coexistence Discovery and Information Server (CDIS).

(i) Coexistence Enabler's (CE) role is to enable communication between coexistence manager and TVBD network

(ii) Coexistence Manager's (CM) role is to discover other coexistence managers and make decisions to facilitate the coexistence of networks it serves.

(iii) Coexistence Discovery and Information Server's (CDIS) role is to support discovery of other coexistence managers, storesthe information related to coexistence in TVWS and also communicate with TVWS database to get the information related to primary user's activity.

Even though the IEEE 802.19.1 standard was released in 2013, there has been little research tackling the challenge of self-coexistence among secondary networks, and not many coexistence decision mechanisms (CDM) have been proposed.

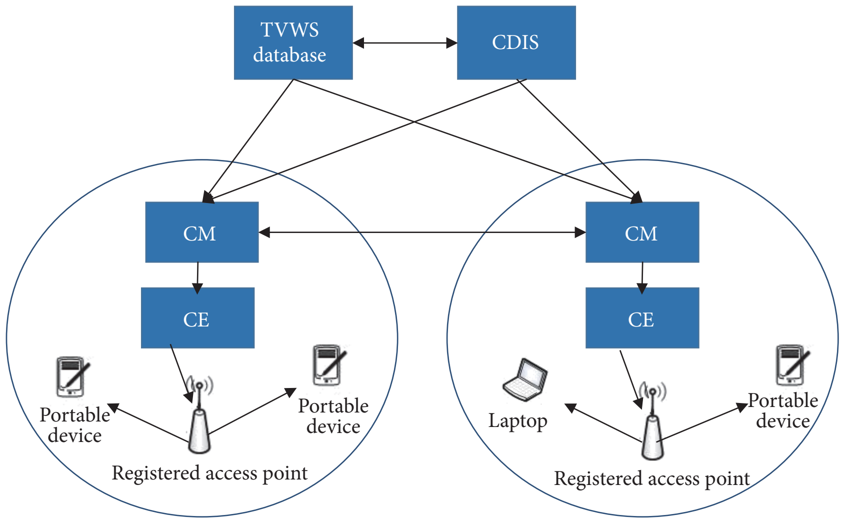

Figure 3: IEEE 802.19.1 architecture.

CDMs ideally facilitate spectrum sharing between networks and support resource allocation function:

(i) By ensuring fairness between the different networks

(ii) By optimizing energy consumption:

(iii) By mitigating cross-network interference

(iv) By respecting different transmission constraints and satisfying as best as possible the demands of each network

However, these goals are difficult to reach when distributed topologies are considered.

4.2. Signal-Based Schemes Tackling the Hidden Terminal Problem. A partially distributed scheme for spectrum sharing in TVWS, using beacon signals, is proposed in [72]. The work focuses specifically at the coexistence problem between TDM and CSMA MAC networks. As the authors underline, the fact that the two networks use different MAC protocols, poses serious challenges for spectrum sharing. The solution proposed, titled SHARE, specifically targets the problem of hidden terminals, which is particularly apparent when heterogeneous networks cohabit the same spectrum space. There are two types of collisions that can occur due to the hidden terminal problem: collisions at TDM receivers caused by hidden CSMA transmitters and vice versa. To mitigate the first group of collisions, the algorithm utilizes beacon signals to prevent CSMA transmitters to access the shared channel. To mitigate the other group of collisions, a dynamic quiet time period is proposed for the TDM transmitters, to reduce the probability of collisions and ensure long-term fairness in spectrum sharing among coexisting networks. The authors assume the presence of a 802.19.1 controller that manages the coexistence for the TDM based secondary networks, which are at all times registered with the 802.19.1 system and are completely synchronized with each other.

A similar autonomous scheme is proposed in [73], for enabling coexistence between IEEE 802.11af and 802.22 networks. The basic idea is to use the sensing antenna available at the 802.22 receiver (which normally remains unused during reception period), to send out a busy tone in order to protect its communications from hidden 802.11af terminals. The busy tone, a constant signal transmitted at the same power level as an 802.11af signal, is transmitted by the 802.22 receiver, while it simultaneously receives data from the 802.22 transmitter. The scheme's goal is to protect the communications within 802.22 network, but it does not address the reverse problem or the fairness achieved during channel access. Furthermore, the authors assume that all 802.22 devices, both the base stations and the mobile users, are equipped with two antennas, one of which is used exclusively for sensing.

The problem of continuous primary user is largely ignored in both approaches, and the authors in [72] explicitly assume that the secondary networks obtain the list of available channels from a TVWS database via 802.19.1 air interface. Therefore, while it is indeed a partially autonomous algorithm, its performance relies heavily on centralized exchange of information. On the other hand, due to the asymmetric transmit powers; neither scheme is able to ensure fairness for the low-power 802.11 networks.

4.3. Distributed and Decentralized Approaches for Self-Coexistence of CR Networks. A game theoretic approach for solving the coexistence problem between cognitive radio networks sharing the same spectrum in the uplink is proposed by Gao *et. al.* in [74]. The problem is formulated as an uplink channel allocation problem, which is further subdivided into two subproblems: the subchannel allocation problem and the transmit power allocation problem. The cognitive radio networks, which in the worst case scenario are controlled by different operators, participate in a noncooperative game in which each CR network independently selects the channels it will use in a way that will maximize their own utilities. The game is played in two levels, where players' solve the subchannel allocation game and then in the second level solve the transmission power problem. The authors note, that the second level game has a Nash equilibrium, which can be reached using algorithms such as iterative water filling. The subchannel allocation game, on the other hand, does not possess the properties which guarantee a Nash equilibrium. The authors propose a practical heuristic algorithm, which does not reach the global optimum, but is more efficient as it does not require global knowledge about all the cells operating in the same space. However, the authors address the coexistence problem only in the uplink and on a single channel basis, assuming all other channels have the same characteristics. Furthermore, they do not consider the presence of heterogeneous networks but rather assume that all secondary networks are of the same type, but belonging to different operators. Therefore, issues arising due to differences in MAC/PHY layers are not addressed.

An interference avoidance strategy is proposed in [75] which aims to adaptively and autonomously enable the CR networks select the channels so as to maximize the throughput in presence of coexistence interference. The coexistence problem is formulated as an *optimal sensing sequence* and *optimal stopping rule* optimization problem, with the objective of maximizing the expected reward, i.e., average throughput achievable by the secondary user in a given time-slot. The algorithm is attractive because it features no cooperation overhead among the various networks, i.e., each network independently selects the TVWS channels to use. However, some of the assumptions are too simplistic, such as the hypothesis of identically and independently distributed coexistence interference levels. Furthermore, the authors compare the performance of the algorithm only to a simple *sense-before-talk* algorithm in terms of expected average throughput, while the complexity of the algorithm is compared to an exhaustive search solution, which is known to have excessive computational times, especially when considering higher number of available channels.

In [76] the authors propose a decentralized algorithm to address the problem of self-coexistence in TVWS, between secondary networks of three different types, IEEE 802.22, IEEE 802.11af and IEEE.802.15. They consider the usage of independent mechanisms where there is no central manager for decision-making, no database for information queries and storage and no common physical communication channel between the networks for information exchange. The self-coexistence and interference mitigation are ensured only based on the individual observations of the secondary users, which means that there is no need to synchronize and coordinate between networks to reach a fair solution. The SCDM algorithm is based on congestion-averse games (CAG) for self-coexistence decision-making in TVWS and addresses the challenges of self-coexistence in terms of fairness and efficiency of resource allocation. For comparative purposes to centralized solutions, the same the game is solved also in centralized manner where the authors assume the presence of a controller with global knowledge who applies the CAG algorithm on behalf of networks.

4.4. Centralized Approaches for Self-Coexistence of CR Networks. In [77] the authors propose a centralized algorithm that deals with the problem of spectrum sharing among secondary networks and compare the results to other CDM algorithms that are specified in the IEEE 802.19.1 standard. The algorithm is called Fair Algorithm for Coexistence decision-making in TV whitespace (FACT). Constrains considered in the decision-making process are: contiguous channel allocation, interference, fairness, channel allocation invariability and transmission scheduling constraints. The results showed that FACT algorithm outperforms two other algorithms [78, 79] based on the overall system performance in terms of fairness and percentage of demand serviced. However, being a centralized algorithm, there are evident drawbacks due to the amount of communication overhead and complexity. Indeed the gains in performance compared to the other two algorithms come at the price of higher computational running time. Furthermore, the algorithm cannot guarantee fairness, once the available channels are insufficient to accommodate the users' demands.

The authors in [80], on the other hand, formulate the coexistence problem as a multiobjective optimization problem and propose a centralized evolutionary algorithm that shares the TVWS among coexisting networks so that the allocation satisfy the channel occupancy requirements of each network. The objectives modeled include fairness, system throughput maximization and users' demand satisfaction. The authors compare the performance of their algorithm to two other centralized solutions, detailed in [77, 81], and show that while their algorithm does not significantly improve system throughput and spectral efficiency, it ranks significantly higher in the fairness indicator, measured using the Jain index. While the authors show that the computation time is significantly shorter than the FACT algorithm, they do not address the overhead incurred, which is significant in both algorithms.

4.5. The Comparative Analysis of Coexistence Algorithms in TV White Spaces. In this section we present a comparative analysis between some of the coexistence decision-making algorithms listed above, namely the FACT algorithm presented in [77] and the CAG algorithm presented in [76]. Algorithms are compared in terms of demand, fairness, and achieved theoretical throughput.

Firstly the algorithms are compared in their ability to satisfy bandwidth demand of the networks. We observe in Figure 4 (left) that centralized CAG algorithm significantly outperforms FACT algorithm, while the decentralized CAG algorithm has poorer performance but still performs better than FACT.

Secondly we evaluated the fairness of each algorithm. As shown in Figure 4 (right) CAG game solved centrally performs best in terms of fairness and even though FACT performance increases steadily as the number of available channels increases it does not outperform the decentralized CAG.

Lastly the algorithms are compared based on the theoretical data rates obtained by each individual user. We observe in Figure 5 that in general the rates obtained with CAG are

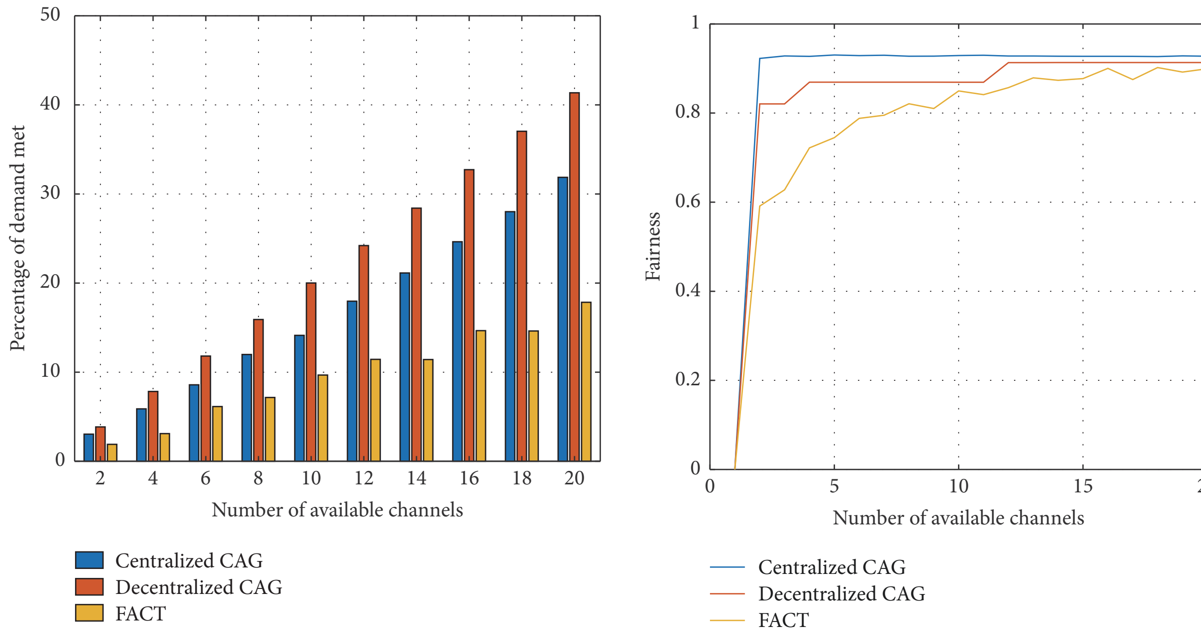

Figure 4: The comparison between CAG and FACT algorithms. Left: the comparison in terms of demand met. Right: the comparison in terms of fairness.

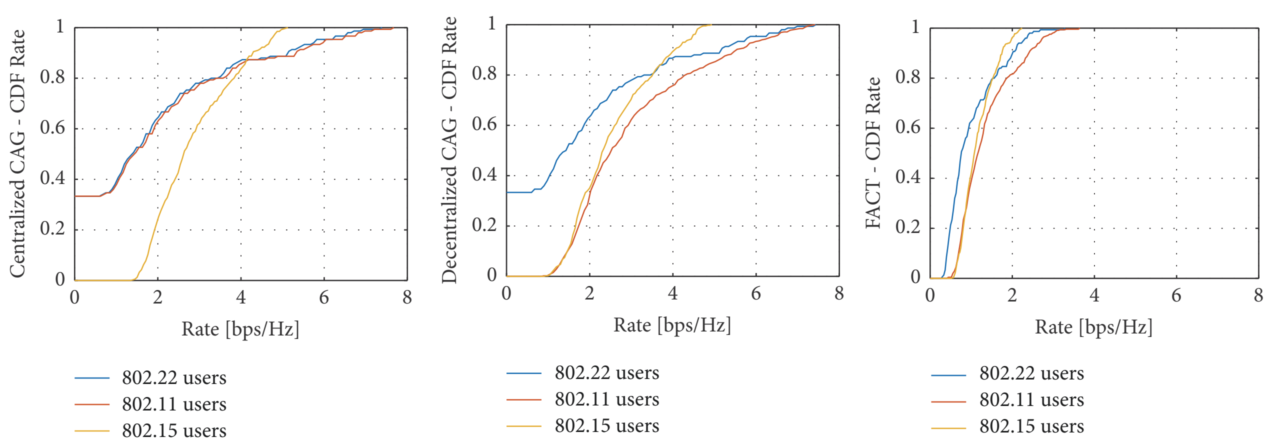

Figure 5: The cumulative distribution function (CDF) of the obtained throughput for the different types of CR networks using CAG and FACT. Left: centralized CAG; middle: decentralized CAG; and right: FACT.

much higher than those obtained with FACT for all types of users.

These results imply that even when networks independently make decisions, the performances are remarkable considering that decentralized implementation does not require overhead or global knowledge.

The results are that when the number of channels available is less than demand of the CR networks both cooperative and noncooperative method are able to deliver similar performance in terms of throughput.

Things change when the number of channels is increased over the number of channels required. The results shows that the noncooperative method may deliver better results in terms of network throughput, because the centralized/zcooperative methods require more computational time in order to decide which is the best channel allocation.

We need to bear in mind that longer computational time limits the time available for users to transmit and receive information. On the other hand, if the number of devices requiring the spectrum is increased, the centralized/cooperative method has better performance compared to noncooperative method in terms of fairness.

5. Conclusions and Future Work

In this survey comprehensive overview is provided on the use of cognitive radio technology to utilize the recently released TV White Spaces. In the first two sections we present the basic concepts of cognitive radio technology and networks, describing the features of various cognitive device types, and list some of their potential applications. More importantly we present the relevant literature and list some of the biggest challenges in the implementation of cognitive radio networks in TVWS. It is expected that the opportunistic use of TVWS will be available to several different wireless access technologies such as 802.16, 802.22, and 802.11. All these technologies typically use different PHY/MAC protocols, use varying levels of transmit power, and have different sensitivity threshold. Therefore, one of the biggest challenges will be enabling the coexistence between the different cognitive radio networks utilizing the same spectrum resources simultaneously. As our overview shows this issue has recently attracted a lot of attention by the research community. We identify the coexistence issue as critical for the implementation of TVWS.

In the last section we list some of the most recent algorithms proposed for solving this problem. Some coexistence decision-making mechanisms are also included in IEEE 802.19.1 standard, which mainly relies on the existence of a central mechanism to mediate between the heterogeneous networks. Some autonomous algorithms described in the previous section use concepts such as busy tone signaling, beacon transmission, and dynamic quit periods but they are usually heavily outperformed by centralized/coordinated mechanisms and the extensions they propose tend to be specific to the particular wireless access technology considered. Furthermore, primary user protection is often ignored, and the coexistence between secondary networks and primary networks is considered separately, although in practice it is not so easily decoupled.

Summarizing, some topics for future consideration will be the following:

(i) Design and assessment of reliable network discovery mechanisms for heterogeneous scenarios (mechanisms for detection of secondary networks)

(ii) Assessment of channel schemes based on channels with different characteristics so that each WRAN cell can decide on the best channel according to the quality of service requirements of application

(iii) Secondary user choice to have cooperative or noncooperative behavior

(iv) Design and assessment of realistic channel models to accurately predict the propagation losses and effects of multipath and fading.

For the future, the goal will be to develop a CDM algorithm to address some of the above listed aspects, concretely to include realistic channel models to account for propagation losses and also the inclusion of channels with different characteristics in terms of bandwidth and quality of service requirements.

Data Availability

The results were obtained using MATLAB simulation software. The underlying data supporting the results can be obtained upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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