

Chapter 1

Introduction to Cognitive Radio and Television White Space

Are wireless communication systems smart?

Wireless communication is a key enabler for smart systems such as smart cities, autonomous ports, and so on. However, are the current wireless communication systems themselves smart? This book looks at some initial aspects of smartness in wireless communication that could pave the way for future smarter wireless communication systems.

In the past decades, the demands for wireless communications grew exponentially. There is no sign of slowing down; instead, the growth seemed to be accelerating. Besides traditional television and audio broadcasting, today wireless communications are used everywhere from public cellular phone systems to enterprise wireless networks, as well as specialized systems in railway, maritime, and aviation transports, medical electronics, remote sensing, emergency services, security surveillance, military, radio astronomy, satellite, and so on.

Due to the emergence of Internet of Things (IoT), wireless applications are rapidly expanding into machine-to-machine (M2M) connections. All these applications make extensive use of the frequency spectrum. Many of such applications are bandwidth hungry. To cater for the growth of various new services, many countries all over the world have crafted their national broadband plans to address future communication needs with the aim to stimulate economic growth by providing better information infrastructure. Among the broadband alternatives, wireless is one of the most important items in these plans.

Unfortunately, spectrum is a scarce resource. While technologies are improving to squeeze more data into each frequency channel, policy makers still face stiff challenges in addressing the needs of everybody since the demand (in bandwidth) outpaced that of supply. For services that require dedicated channels, for example, cellular, it becomes harder and harder for regulators to clear up a chunk of

TV White Space: The First Step Towards Better Utilization of Frequency Spectrum, First Edition.

Ser Wah Oh, Yugang Ma, Ming-Hung Tao, and Edward Peh.

© 2016 by The Institute of Electrical and Electronics Engineers, Inc. Published 2016 by John Wiley & Sons, Inc.

frequency bands for these services. For example, the regulators worldwide find it hard to fully harmonize the spectrum for the fourth generation (4G) Long Term Evolution (LTE) networks since different countries have different fragments of spectrum left for such assignment. This issue is becoming more and more prominent as can be seen in the proposals toward the fifth generation (5G) networks where there is simply no common frequency spectrum available.

On the other hand, regulators also assigned some frequency spectrum as unlicensed bands such as the industrial, scientific, and medical radio bands (ISM). In these unlicensed bands, different wireless systems share the same spectrum resource and coexist by adopting politeness protocols. Wireless systems that use unlicensed bands, such as Wi-Fi, Bluetooth, ZigBee, and so on, are becoming more and more attractive since they have better spectrum utilization rate and there is no charge in spectrum usage.

One might ask why not the regulators assign all spectrums to be unlicensed? This book attempts to shed some light on the various considerations for spectrum usage.

In this chapter, we look at the various aspects of the spectrum, including their utilizations (Section 1.1), the future needs (Section 1.3), and why do we need more agile and dynamic spectrum access technologies (Sections 1.4 and 1.5).

Taxonomy

In this book, readers will see terms such as spectrum, frequency, band, channel, bandwidth, data rates, and so on appearing quite frequently. In some instances, they may be used interchangeably. In other cases, they refer to slightly different phenomena. In order to help the readers understand the differences, we use another natural resource, that is, land, as analogy.

Spectrum	Land
Frequency Band	Different types of lands, hilly, flat, forest, wetland, and so on Division of land for different usage, for example, parks, housing, roads, and so on
Channel	Marking of land so that rules could be followed more easily, for example, lane markings on roads
Bandwidth	Using the road as an example, this will be how wide the lane is being marked, for example, lanes for cars on highway are much wider than lanes for motorcycles
Data rates	If you view different vehicles as data packets, this is how fast the vehicles can flow through the road

1.1 SPECTRUM SURVEY

Let us take a look at the current spectrum utilization. Figure 1.1 shows the frequency allocations from 30 MHz to 300 GHz in the United States. It can be seen that the spectrum in this frequency range has been fully assigned.

On the other hand, if we take a look at the spectrum utilization of the assigned frequencies in Table 1.1, which is the spectrum occupancy measurement at Green Band, West Virginia, we will be surprised that the utilization rate of the assigned frequencies is so low, and the average spectrum use is just 1% from 30 MHz to 2.7 GHz. There is a similar measurement report shown in Figure 1.2, where we can see that the spectrum efficiency is about 6.5% from 30 MHz to 7 GHz in Singapore. This implies that there are plenty of rooms for improvement. Spectrum is a natural and finite resource that all wireless communications rely on. Only if we continuously increase the spectrum utilization can the growth of wireless communications be sustainable.

1.2 SPECTRUM HARMONIZATION

As we know, the spectrum can be used according to different frequencies, different time, and different locations, namely, frequency division, time division, and space division. If all assigned spectrums are used by a single user, the utilization of spectrum can be synchronized well. Perfect frequency, space, and time divisions can be achieved. However, the challenge is that different frequencies are used by different users with different wireless communication systems, including cellular, broadcasting, navigation, transports, medical, remote sensing, satellite, and so on. Moreover, these systems upgrade along technology improvement independently. How to coordinate them becomes an issue.

Due to potential interference among different spectrum users, many portions of the radio spectrum are controlled through regulations by various governments. Although the individual national government has the right to make their own radio regulations, the radio signal and frequency usage do not stop at national boundaries. It would be much more economical and convenient for the users, manufacturers, and suppliers if common frequencies are used for the same services in different countries. Thus, regulations of frequency usage for various applications among the geographically neighboring countries or even across the world are usually intentionally coordinated by these regulators. The pioneering regulations from more advanced countries are usually followed and adopted by the other countries. For example, the regulations from the Federal Communications Commission (FCC) of the United States are widely used by many other countries.

Besides regulations, standardizations are also required for efficiently utilizing the limited resources by establishing a basis for harmonized use of spectrum. This is achieved by setting appropriate technical specifications, such as radiation power, bandwidth, emission limits, air interface, communication protocol, and so on.

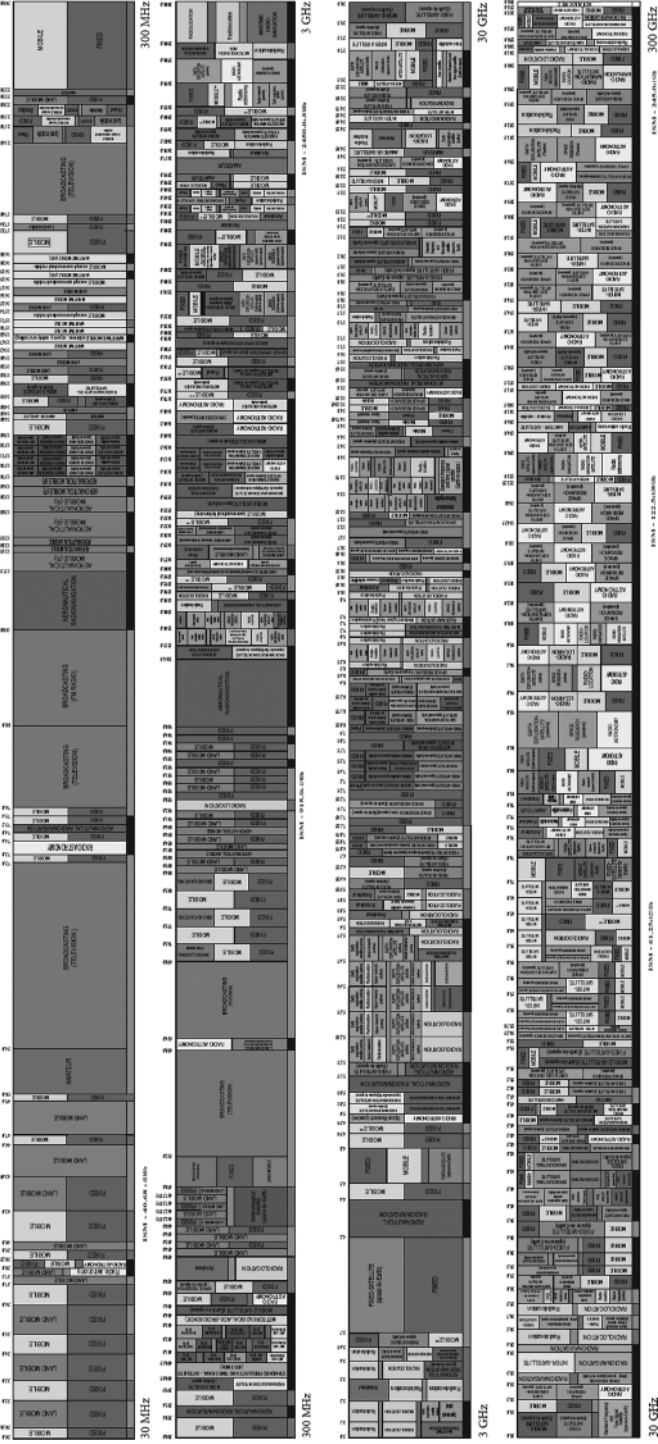


Figure 1.1 A typical frequency allocation from 30MHz to 300GHz. (The chart was produced by the U.S. Department of Commerce, National Telecommunications and Information Administration, Office of Spectrum Management, January 2016.) (From Ref. [1]. Public domain.)

Table 1.1 Summary of Spectrum Occupancy in Green Bank, West Virginia [2]

Start Frequency (MHz)	Bandwidth (MHz)	Spectrum Band Allocation	NRAO Spectrum Fraction Used	NRAO Occupied Spectrum (MHz)	Average % Occupied
30	24	PLM, Amateur, others	0.00045	0.01	0.0
54	34	TV 2–6, RC	0.11056	3.76	11.1
108	30	Air Traffic Control, Aero Nav	0.15485	4.65	15.5
138	36	Fixed Mobile, Amateur, others	0.02745	0.99	2.7
174	42	TV 7–13	0.00220	0.09	0.2
216	9	Maritime Mobile, Amateur, others	0.00556	0.05	0.6
225	181	Fixed Mobile, Aero, others	0.01842	3.33	1.8
406	64	Amateur, Radio Geolocation, Fixed, Mobile, Radiolocation	0.00379	0.24	0.4
470	42	TV 14–20	0.00379	0.16	0.4
512	96	TV 21–36	0.04283	4.11	4.3
608	90	TV 37–51	0.00156	0.14	0.2
698	108	TV 52–69	0.00113	0.12	0.1
806	96	Cell phone and SMR	0.00017	0.02	0.0
902	26	Unlicensed	0.00004	0.00	0.0
928	32	Paging, SMS, Fixed, BX Aux, and FMS	0.02459	0.79	2.5
960	280	IFF, TACAN, Global Positioning System (GPS), others	0.00000	0.00	0.0
1240	60	Amateur	0.00012	0.01	0.0
1300	100	Aero Radar, military	0.00000	0.00	0.0
1400	125	Space/Satellite, Fixed Mobile, Telemetry	0.00000	0.00	0.0
1525	185	Mobile Satellite, GPS L1, Mobile Satellite, Meteorological	0.00082	0.15	0.1
1710	140	Fixed, Fixed Mobile	0.00000	0.00	0.0
1850	140	PCS, Asyn, Iso	0.00001	0.00	0.0
1990	120	TV Aux	0.00009	0.01	0.0
2110	90	Common Carriers, Private Companies, MDS	0.00353	0.32	0.4
2200	100	Space Operation, Fixed	0.00000	0.00	0.0
2300	60	Amateur, WCS, DARS	0.10521	6.31	10.5
2360	30	Telemetry	0.00004	0.00	0.0
2390	110	U-PCS, ISM (unlicensed)	0.00007	0.01	0.0
2500	186	ITFS, MMDS	0.00137	0.26	0.1
2686	214	Surveillance radar	0.00288	0.62	0.3
Total	2850			26.14	
Total available spectrum				2570	
Average spectrum use (%)				1.0%	

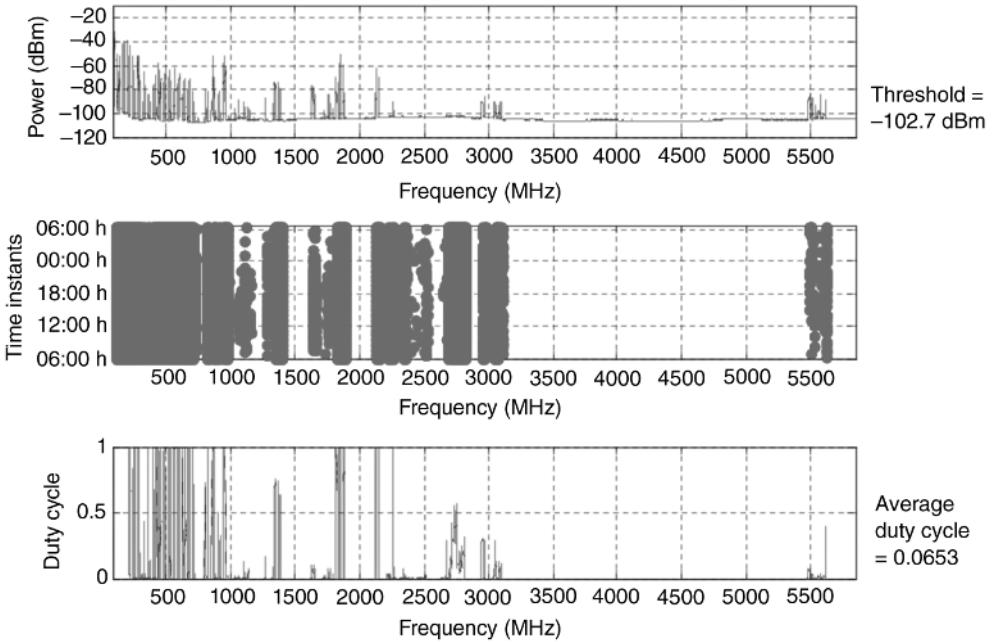


Figure 1.2 Spectrum utilization from 30 MHz to 6 GHz in Singapore. (Reproduced from Ref. [3] with permission from IEEE.)

On the spectrum coordination and standardization for wireless communications, the international standards bodies play important roles. At the global level, the International Telecommunication Union (ITU) is the flagship organization, which seeks global coordination of spectrum usage. Its World Radiocommunication Conference (WRC) is taking place approximately every 4 years or whenever necessary to review and revise the multinational global radio regulations governing the use of the radio frequency spectrum and also the geostationary/nongeostationary satellite orbits. ITU also holds Regional Radiocommunication Conference (RRC), which covers region and group of countries, to develop agreements concerning particular wireless communication services or frequency bands. The decision in RRC could not modify the global radio regulations, but has binding effect on those countries that are party to the agreement. The Institute for Electrical and Electronics Engineers (IEEE), as the world's largest professional association, is also active in globally standardizing wireless communication technologies. One successful example of global standards from IEEE is the 802.11 series of standards for Wireless Local Area Networks (WLAN), which are widely adopted in the world.

At the regional level, European Telecommunications Standards Institute (ETSI) is a well-known organization making telecommunications standardizations for European Union. Its European Conference of Postal and Telecommunication Administrations (CEPT) aims to coordinate spectrum use in the European Union.

In the European Union, the regulatory framework is defined in the Radio Spectrum Policy Decision (Decision No. 676/2002/EC), which seeks to

- link spectrum demands to EU policy initiatives,
- bring out legal certainty for technically unified measures carried out by CEPT,
- enhance transparency and unified format of information on the use of spectrum by member states, and
- promote European interests in international negotiations.

In the European Union, Radio and Telecommunications Terminal Equipment (R&TTE) follows R&TTE Directive, which obeys harmonized standards developed by ETSI according to the request of the European Commission. These standards cover technical characteristics, including effective use of the radio spectrum as well as interference avoidance. Equipment manufactured in accordance to ETSI Standards is allowed to get into the EU market. Network operators cannot decline connecting compliant equipment with ETSI standards. In the European Union, spectrum management remains a national matter, and authorities of the member states are allowed to regulate radio interfaces, in the terms of the Directive, and the member states need to publish their regulations in the same format.

Japan is another country where they publish and adopt their own standards for many wireless communication systems. This situation changed when Japan harmonized their third generation (3G) cellular standard with that of ETSI in the late 1990s. In contrast, as China is growing to become the world's second largest economy together with the world's largest population, it has started to define its own standards. Most other countries in the world tend to follow the regulations and standards defined by the larger economies.

An obvious trend of the spectrum management is the growth of license-exempt spectrum. In the past, exclusive licenses for specific frequency bands and specific purposes dominated government spectrum policy. In the last decade, however, governments around the world have embraced the concept of "license-exempt" (also known as "unlicensed") spectrum as another way to encourage their citizens to adopt innovative new wireless technologies. License-exempt spectrum refers to frequency bands, such as those bands used for Wi-Fi technologies, for which regulators do not grant exclusive licenses, but instead protect against interference and achieve important operational safeguards through equipment certification and clear and enforceable technical rules.

The result of this shift is dramatic. License-exempt spectrum has been, and continues to be, a powerful catalyst for innovation and investment. Today, there are over 10 billion devices connected to the Internet, and connections leveraging license-exempt spectrum access carry the majority of Internet traffic.

1.3 NATIONAL BROADBAND PLAN

To meet the exponentially growing demands on high-speed communications, many countries crafted their own national broadband plan (NBP). For most countries, wireless access is a key focus.

1.3.1 The United States

In the United States, the FCC released its NBP on March 17, 2010 by setting out the roadmap for initiatives aiming to stimulate economic growth, increase jobs, and boost U.S. capabilities in health care, education, homeland security, and even more [4,5]. The plan includes the following:

1. Promote world-leading mobile broadband infrastructure and innovation, which is a plan to make an additional 500 MHz of spectrum available for mobile broadband within the next 10 years through unleashing more spectrum for mobile broadband usage; increasing opportunities for innovative spectrum access models; removing barriers to spectrum utilization; improving data and transparency regarding spectrum allocation and utilization.
2. Accelerate universal broadband access and adoption, and advance national purposes such as education and health care. This is a plan to provide an array of recommendations to accelerate universal broadband access and adoption—including for rural use; low-income Americans; schools and libraries; hospitals, clinics, doctors and patients; Americans with disabilities; and native Americans—and to advance national purposes such as education, health care, and energy efficiency.
3. Foster competition and maximize consumer benefits across the broadband ecosystem, which is a plan containing several recommendations to promote competition and empower consumers across the markets that make up the broadband ecosystem: network services, devices, and applications, through removal of barriers to entry by streamlining access to key broadband inputs; improve data collection, analysis, and disclosure to promote broadband competition and protect and empower consumers; and unleash innovation and competition in video devices.
4. Advance robust and secure public safety communications networks, which is a plan recommending a series of actions to help ensure that broadband can support public safety and homeland security, respond swiftly when emergencies occur, and provide the public with better ways of calling for help and receiving emergency information, through facilitating creation of a nationwide interoperable public safety mobile broadband network; promoting cyber security and protect critical communications infrastructure; and promoting development and implementation of next-generation 911 and alerting systems.

1.3.2 Canada

In Canada, NBP started in March 2009. Canada was one of the first countries to implement a connectivity agenda geared toward facilitating Internet access to all of its citizens. However, gaps in access to broadband remain particularly in rural and

remote communities. In Canada's NBP, it is planned to fill up the broadband gap by encouraging the private development of rural broadband infrastructure.

1.3.3 The European Union

In the European Union, the NBP is in the form of Digital Agenda, which is one of the seven flagship initiatives of the Europe 2020 strategy. The objective is to bring "basic broadband" to all Europeans by 2013 and also to ensure that, by 2020, all Europeans have access to much higher Internet speeds of above 30 Mbps with 50% or more of European households subscribing to Internet connections above 100 Mbps. In September 2010, the European Commission published a "Broadband Communication," which describes the measures the Commission will take to achieve the targets of the Digital Agenda.

1.3.4 The United Kingdom

In August 2009, the UK Government published its Digital Britain Implementation Plan setting out the government's roadmap for the rollout of its plans mentioned above [6].

Next-generation broadband networks will offer not just conventional service but also more revolutionary applications, including tele-presence, allowing for much more flexible working patterns, e-health care in the home, and for small businesses the increasing benefits of access to cloud computing, which substantially cuts costs and allows much more rapid product and service innovation.

Next-generation broadband will enable innovation and economic benefits that we cannot predict today. First generation broadband provided a boost to GDP of some 0.5–1.0% a year. In recent months, the United Kingdom has seen an energetic, market-led roll-out of next-generation fixed broadband, which will inevitably increase the demands for wireless.

Following decisions by the regulator, Office of Communications (Ofcom), which have enhanced regulatory certainty, British Telecommunications (BT) Group has been encouraged by the first year capital allowances measures in Budget 2009 and the need to respond competitively to accelerate their plans for the mix of fiber to the cabinet and fiber to the home. BT's enhanced network will cover the first 1,000,000 homes in their network. The £100m Yorkshire Digital Region programme approved in Budget 2009 will also provide a useful regional test bed for next-generation digital networks.

1.3.5 Japan

The Japanese Cabinet released the e-Japan Priority Policy Programme in 2001. In this programme, the private sector plays the leading role in information technology, and the government is to implement an environment in which markets function

smoothly through the promotion of fair competition and removal of unnecessary regulations. The e-Japan program extended tax incentives and budgetary support for carriers building advanced communication infrastructure.

Under this programme, there are two policies: the National Broadband Initiative, which mandates that federal and local governments deploy fiber to underserved areas; and the e-Japan strategy, which set forth the goal of providing access at affordable rates by 2005 to high-speed Internet networks for at least 30 million households and to ultrahigh-speed Internet networks for 10 million households.

These policies provided US\$60 million to municipalities investing in local public broadband networks, as well as low-interest loans to carriers to encourage them to build other broadband networks, including DSL, wireless, and cable systems.

1.3.6 South Korea

In February 2009, the Korea Communications Commission (KCC) announced a plan to upgrade the national network to offer 1 Gbps service by 2012. In wireless broadband aspect, the earlier plan was WiBro, which could offer seamless 100 Mbps hybrid networking. Its Heterogeneous Network Integration Solution (HNIS) technology combining 3G/4G service with any open Wi-Fi network to deliver speeds many times faster than North Americans can get from their wireless providers. The technology is designed to work without a lot of consumer intervention. HNIS will automatically provision open Wi-Fi access wherever the subscribers travel. The combination of mobile broadband with Wi-Fi works seamlessly as well. Currently, smartphones can use Wi-Fi or mobile data, but not both at the same time. While mobile operators cope with spectrum and capacity issues, HNIS can reduce the load on wireless networks without creating a hassle for wireless customers who used to register with every Wi-Fi service they encountered. The theoretical speed of an HNIS-enhanced 3G and Wi-Fi connection in South Korea will be 60 Mbps when SK Telecom fully deploys the technology. With 4G networks, theoretical maximum speeds are increased to 100 Mbps.

In 2014, the South Korea government launched the “Giga Korea Project” (GigaKorea) in both wired and wireless domains. The goal is to promote the growths of core technologies, future service, and innovative ecosystem so as to generate new jobs. According to the roadmap of GigaKorea, Korea will be able to provide hologram interaction service and supporting device and communication platform by 2020.

1.3.7 Singapore

The Singapore government plans to fund about US\$520 million to establish the next-generation National Broadband Network. It covers wireline and wireless, and provides speeds ranging from 100 Mbps to 1 Gbps. The network will be opened to all service providers, instead of just limiting to major telcos such as Singtel and StarHub. However, the government will not prevent companies from building their own networks. Bidding consists of two stages. The first stage is the passive

infrastructure. It has been started in September 2008. Information Development Authority (IDA) of Singapore selected OpenNet, which Singtel owns 30% shares for designing, building, and operating the passive infrastructure.

In the wireless area, IDA developed a wireless broadband programme, Wireless@SG, which was launched on December 1, 2006. Wireless@SG is a part of its Next-Generation National Infocomm Infrastructure initiative. In phase 1, Wireless@SG was operated by three wireless operators, iCell, M1, and Singtel. It was provided free to all Singapore residents and visitors. The phase 1 was completed in 2013. Users can enjoy free, both indoor and outdoor, seamless wireless broadband access with speeds of up to 1 Mbps at most public areas. Now, Wireless@SG programme is extended to phase 2 providing higher connection speed up to 2 Mbps and much more hotspots. So far, there are more than 2600 Wireless@SG hotspots for free WiFi access at many public places, such as restaurants, government offices, airport terminals, shopping malls, community clubs, hospitals, libraries, tourist attractions, and schools all over Singapore. Currently, these hotspots are operated and maintained by Singtel, StarHub, M1, and Y5ZONE.

Besides Wireless@SG, IDA in 2015 initiated a Heterogeneous Network (HetNet) programme in Jurong Lake District (JLD) as part of the Smart Nation initiative to align with the “Infocomm Media Masterplan 2025” announced by the Ministry of Communications and Information in Singapore. This programme is to deploy and test the advanced broadband wireless networks combining cellular mobile system and Wi-Fi to provide the customers seamless and much higher speed connection than either cellular or Wi-Fi systems.

1.3.8 Australia

In 2009, the Australian Government announced to establish National Broadband Network (NBN) through starting up a new company that will invest up to \$43 billion over 8 years. The new network will provide optic fiber to home and workplace, as well as the next-generation wireless and satellite technologies to deliver superfast broadband services. In 2009, the government also released a discussion paper entitled “National Broadband Network: Regulatory Reform for 21st Century Broadband.” The paper is based on public comments on the NBN. The paper appears to be similar to an FCC NPRM or NOI. It outlines the method of establishing the NBN and also sketches general regulatory reforms to assist the market in the future. To facilitate fiber build-out, the government will simplify land right of way procedures.

1.4 COGNITIVE RADIO

We could see from the various national broadband plans that more spectrums are required in order to fulfill the ever-increasing needs of wireless communications. We also understand from spectrum surveys conducted all over the world that there is not much spectrum available for allocation. On the contrary, the utilization of

these allocated spectrums is low. This calls for a need to use spectrum in a more innovative manner.

The main regulatory bodies in the world such as FCC, Ofcom, and IDA as well as some independent measurements [3,7] found that most radio frequency spectrum was inefficiently utilized, except cellular network bands, which are overloaded in most areas of the world. A number of studies concluded that spectrum utilization depends on time and place. Moreover, these studies also show that the traditional fixed spectrum allocation prevents rarely assigned frequencies for specific services from being used, even when the unlicensed users do not cause noticeable interference to the assigned ones.

The above inefficiencies stimulated a new concept of Cognitive Radio (CR) where the radio itself is intelligent, aware of the environments, and able to learn and adjust its operating parameters in order to maximize delivery of wireless communication services. The concept of CR was first raised by Joseph Mitola III [8]. A CR is an intelligent radio that can detect the environmental conditions, including the spectrum availability, interference, and so on in its working area, and further dynamically configure its transmitter and receiver parameters so as to use the best wireless channel in the best way. This kind of mechanism can maximize the transmission of a user's own information, while also avoid the interference to the other spectrum users.

Some people equate CR as the extension of another technology called software defined radio (SDR). This is a misconception. SDR is a platform technology that allows the waveforms to be changed dynamically depending on needs since most processing is done at the digital domain. SDR may not need to understand the operating parameters of other users. SDR is being used even in cellular base stations so that changes to the system could be done quickly without having to replace the hardware in the deck. On the other hand, CR needs to understand the operating parameters of other users operating in the same environment since CR is typically operating as secondary users (SUs) who do not have the first right to the channels. CR could leverage on SDR platform for added flexibility but using SDR platform is not a prerequisite for CR.

Dynamic spectrum access (DSA) is one type of CR system. The major parameter that DSA needs to detect is frequency availability, which indicates the other users' spectrum utilization in the same working area. The other parameters also include the noise level, multipath, and so on. What a DSA system can reconfigure includes one to all of parameters consisting of operating frequency, signal waveform, bandwidth, emission power, antenna beam forming, network protocol, and topology.

Of the various features of DSA, the most challenging work technically is spectrum sensing, which detects the spectrum availability, namely, the other users' transmissions and frequencies. To protect the primary users (PUs), which are originally assigned to the spectrum, the spectrum sensing needs to be reliable even in multipath fading, blocking, and weak signal conditions (many decibels below noise level). This is the most challenging task. Most research work focuses on spectrum sensing.

It has been shown that a simple energy detector cannot guarantee the accurate detection of signal presence. To enhance the detection reliability, cooperative sensing that involves multiple nodes at different locations and sensing information exchange are necessary. This raises another issue since communications among these nodes are required before they could establish the communication links. This could be done either through in-band signaling or through a supplementary channel, for example, wireline Internet connection.

Besides spectrum sensing used in the CR system, a practical solution to protecting the primary users is to use a centralized database, which records the PUs' action details. Through checking the database, the SUs can avoid jamming the PUs. This is what Television White Space (TVWS) system is being designed currently. We will introduce TVWS in the next section.

1.5 TELEVISION WHITE SPACE

As mentioned earlier in this chapter, the usage of license-exempt spectrum grows in the past decade. Now many countries are taking the next step in the evolution of spectrum policy, through the license-exempt use of the TVWS. TVWS is the unused TV channels assigned to TV broadcasting. As digital TV has higher spectrum efficiency than analog TV, the worldwide trends of switching from analog to digital TV have freed up more spectrums in TV bands for TVWS. Spectrum sharing through TVWS is an important topic as it is the first step toward efficient use of spectrum in an opportunistic and dynamic manner. TVWS is expected to be the first CR system.

TVWS has superior propagation characteristics as it is in the very-high frequency (VHF) and ultrahigh frequency (UHF) spectrum bands. This results in longer communication distance and better penetration through obstacles. The long communication distance makes TVWS an attractive option for rural connectivity, while the better penetration gives TVWS an edge over other technologies for machine-to-machine applications in dense areas. Due to urbanization, TVWS provides a good option as the connectivity backbone for smart cities.

The favorable propagation characteristics of the TV white spaces promise to make white space devices (WSDs) even more powerful than their Wi-Fi ancestors. White spaces technologies will greatly expand the utility and help reduce the cost of using license-exempt devices to be used on broadband networks. It is also likely to make deployment of last-mile connections in hard-to-serve areas more affordable. These benefits, in turn, have significant economic and development benefits. Even though many of the world's citizens lack reliable Internet access, the Internet in 2010 has already contributed an average of 1.9% or \$366 billion to GDP in 30 emerging markets.¹ With greater access to the Internet and to affordable devices, this number is certain to grow.

¹O. Nottebohm, J. Manyika, J. Bughin, M. Chui, A.-R. Syed, *Online and Upcoming: The Internet's Impact on Aspiring Countries*, McKinsey & Company, 2012. Available at http://www.mckinsey.com/client_service/high_tech/latest_thinking/impact_of_the_internet_on_aspiring_countries.

White spaces access can be deployed quickly and takes advantage of otherwise unused spectrum. Because enabling spectrum access to white space devices does not require relocating incumbents and because the rules protect those incumbents, a license-exempt framework for access to TV white spaces can be adopted and put into use without disruption to incumbent operations.

The opportunistic or dynamic use concept central to license-exempt white spaces use ensures that rules can accommodate changing circumstances. Dynamic use is the idea that radio technologies should identify and use different frequencies within a defined band, based on what frequency is available for interference-free operation at a given time in a given geographic location. Although the particular unused TV channels vary from location to location, white space devices have the flexibility and agility to locate and operate on the unused channels, no matter where the devices are located in a country that permits such access. This means that previously unused spectrum becomes a valuable resource. It also means that both the technology and the rules can operate before, during, and after the digital television transition—regulators merely have to provide industry with information regarding occupied channels, switchover timeline, and new channel assignments and locations, and devices will be able to avoid broadcast operations and other licensed uses.

To enable more innovative services, the FCC released a notice of proposed rulemaking (NPRM) in May 2004 to allow unlicensed radio transmitters to operate in the broadcast TV spectrum at locations where that spectrum is not being used [9]. As TV band is the target spectrum to be used, this kind of system is also generally referred to as TVWS. Although CR concept could be used in any frequency bands, TVWS is gaining more traction due to the better propagation characteristics of TV bands that travel further and penetrate walls easier. In addition, the migration from analog to digital TV opens up more bandwidth for such innovation.

In order for white space devices to utilize TVWS, they must not cause noticeable interference to PUs. There are many proposed techniques to protect PUs from WSDs, such as spectrum sensing, beacon, and white space database (WSDB). While each technique has its own pros and cons, there was no consensus previously on which was the most suitable technique for determining TVWS channels.

To understand which technology is the most suitable for TVWS, the FCC conducted its first test of TVWS in 2007. The test concluded that spectrum sensing-based approaches had not reached the acceptable accuracy and reliability on detecting PUs. In 2008, FCC released another report after conducting the second trial, which concluded that the TVWS prototypes submitted by Adaptrum, Institute for Infocomm Research (I²R), Motorola, and Philips had met the burden of “proof of concept” in their ability to detect and avoid PUs’ transmissions.

However, after receiving arguments from various parties, FCC finally decided that the current spectrum sensing technologies are not reliable enough to be used solely as a means to determine vacant TVWS. In 2010, FCC released a Memorandum Opinion and Order that determined the rules for TVWS that are fine-tuned several times subsequently with WSDB as the main method for determining vacant TVWS with spectrum sensing as an option. After the United States, Singapore also finalized its TVWS regulation in 2014, followed by the United Kingdom and

Canada in 2015. Besides the United States, Singapore, the United Kingdom, and Canada, CEPT, Finland, New Zealand, and other countries have also released their draft standards or regulatory frameworks for TVWS. WSDB remains as the main choice for determining vacant TVWS channels.

TVWS becomes the first spectrum open to CR for real application for better spectrum utilization. However, one should not be confused between TVWS, being a new way of accessing frequency spectrum, and specific wireless products such as Wi-Fi. For illustration, the land transport regulator could define the usage of lanes in a particular road to be normal lanes, carpool lanes, and so on. When there is emergency vehicle on the way, normal cars have to give way. The lanes are analogy to TVWS, while the cars are analogy to Wi-Fi and other wireless technologies. This also means that Wi-Fi could operate in TVWS spectrum and so is cellular.

1.5.1 TVWS Regulation

Although TVWS applications rely mainly on WSDB, there are other requirements such as protection contour, self-positioning, out-of-band (OOB) limits, update cycle, and so on that are important parameters to be aware of when implementing TVWS in specific countries as these parameters differ for different territories. Thus, suitable regulation is necessary.

In the regulatory front, FCC is the clear leader as it was the first regulator to experiment TVWS in a series of prototype trials [10,11]. In November 2008, FCC announced opening up of TVWS for unlicensed access after it was convinced that the prototype it tested met its initial expectations [12]. This marked a critical milestone in TVWS development worldwide as this groundbreaking regulation is often being referred to in subsequent regulations carried out in other countries. The initial FCC regulation was later superseded with updates in the final rules and regulation for the use of TVWS in 2010 [13]. After considering further comments to the regulation, the rules were further updated in April 2012 [14]. The release of the third memorandum can be interpreted as stabilization of TVWS regulation since most of the concerns raised have been resolved. In 2014, FCC released a new notice proposing some amended rules and operation parameters, although it has not been finalized yet. The proposed changes included allowing white space device operations in some reserved channels for wireless microphones and a few prohibited channels before with some conditions such as requiring WSDs to access WSDB more frequently and emission power restrictions. The detailed information can be found in Chapter 2.

After the successful FCC regulation, the Office of Communications (Ofcom) in the United Kingdom followed suit but adopting a different approach. In the United States, various trials were carried out by individual or groups of organizations without much coordination. In contrast, a strong consortium was formed in the United Kingdom called the Cambridge White Spaces Consortium to carry out various trials in Cambridge with the blessing from Ofcom. Satisfied with the outcome, Ofcom has also approved license-exempt use of TVWS in the United Kingdom in

2011 [15]. In other parts of Europe, the Electronic Communication Committee (ECC) is also actively looking into adopting TVWS where the Finnish Communications Regulatory Authority has issued a test license to implement Europe's first TV white space geolocation database in August 2012.

In Asia, Singapore is the leader in TVWS development where the Cognitive Radio Venue (CRAVE) trial was conducted in March 2011 [16]. Subsequently, the Singapore White Spaces Pilot Group (SWSPG) was formed in April 2012 by the Institute for Infocomm Research, Microsoft, and StarHub to look at commercial pilots of TVWS technologies [17]. The SWSPG is unique compared with its American and European counterparts in the following aspects:

- The test environment is different where Singapore is a city state with many high-rise buildings.
- Singapore is “sandwiched” between Malaysia and Indonesia. Many of the interleaved TV bands, as a result of coordination with Malaysia and Indonesia, could be exploited provided the pilots do not interfere with Malaysia and Indonesia users.
- SWSPG involves many end users apart from technology providers. This will bring TVWS to the next level of potential commercialization.

Apart from the few countries mentioned above, there are also a growing number of developments and trials conducted elsewhere worldwide as summarized in Chapter 5. This further confirms the momentum of TVWS worldwide.

1.5.2 Standardization

To respond to the new FCC initiative, IEEE started a new standardization activity to look at how to reuse TV broadcast bands as secondary access for Regional Area Network under the IEEE 802.22 standard [18]. The main application of IEEE 802.22 is to serve rural areas using the range benefits of TVWS. In July 2011, this first IEEE standard on TVWS was released to mark an important milestone in the history of TVWS standardization.

Following this, the IEEE 802.11 standardization also tried to leverage on this new method of spectrum access to come out with IEEE 802.11af standard in order to allow Wi-Fi to operate in the TV bands. This will allow TVWS to be used as Wi-Fi hotspot or other applications.

Another IEEE standardization group for Wireless Personal Area Network (WPAN) also proposed to use TVWS as IEEE 802.15.4m standard. This will allow WPAN to extend its range so as to serve WPAN as well as machine-to-machine (M2M) application. Another proprietary standard weightless is also looking into the use of TVWS for M2M.

Some might be confused by the many systems defined by different standards as they view TVWS as a single system. In reality, TVWS is a method of gaining access to spectrum. After the spectrum is secured, one can design many different systems using this spectrum. An easier to understand example is the ISM band.

Once the ISM bands are allocated, many different systems can be designed using the same bands, which include Wi-Fi, Bluetooth, ZigBee, baby monitoring, drone control, and so on. The same applies to TVWS.

Given the current momentum, it is believed that TVWS will be an option for many standards that uses frequency spectrum. Reference [19] gave a summary of various standardization activities related to CR.

1.5.3 Potential Applications

Due to range and penetration benefits as well as the potentially huge frequency spectrum available, many applications are possible with TVWS.

Machine-to-Machine Communications (M2M) One of the hottest applications of TVWS is for M2M communications. Traditionally, M2M faced problem of range from the current ISM band solutions or cost from public network solution. TVWS is positioned uniquely between these two where it is license-exempt as well as have good range. One of the earliest M2M applications is smart grid.

Super Wi-Fi Globally, mobile data consumption rises exponentially. This is due to the increase in the number of mobile broadband subscribers as well as increased use of mobile broadband per user. This tremendous increase in mobile data has resulted in great pressure over the current cellular mobile network. Mobile offloading has been exploited to alleviate this problem and Wi-Fi is a leading candidate for this option. Nevertheless, due to its range limitation, Wi-Fi offloading will incur high capital expenditure for setting up of the network as well as high operating expenses for the lease line for the backbone. TVWS is suitable to reduce the burden of Wi-Fi due to its superior range and abundant frequency spectrum, namely, super Wi-Fi.

In-Home Distribution There is also an increase of data going into the home. However, in-home distribution still lacks convincing solution. While Broadband Powerline Communication (BPLC) could be a possible solution, the use of BPLC for large-scale adoption has not been proven. In addition, the bandwidth allocated for BPLC is also limited. Therefore, it will limit the future expansion of BPLC technology. TVWS could be a good candidate for in-home distribution given its good penetration characteristics.

Video Surveillance Another promising area for TVWS is to use it for wireless video surveillance. Until now, wired solution is still preferred for video surveillance primarily due to the lack of bandwidth for the current wireless solutions. However, wired solution is expensive due to setup cost. This will slow down video surveillance deployment. The current popular wireless solution for video surveillance is to use 3G data connection. However, one should bear in mind that video surveillance

is using the uplink channel that has much lesser bandwidth than the downlink in 3G. Due to this, the current 3G-based wireless solution is not able to scale up quickly. To enable fast wireless video surveillance deployment, TVWS is a good candidate. It provides the necessary data rates to support high-quality video surveillance with the abundant bandwidth. It also gives the video surveillance operators freedom to deploy surveillance cameras at their preferred locations.

Disaster Planning In 2015, Gigabit Libraries Network and State Library Agencies in the United States started to explore the possibility of using the portable TVWS broadband equipment in community disaster planning. The rationale is that after a disaster, the public communications infrastructure could be down for 2–5 days. In that case, the community needs temporary connectivity until the public utilities recover. A TVWS network can help fill the communications gap through deploying temporary Internet hotspots around the community in much greater distances compared with that the traditional Wi-Fi can reach. The TVWS trial for disaster planning will be partially funded by a grant from the Knight News Challenge on Libraries. It will explore how libraries can be a platform to build more knowledgeable communities.

Apart from the applications mentioned above, there are many other possible applications such as telemetry, neighborhood network, transportation, maritime, and so on. In short, the potential application can only be limited by our imagination.

1.5.4 Technologies

The original idea of CR and TVWS was to use technological approach to identify underutilized frequency spectrum for communication. The key technology to achieve this purpose was to use spectrum sensing to detect primary users (e.g., broadcast signals and wireless microphone signals). Spectrum sensing could be classified into blind sensing and feature sensing. The former does not need to know the waveform of the intended signal to sense, whereas the latter needs to know certain features, although not all, of the primary user. To improve sensitivity of spectrum sensing, coordinated sensing may be adopted. Reference [9] provides some comparisons of the different sensing schemes.

In the trial conducted by FCC in 2008, spectrum sensing was the main focus, although the geolocation database (WSDB) from Motorola was also tested [13]. As a result of concerns from the primary users in the confidence level of spectrum sensing accuracy, WSDB approach emerged as the preferred option for accessing TVWS. This can be seen from both FCC and Ofcom's regulatory framework. For wireless microphone, a safe harbor approach is adopted.

WSDB is more a policy solution rather than a technological solution, although certain technologies are involved. Before accessing TVWS frequency spectrum, a TVWS device sends a query to a WSDB server stating its current location. The WSDB server then responds with the list of frequency channels available for communication.

The WSDB server obtains the information of primary users through regulators as well as user inputs. In the United States, FCC awarded licenses to 10 organizations to operate WSDB. Currently, the WSDB from Spectrum Bridge, iconetiv, Google, RadioSoft, LSTelcom, and Key Bridge Global have been approved for operation in the United States.²

Although WSDB is the *de facto* option for TVWS spectrum access now, FCC does not rule out spectrum sensing only devices. In fact, in countries where regulation executions are weak, technological solution such as spectrum sensing might be preferred. For CR systems other than TVWS, WSDB implementation might not be easy if the primary usage pattern can only be determined in an *ad hoc* manner. Therefore, spectrum sensing is still a hot topic in the research community.

1.5.5 Moving Forward

Although TVWS has some promising applications and results now, the system can be further enhanced when it becomes more mature in the near future. This section touches briefly three aspects of potential enhancements to the current TVWS systems. More details of the future directions can be found in Chapter 7.

Emission Masks One of the most challenging requirements for TVWS is the emission masks requirements, especially the emission masks specified by the FCC. One of the reasons for stricter emission mask requirements from FCC was due to technology uncertainty when FCC opened up TVWS previously. Other non-technical reason included protest from the existing primary users on the potential interference with their existing system. As there were not enough data to back these claims, FCC adopted a more cautious approach with regard to the emission mask requirements. With more studies conducted and results collected, the requirements on emission masks were relaxed as can be seen from the regulation by Ofcom [20] and Singapore [21]. Moving forward, there is no reason why FCC could not lower its emission mask requirements if the other regulators and trial results show its viability.

WSDB with Sensing There is almost consensus of using WSDB for TVWS access currently. The present WSDB is conservative in the sense that a large range of protection contour is defined in order to ensure no interference to the primary users, although the primary user might be far apart. This results in many otherwise vacant channels being left unused. This also presents another opportunity to further enhance spectrum occupancy rates.

One approach is to combine WSDB with spectrum sensing. By using real-time spectrum sensing results provided by TVWS devices or other devices operated to gather channel information, the protection contour could be adjusted according to the real information gathered in the field. Spectrum sensing results will also help in

² <https://www.fcc.gov/encyclopedia/white-space-database-administrators-guide>.

fine-tuning the various parameters used in WSDB calculations such as terrain profile, climate profile, and so on. On the contrary, WSDB information could also be used to adjust the sensitivity (and thus threshold) requirements for spectrum sensing so as to increase the results of spectrum sensing. In short, both technologies could coexist and reinforce each other in order to ensure better spectrum utilization. With this approach, spectrum sensing only system will have the opportunity to emerge in the future when the end users have better confidence in spectrum sensing.

WSDB with Quality-of-Service Support The current WSDB only protects the primary users. It does not guarantee the performance of the secondary users (SUs). While this is understood from the current regulation practices, it has to be enhanced so as to allow differentiated access even for SUs. Otherwise, quality of service (QoS) may become a big issue when TVWS is widely adopted.

A novel method called WSDB with QoS (WSDB-Q) can grant access to higher priority communication via reserved channels based on a set of criteria predefined in order to maintain QoS of communication systems accessing TVWS spectrum. The set of criteria covers regulatory, technical, and commercial aspects. The details of WSDB-Q will be presented in Chapter 3.

1.5.6 Features of TVWS

TVWS are using the frequency bands originally assigned to TV broadcasting in an opportunistic manner. The signals in these frequency bands have strong propagation and penetration. A single broadcast TV tower can cover a large area with sufficient quality of reception. Compared with the Wi-Fi frequencies and most cellular systems, a TVWS signal can reach longer transmission distance with the same transmission power, or emit lower transmission power for the same communication distance. Moreover, TVWS span a large frequency range: from VHF to UHF. The potential TVWS bandwidth is more than 500 MHz. This is much wider than that currently assigned to cellular systems. This means huge opportunities for TVWS even if only a fraction of it is being explored currently.

1.6 SUMMARY

In this chapter, we showed some spectrum survey results and understood that the current spectrum utilization is very low, although radio spectrum is almost fully allocated. This shows that the traditional spectrum allocation is not sustainable. New dynamic spectrum sharing is necessary to meet the requirements of the wireless explosion era.

We introduced CR, the new technology that can sense the radio environment before using the spectrum with a suitable transmission approach. This leads to much higher spectrum utilization.

TVWS is the first CR system for real applications. As of now, most of the major authorities have crafted TVWS regulations to support TVWS development

as well as protect the existing spectrum users. There are significant potentials with wide application areas. Also, there are challenges in terms of technology and regulation and commercialization. TVWS is a pioneering system for DSA. The experiences gained from TVWS can be used in other frequency bands adopting DSA. Thus, studying TVWS is essential for the future new paradigm of spectrum allocation and utilization.

In this book, we discuss TVWS in terms of regulation, technology, standardization, deployment, and commercial and market potential as well as development beyond TVWS. In Chapter 2, we will discuss various TVWS regulations across the world and attempt to provide some comparisons so that the readers can understand the rationale and considerations behind different regulations. We will explain the technical challenges in TVWS and some novel solutions in Chapter 3. The standardizations related to TVWS will be described in Chapter 4. In Chapter 5, the status of global TVWS deployments will be discussed. The commercial and market potentials of TVWS are explored in Chapter 6. Finally, we will list some further development topics related to TVWS.

REFERENCES

1. https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf.
2. National Radio Astronomy Observatory (NRAO), Spectrum Occupancy Measurements Location 5 of 6, Revision 3, Green Bank, West Virginia, October 10–11, 2004.
3. Md. H. Islam, C. L. Koh, S. W. Oh, X. Qing, Y. Y. Lai, C. W., Y.-C. Liang, B. E. Toh, F. Chin, G. L. Tan, and W. Toh, Spectrum survey in Singapore: occupancy measurements and analyses. *Cognitive Radio Oriented Wireless Networks and Communications*, IEEE, 2008.
4. J. Eggerton, FCC broadband plan: Commission sets 2015 spectrum deadline, *Broadcasting & Cable*, March 15, 2010 (retrieved March 23, 2010).
5. FCC, National Broadband Plan, Broadband Action Agenda, March 17, 2010.
6. Digital Britain Implementation Plan, August 2009.
7. V. Valenta et al., Survey on spectrum utilization in Europe: measurements, analyses and observations, in *Proceedings of the Fifth International Conference on Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM)*, 2010.
8. J. Mitola, III, and G. Q. Maguire, Jr., Cognitive radio: making software radios more personal. *IEEE Pers. Commun.*, 6, 13–18 (1999).
9. Federal Communications Commission, Notice of Proposed Rule Making FCC 04–113: Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04–186, FCC), 2004.
10. S. W. Oh, Y. Ma, M.-H. Tao, and E. C. Y. Peh, TVWS in the world: regulations and comparisons, in *Proceedings of the International Conference on Frontiers of Communications, Networks and Applications (ICFCNA)*, 2014.
11. S. K. Jones, T. W. Philips, H. L. Van Tuyt, and R. D. Weller, Evaluation of the performance of prototype TV-band white space devices phase II, FCC, 2008.
12. Federal Communications Commission, Second Report and Order and Memorandum Opinion and Order, in the Matter of ET Docket No. 04–186 and ET Docket No. 02–380, FCC, 08–260, 2008.
13. Federal Communications Commission, Second Memorandum Opinion and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04–186) and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (ET Docket No. 02–380), FCC, 2010.
14. Federal Communications Commission, Third Memorandum Opinion and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04–186) and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (ET Docket No. 02–380), FCC, 2012.

15. Office of Communications, Implementing geolocation: summary of consultation responses and next steps, September 1, 2011.
16. Infocomm Development Authority of Singapore, Trial of white space technology: accessing VHF and UHF bands in Singapore, June 2010.
17. Singapore White Spaces Pilot Group, D 2015. Available at <http://whitespace.i2r.a-star.edu.sg/> (accessed February 15, 2015).
18. IEEE 802.22 Wireless Regional Area Networks, D 2015. Available at <http://www.ieee802.org/22/> (accessed February 15, 2015).
19. Y. Zeng, Y-C. Liang, Z. Lei, S. W. Oh, F. Chin and S. Sun, Worldwide regulatory and standardization activities for cognitive radio, C in 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum, IEEE, Singapore, 2010.
20. W. Webb, On using white space spectrum, *IEEE Commun. Mag.*, V 50, 145–151 (2012).
21. IDA, Regulatory framework for TV white space operations in the VHF/UHF bands, June, 2014.