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Cognitive radio for TVWS usage

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Abstract

Spectrum scarcity is an emerging issue in wireless communication systems due to the increasing demand of broadband services like mobile communications, wireless internet access, IoT applications, among others. The migration of analog TV to digital systems (a.k.a. digital TV switchover) has led to the release of a significant spectrum share that can be used to support said additional services. Likewise, TV white spaces emerge as spectral opportunities that can also be explored. Hence, cognitive radio (CR) presents itself as a feasible approach to efficiently use resources and exploit gaps within the spectrum. The goal of this paper is to unveil the state of the art revolving around the usage of TV white spaces, including some of the most important methods developed to exploit such spaces, upcoming opportunities, challenges for future research projects, and suggestions to improve current models.

Keywords: *cognitive radio, digital switchover, DSA, spectrum sensing, TVWS*

1. Introduction

Nowadays, wireless communication services are showing an exponential increase as a consequence of the deployment of new technologies and solutions such as the internet of things (IoT), broadband internet access, digital TV, enhanced mobile communications, smart grid networks, among others, which are continuously requesting for additional spectral resources aiming to increase bandwidth, reliability and consistency [1, 2]. However, due to the current static spectrum allocation approach, scarcity has become a growing issue [3].

In most countries, the spectrum assignment process follows a static approach, meaning that frequencies are statically distributed among the required services regardless of whether they are used partially or all the time. This strategy has been operating all over the world as of now yet recent studies are revealing that frequency bands are being used inefficiently as long periods where they remain free. Spectrum usage measurements [4-8] carried out in Virginia, Chicago, South Africa (Pretoria), Pakistan and some European countries demonstrate that it is used inefficiently. Due to this situation, dynamic spectrum assignment (DSA) techniques have been explored based on the dynamics of services. Recently, cognitive radio (CR) has emerged as a part of the new wave of alternatives thus providing devices the capacity to sense the spectrum, re-configure its parameters and learn from the experience. Therefore, it is conceived as a highly feasible way to address the problem of spectrum scarcity [3, 9-11].

On another note, the migration of TV services from the analog to the digital domain (a.k.a. digital TV switchover) is an ongoing process which has already been completed in most developed countries including the USA, the UK, China and Japan. This migration offers a set of advantages and additional services specially the release of frequency bands required for the efficient usage of the spectrum. As a result, spectral opportunities within TV bands, known as TVWS (TV White Spaces), have emerged [9-12].

According to the previous statement, the proposition of the problem in the present article is based on the following research question: How can spectral opportunities of digital television, known as TVWS, be harnessed, what solutions have been proposed so far and what research challenges are yet to be solved?

In addition to presenting the current state of TVWS usage techniques, the goal of this article is to describe cognitive radio and TVWS concepts as well as the research challenges in said usage. Hence, the researcher and reader of this article can deliver proposals for the access

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of spectral opportunities by exploiting the spectrum sensing and decision-making capabilities of cognitive devices based on literature and field measurements.

Several studies have been carried out in the field and some regulations have been proposed in the USA and the UK to allow the use of TVWS in an unlicensed basis. Standards such as IEEE 802.22 WG (Working Group) have been released in the field as well [13]. Besides, most studies have focused their efforts in developing a framework based on geo-location databases which ignore the spectrum sensing capabilities of the device according to the CR paradigm. Nonetheless, this is a relatively recent research subject in which there is much to be explored and proposed. It is then necessary to determine the current state of literature regarding cognitive radio for TVWS usage and establish the research challenges that lie ahead.

The article is organized as follows: In the second section, a description of the CR concept and methodology is presented. The third section includes a definition of TVWS as well as an overview of digital TV standards. The fourth section describes current applications and pilots carried out worldwide and an overview of the possible challenges and opportunities. The fifth section presents the conclusions0.

2. Cognitive Radio

As stated in the introduction, Cognitive Radio (CR) is a dynamic spectrum access (DSA) technology which is a highly feasible solution for spectrum scarcity problem. The term was firstly introduced by J. Mitola [10] who defined it as follows: “the term cognitive radio identifies the point at which wireless personal digital assistants and the involved networks are sufficiently intelligent in terms of computational and radio resources as well as computer-to-computer communications used to (a) detect user communications needs as a function of the use context and, (b) to provide the radio resources and wireless services that are most appropriate for those needs”.

A more technical definition of cognitive radio can be found in [14]: A CR is a radio system which employs technology to obtain knowledge of its operational and geographical environment, established policies, and its internal state. This is known as a cognitive capability; A CR can dynamically and autonomously adjust its operational parameters and protocols according the gathered knowledge in order to achieve predefined objectives. This function is called the reconfigurable capability. Finally, a CR can learn from the obtained results which is known as its learning capability.

Within the cognitive cycle of a CR, four basic functions are considered: Spectrum sensing, Spectrum decision, Spectrum Sharing and Spectrum mobility [12, 15-18]. The first one refers to the ability to sense the radio environment and detect possible holes in the spectrum which will depend on time, location and spectrum usage by PUs (Primary Users). In [19], a deep study of different PU activity models is described. Once the spectral opportunities have been identified, the next step of the process is to decide which opportunity should be used based on user needs such as bandwidth, QoS and reliability. CR could either carry out a reactive action by making a quick decision or a proactive action where parameters like QoS or internal/external policies need to be considered in advance. Spectrum sharing will be required since many CRs would probably use the same bands at the same time and location. Hence, spectrum sharing techniques will need to be implemented to allow the SUs to cooperate and use the spectrum in a coordinated manner thus preventing any kind of interference over the PUs. In [18], a highly-detailed analysis of the resource allocation techniques in cooperative CR networks is thoroughly presented. Lastly, the CR should be able to vacate the spectrum hole everytime that a PU is detected since licensed users have a priority in terms of band usage. This is called the spectrum mobility function. A graph of the cognitive cycle is shown on the Figure 1.

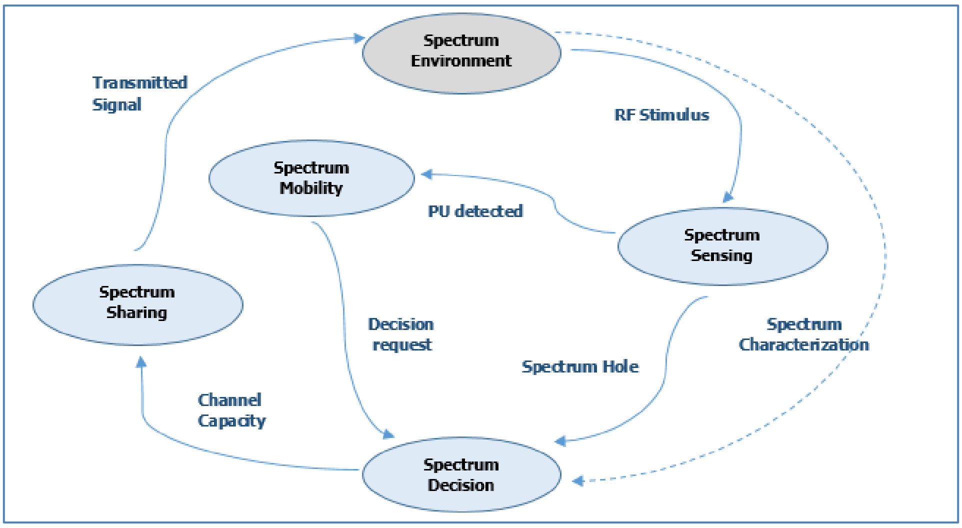


Figure 1. Spectrum cycle, based on [10]

3. TV white Spaces

According to different spectrum usage studies, there are gaps on time/location where the spectrum is not being utilized by the primary users (PU) and hence, the opportunities for SUs (secondary/unlicensed users) become available [3, 9, 12, 20-22].Those gaps are known as spectrum holes [3] and are classified in two different types: (a) time spectrum holes: periods of time in which the primary user is not transmitting and (b) frequency spectrum holes: Frequency bands in which a secondary user can transmit without interfering with any PU.

On a side note, TV bands are usually licensed in almost any country of the world and occupy the VHF-UHF bands which range from around 54 MHz to 806 MHz where each TV channel may have a bandwidth of 6 to 8 MHz depending on the country and the adopted standard [23, 24]. Each TV station is assigned a fixed TV channel within the spectrum where it is allowed to transmit its signals all the time. Policies and legislation regarding spectrum usage assure that primary or licensed users are protected from interference. TV signals are broadcasted by continuously using the spectrum regardless of whether primary receivers are taking said signals [25, 26]. However, it has been evidenced that TV bands are not being used the entire time and some gaps are visible on the TV spectrum in order to prevent co-channel interference. The “unused” portions of the TV bands are known as TVWS (TV white spaces) [2-3, 10, 17]. This type of spectral opportunity could be classified as a frequency spectrum hole.

3.1. Spectrum Sensing in TV Bands

In the field of TVWS, different spectrum sensing approaches have been studied [3, 10, 27-29]. Most of them are mainly focused on primary transmitter detection and can be classified into three categories: matched filter, energy detection and signal feature detection. The purpose behind these alternatives is to determine the presence of the PUs.

The matched filter technique is considered an optimal detection method as it maximizes the received SNR ratio and also requires the demodulation of a PU signal. Hence, prior knowledge of the signal is required: modulation type, order, pulse shaping and packet format. Once the original signal is received, it is then operated with a pilot sequence which results in a power criterion subsequently compared with a threshold. This comparison determines whether the signal is considered occupied or available. The main advantage of this technique is that it requires less time to determine a given detection probability since it needs a lower number of samples due to its high coherence. However, its disadvantage is that a CR would need a dedicated receiver for every type of PU [2, 3, 10, 17, 30].

Energy detection is a non-coherent detection method which does not require a priori knowledge of the PU signal. It ignores the structure of the signal and hence has a low computational cost. It assumes that the energy of the signal to be detected is always higher than the energy of the noise. It estimates the presence of a signal by comparing the energy received with a known threshold derived from noise statistics. The performance of the energy detector is directly linked to the number of samples. A higher number of samples would reduce the noise power thus improving the SNR. However, the energy detection method has many drawbacks: (a) the threshold used for primary user detection is very susceptible to unknown or shfiting noise levels. (b) The energy detector does not differentiate between modulated signals, noise and interference so it cannot benefit from adaptive signal processing to cancel out the source of the interference [2, 3, 10, 17, 30].

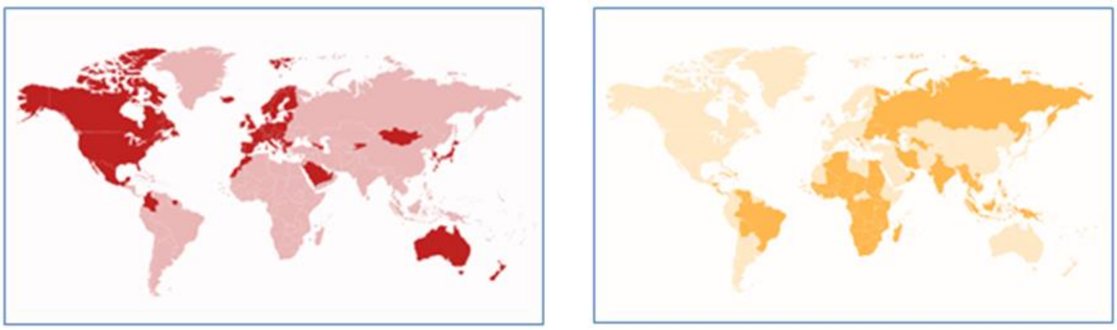
Another popular method for spectrum sensing is cyclostationary feature detection, in which modulated signals are coupled with sine wave carriers, pulse trains, repeated spreading sequences, hopping sequences or cyclic prefixes, as seen in TV systems. This results in built-in periodicity. The signals are characterized as cyclostationary because their mean and autocorrelation exhibit a certain periodicity. Therefore, it is possible to differentiate it from noise, which is a wide-sense stationary signal with no correlation. The advantages of this technique include its stronger performance under low SNR regions, its signal classification ability and its flexibility of operation. Nonetheless, more complex processing is needed and high-speed sensing cannot be achieved. Furthermore, a priori knowledge of the original signal characteristics is also needed [2, 10, 17, 30].

3.2. Digital TV Operation and Characteristics

Nowadays, most countries are migrating from analog TV systems to the digital world due to the latter's enhanced capabilities such as [23]:

a. High definition television (HDTV) in the form of digital signals improve the resistance to interference and do not accumulate noise.
b. Digital signals use spectrum frequencies more efficiently. About the same amount of spectrum share required by an analog TV channel can be multiplexed into 10 SDTV (digital standard definition TV channels). Hence, the spectrum is used more efficiently.
c. Digital technology eases the information encryption process and adds support to interactive services such as electronic programming guides (EPG), individualized TV, internet over TV, video on demand (VOD), mobility/portability, and enhanced commercials, among others [24].
d. It eases how the information is stored, processed and distributed.

Similarly, different digital TV standards have been developed around the world with the most important ones being the ATSC (Advanced Television Systems Committee) from the USA, the DVB (Digital Video Broadcasting) from Europe, the ISDB (Integrated Service Digital Broadcasting) from Japan and the DTMB (Digital Terrestrial Multimedia Broadcasting) from China. These four standards have been technically accepted by the ITU (International Communications Union) and are being implemented around the world as seen in the ITU website [14]. The status of the transition to DTT (Digital Terrestrial TV) technology can also be reviewed. Figures 2 and 3 show a world map highlighting the countries where migration to DTT has been completed (Figure 2 (a)) or is still ongoing (Figure 2 (b)) and a pie chart with the statistical distribution of the DTT standard implemented worldwide.



(a) (b)

Figure 2. Status of the digital switchover process in the world, (a) completed and, (b) ongoing [31]

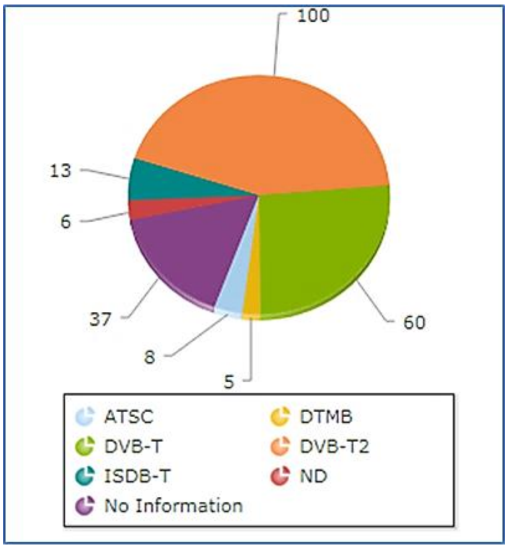


Figure 3. Distribution by type of standard implemented [31]

As evidenced in the figures, various countries have already completed the migration process to DTT technology. According to the chart, it can be stated that most of them have implemented either the DVB-T or DVB-T2 standards. Colombia is an example of a country that has already moved to DTT technology by implementing the DVB-T2 standard. An overview of the most important digital television standards including their main characteristics can be seen in Table 1 [23, 24, 32].

Table 1. Digital TV Standards Comparison

DTV Standard	Channel Bandwidth (MHz)	Operation Frequencies (MHz)	Transmission Capacity– Terrestrial (Mbps)	Modulation Schemes	Video Encoding	Audio Encoding	Middleware*
DVB	6, 7 or 8	174-230, 470-862	5 to 31.7	COFDM (Terrestrial) QAM (Cable and MMDS**) QPSK (Satellite ad LMDS***)	MPEG-2	MPEG-2 ACC	Multihome Platform (MHP)
ATSC	6	54-72, 76-88, 174-216, 470-698	19.3	8-VSB (Terrestrial) 64-QAM (Cable) QPSK (Satellite)	MPEG-2	Dolby AC-3	DTV Application Software Environment (DASE)
ISDB	6, 7 or 8	470-770	3.65 to 23.2	COFDM (Terrestrial) 64-QAM (Cable) 8-QPSK (Satellite)	MPEG-2	MPEG-2 ACC	Association of Radio Industries and Business (ARIB)
DTMB	8	470-862	4.81 to 32.4	COFDM (Terrestrial) QPSK (Satellite)	MPEG-2	MPEG-2	Interactive Media Platform (IMP)

*Middleware is the software layer, or programming platform, between the system and its applications, and enables interactive services on digital TV.
**MMDS stands for Multipoint Multichannel Distribution System. Microwave DVB up to 10 GHz.
***LMDS stands for Local Multipoint Distribution System. Microwave DVB above 10 GHz.

3.3. DVB-T2 Standard

Our study focuses on the TV standard implemented in Colombia and offers a deeper overview of the DVB-T2 features and its technical parameters. DVB-T2 is a very popular standard around the world due to its superior robustness, flexibility and efficiency. It supports SD (standard definition), HD (high definition), UHD (Ultra High Definition), mobile TV, radio and any combination of them. This standard uses OFDM (Orthogonal Frequency Division Multiplex) modulation with a large number of subcarriers thereby delivering a robust signal. It offers a wide range of operation modes and uses the LDPC (Low Density Parity Check) error correction coding combined with BCH (Bose-Chaudhuri-Hocquengham) coding, which results in a robust signal. The number of carriers, the sizes of the guard intervals and the pilot signals can be adjusted, so the overheads can be optimized for any target transmission channel [33-36]. The additional features of the DVB-T2 standard are the following [33]:

a. Multiple Physical Layer Pipes: Allows the individual adjustment of the robustness of each delivered service within a channel to meet the required reception conditions (such as in-door or rooftop antennas). It allows receivers to save power by only decoding a single service rather than the whole multiplex.
b. Alamouti coding: A transmitter diversity method that improves the coverage in small-scale SFN (single frequency networks).
c. Constellation rotation: Provides additional robustness for low-order constellations.
d. Extended interleaving: Offers bit, cell, time and frequency interleaving.
e. Future Extension Frames (FEF): Allows compatibility in future enhancements.

The result is a more robust signal compared to its predecessor, the DVB-T standard, which also delivers a much higher data rate. Table 2 shows the technical parameters for each DVB-T standard where the additional features are highlighted.

Table 2. Technical Parameters of the DVB-T and DVB-T2 Standards

	DVB-T	DVB-T2 (new / improved options in bold)
FEC	Convolutional Coding+Reed Solomon 1/2, 2/3, 3/4, 5/6, 7/8	LDPC + BCH 1/2, 3/5, 2/3, 3/4, 4/5, 5/6
Modes	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM, 256QAM
Guard Interval*	1/4, 1/8, 1/16, 1/32	1/4, 19/128, 1/8, 19/256, 1/16, 1/32, 1/128
FFT Size	2k, 8k	1k, 2k, 4k, 8k, 16k, 32k
Scattered Pilots	8% of total	1%, 2%, 4%, 8% of total
Continual Pilots	2.0% of total	0.4%-2.4% (0.4%-0.8% in 8k-32k)
Bandwidth	6, 7, 8 MHz	1.7, 5, 6, 7, 8, 10 MHz
Typical data rate (UK)	24 Mbit/s	40 Mbit/s
Max. data rate (@20 dB C/N)	31.7 Mbit/s (using 8 MHz)	45.5 Mbit/s (using 8 Mhz)
Required C/N ratio (@24 Mbit/s)	16.7 dB	10.8 dB

*Note: the guard interval is selected based on the active symbol time [35]

4. Results and Discussion

As of today, mainly the FCC in the US and the Ofcom (Office of Communications) in the UK have been at the forefront in the field of TVWS usage, in terms of their efforts by defining the required policies and terms that secondary users or WSD (White Space Devices) need to obey in order to guarantee the protection of PUs. The scheme approved in both countries is based on the geo-location database approach, in which a central database is in charge of the coverage of the TV towers and the availability of channels. Secondary users would be allowed to use said channels based on the maximum transmission power (EIRP) and the WSD type [37-39]. The general model deployed by Ofcom is illustrated in the Figure 4. Interestingly, the authors in [40] propose a TVWS usage model involving a bicameral geo-location database to support both free and paid access to TVWS. Paid access is established through a ‘broker’ which trades and distributes spectral opportunities according to previously defined policies. This method seeks to measure the impact and regulatory market prospects of the solution.

As shown in the graph, the idea behind this model is that a WSD will contact a WSDB (White Space Database) by providing its location and parameters so that the WSDB responds with a list of frequencies or channels that the WSD can use as well as the maximum EIRP adjustable for operation to prevent interference detrimental to the activity of PUs [38].

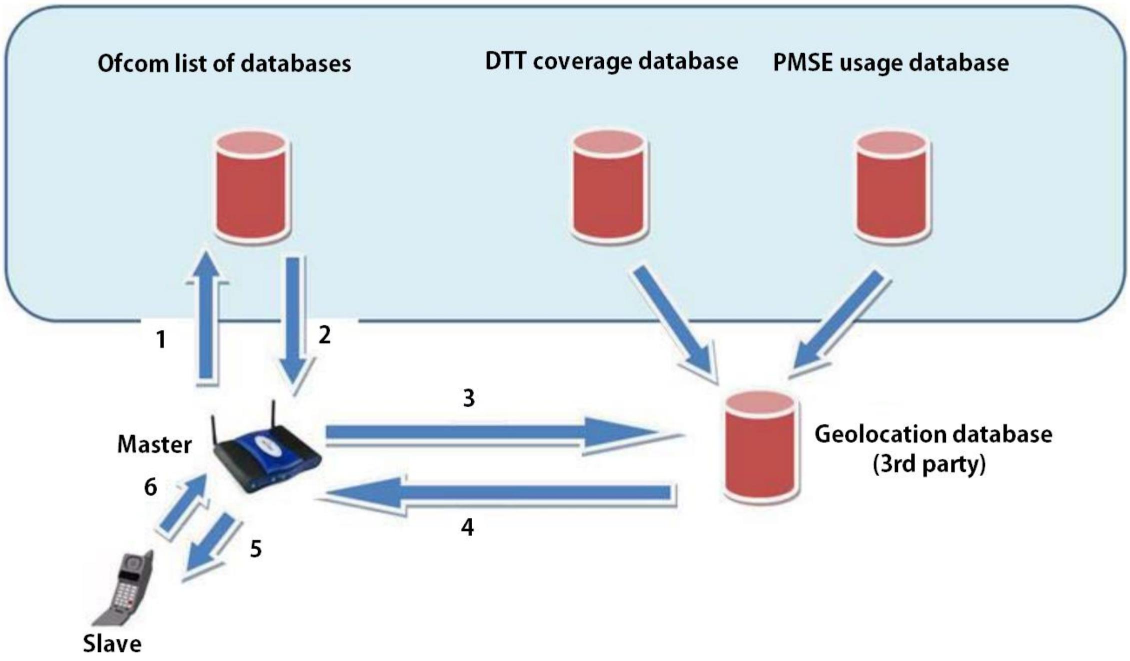


Figure 4. Geo-location database infrastructure proposed by Ofcom TVWS access [38]

4.1. United States

In response to the perceivable spectrum crisis in the US, the FCC released in 2008 a set of rules for spectrum sharing in the television bands under the coexistence model (updated in 2010), where secondary users must guarantee that primary users are relatively unaffected by the existence of the former without help from the latter [9]. The regulation allows unlicensed users to transmit signals using over the air TV broadcast bands according to the FCC restrictions such as maximum EIRP, antenna height and location [9].

In regards to TVWS, studies in the US [9, 17] have concluded that most TV towers are located in highly-populated areas corresponding to urban zones with a lower number of TVWS available. In contrast, these spaces are more common in rural locations where the rate of TV towers/population is not that dense. Figure 5 shows a distribution of the channel availability according to their location within the US.

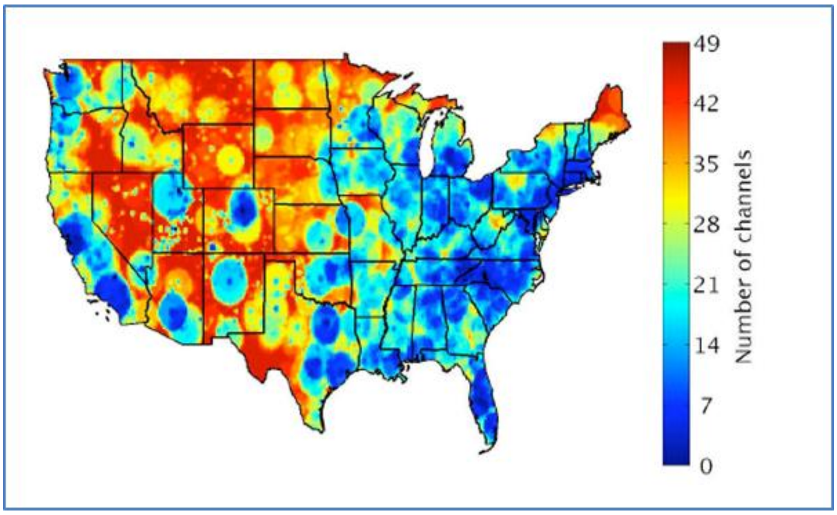


Figure 5. TVWS availability in the USA [9]

As shown in the Figure 5, there are areas where the availability surpasses 45 channels. In other cases, channel availability decreases to up to 6 or 7 channels in coastal areas due to the higher populations. Nevertheless, this highlights the importance of harnessing unused spectrum resources (TVWSs). On another note, according to FCC rules and the geo-location database approach, secondary devices are classified into fixed and portable. Fixed devices can acquire a list of available channels by directly contacting the database and transmit by using a maximum power of 1 Watt delivered to the antenna, a maximum 6-dBi directional gain and a 30-meter height limit. Oppositely, portable devices can transmit by using a maximum EIRP of 100 mW when the adjacent channel separation requirements are met or 40 mW otherwise. There is no height limit for said devices. Two modes are defined for portable devices: Mode nº 1 acquires a list of channels from a fixed device set in Mode nº 2, while Mode nº 2 acquires a list of devices by contacting the database directly [9, 39].

Despite that the FCC recognizes both spectrum sensing and geo-location as feasible approaches, the latter is the preferred choice for development due to the lack of confidence in spectrum sensing techniques presenting issues while sensing very low power signals and the hidden node problem [37]. The IEEE 802.22 standard is deployed for WRANs (Wireless Regional Area Networks) in order to exploit TVWS with CR mostly in rural environments or hard-to-reach areas with low population density [13, 37]. This standard requires the use of geo-location database systems as well as autonomous spectrum sensing capabilities that are deployed in the BS (Base Stations) and the CPE (Customer Premises Equipment). The sensing receiver sensitivity is -116 dBm for digital TV and -94 dBm for analog TV. Microphone sensitivity stands at -107 dBm. The channel detection time for all signal types is 2 seconds. The detection probability is 0.9 while the false alarm probability is 0.1 for all signal types. Hence, the 802.22 framework has to meet all of these requirements in order to use the available TVWS and guarantee the protection of PUs.

4.2. United Kingdom

In the UK, between 2013 and 2014, Ofcom has been working on the deployment of a TVWS framework [38] based on the database geo-location approach, as shown in the introduction section, to exploit the opportunities available within the UHF band. The Figure 6 shows the white space trials in the UK.

Based on spectrum studies over the UK and a defined TVWS framework, Ofcom launched a public invitation to different companies to invest resources on a pilot seeking to provide a proof of concept of the technology. In summary, a total of eight database providers (companies including Google and Microsoft) replied to the invitation and took part in the pilot where multiple potential use case scenarios were involved such as Wi-Fi access, webcam backhaul, CCTV monitoring, remote sensor monitoring, M2M communications and access to marina and rural communications [20]. The results of the pilot implemented over the entire country ratified the validity and usability of the proposed framework and provided feedback to improve aspects such as the communication between the databases and the 'cease transmissions' command sent by the WSDBs to any WSD whenever a source of interference harmful to the PUs is detected.

In terms of the production of the pilot, Microsoft has been one of the main promoters of the use of TVWS opportunities around the world mostly focusing in countries with unsufficient connectivity and internet access due to economic conditions. These countries aim to expand their communication systems by making use of the available spectral opportunities within TV bands [41]. Countries such as Jamaica, Namibia, Philippines, Tanzania, Taiwan, Colombia, the UK and the USA have participated in the deployment of a white space database which provides channel availability based on the location of the devices and determines the maximum EIRP that the WSD may use to transmit in compliance with the device type. Applications such as machine-to-machine communications (M2M), WiFi and mobile connectivity have been proposed. The pilot targets both urban and rural areas which benefit from relevant propagation characteristics of the signals under TV bands which expand coverage up to various kilometers.

For instance, the Microsoft white space database in Colombia provides a web module called the white space finder. By using this module, the user may select the type of device (fixed or portable), the location in coordinates and the antenna height as well. The tool gives the user a list of available, occupied, unavailable and reserved channels within the requested region.

In addition to these pilots, the work in [15] involves a deep study of the deployment of the database system. In [10], the author proposes an indoor multi-vision application that uses a TVWS channel to retransmit incoming TV signals from cable or satellite within a building to a bunch of devices with the required decoders. The TVWS framework includes a database to capture the list of available channels but also uses spectrum sensing to validate the unused channel information provided by the database and refining the terms for its use. Furthermore, the report in [42] from the Dynamic Spectrum Alliance details numerous pilots which have been carried out in many countries spread across all continents.

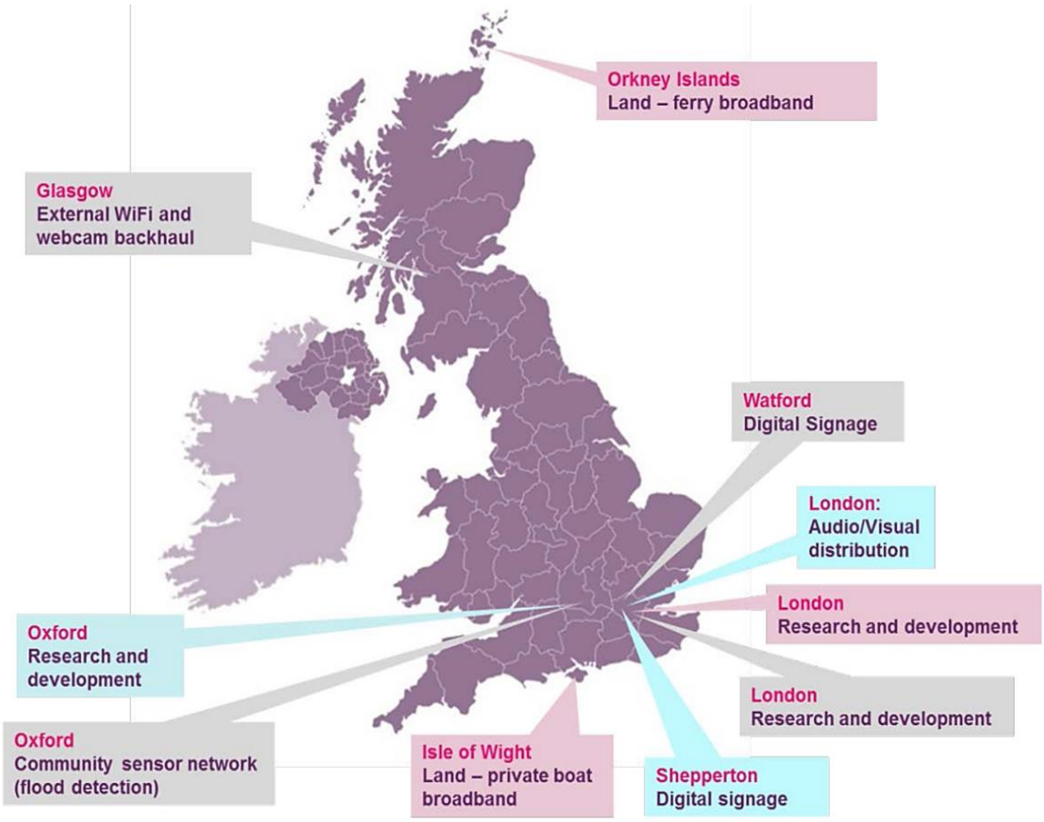


Figure 6. White space trials in the UK [38]

4.3. Colombia

Reconsidering the Colombian case, the work proposed in [43-45] describes a pilot that takes place in the countryside close to the capital city of Bogotá, where some field measurements were carried out through a SDR (Software Defined Radio) device. Said device allowed engineers in the field to identify TVWS which could be used in the future to feed a TVWS database. An architecture was proposed based on the acquired data to provide internet access to some local schools.

On another note, the ANE (Agencia Nacional del Espectro), which is the agency controlling spectrum usage and its distribution in Colombia, launched a pilot to provide internet access to schools in rural regions through the use of TVWS [44]. The deployed infrastructure was based on the geo-location database approach delivering highly positive results and proving the usability of spectral opportunities in the TV bands.

4.4. Challenges and Opportunities

In [39], a very reasonable analysis is presented regardging the FCC rules on TVWS usage as well as some critical remarks to the defined policies. The main points can be summarized as follows: the geo-location database approach results in a lack of TVWS within highly populated areas. Since the coverage prediction of TV transmitters is based on empirical path loss models, these do not consider all the parameters leading to inaccurate and conservative results. The availability of TVWS in highly populated areas is very limited. However, a deeper spectrum analysis shows that there is still a gap to be exploited through spectrum sensing techniques. Therefore, it is suggested to complement the geo-location database spectrum access with the internal spectrum sensing capabilities of the WSD. In that sense, more accurate and precise predictions can be achieved.

There is no consideration of secondary-to-secondary user coexistence. FCC rules do not consider a coexistence between secondary users since their efforts focus only on the protection of primary users. Hence, it is important to keep this aspect in mind and propose some coexistence methods such as LBT (Listen Before Talking), a strategy used in Ofcom ruleset. In contrast with the access to the Wi-Fi spectrum, a challenge lies in defining the framework since TV bands have larger coverage areas.

There is a lack of GPS accuracy for indoor operations. Taking into account that the WSD needs to contact the TVWS DB and provide its location with a certain precision, it can be stated that GPS technology does not work well indoors leading to the loss of significant spectrum holes. A recent update to FCC rules has reduced the precision limit location-wise which is required to access the TVWS. However, an approach that factors in the building penetration loss is still needed.

Spectrum sensing parameters are very conservative and restrain the implementation process. According to FCC rules, the spectrum sensing device must be able to sense TV signals as low as -114 dBm. This is a very conservative threshold considering that noise floor is around -100 dBm in 6 MHz channels. The corresponding SNR values range between -20 dBm to -10 dBm, which can be quite challenging for any of the spectrum sensing methods available. Hence, it would be good to evaluate these thresholds by providing more flexible rules to sense the spectrum.

5. Conclusions

In this article, an overview is presented on TVWS usage through the database geo-location approach adopted by FCC and Ofcom. These entities consider that the spectrum sensing method is still lacking in accuracy and reliability for the TVWS detection. The main reason behind this lies in the restrictive sensitivity thresholds defined by the aforementioned regulations. Various pilots and actual deployments have been carried out in different countries, thus proving the feasibility of database geo-location to harness TVWS. Nonetheless, regulations are very conservative regarding the spectrum sensing method and significant opportunities are missed due to strict policies. Additionally, although the IEEE 802.22 standard per se rules out the use of cognitive radio technology to access TVWS in rural areas, the model has been implemented mostly with fixed wireless devices. However, portable devices still need a proof of concept and operation adjustments.

According to the statement above, the next step is to redefine and carry out deeper research in the spectrum sensing approach. This can be probably achieved through a deeper study of the spectrum usage with strict and highly detailed measurements. The expected result is a better TVWS availability model seeking to develop an improved framework by associating the previously known geo-location database approach with the internal spectrum sensing capabilities of cognitive radio devices.

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