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White space: Definitional perspectives and their role in exploiting spectrum opportunities

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ABSTRACT

The U.S. Federal Communications Commission (FCC) defines white space as the channels that are unused at a specific location or time. For futuristic cognitive radio (CR) based applications and communication networks, white space detection plays an important role. In fact, the proper white space understanding is a prerequisite for effective communication in support of a wide range of information technology systems. Moreover, by clearly defining the white space, the business and technical scenarios for white space usage can be clearly defined and their implementation will be simplified. Also, the decisions of regulatory bodies and telecommunications policy makers for auctions of particular spectrum bands can be facilitated by a thorough white space understanding. White space detection is a critical aspect of Dynamic Spectrum Access (DSA) which ultimately can help in overcoming bandwidth shortages. A major portion of the DSA research to date has been limited to the dimensions of time, frequency, and geographical location while neglecting other perspectives for the detection of white spaces. Generally, what exactly is a white space and how do white spaces differ in various modern contexts of wireless networks? This paper strives to answer these questions by reviewing the conventional white space definitions and exploring advanced perspectives on white spaces that can be used for CR communications. We propose a novel classification of white spaces based on the combination of three perspectives, namely signal dimension, licence, and transmission strategy, and outline open areas for future research on exploiting white spaces for CR communication.

1. Introduction

Radio terminals have traditionally been designed to operate on a prescribed (allocated) set of frequencies and exclusively access these frequencies, i.e., the frequency spectrum space, when they have some data to transmit. When the radio terminals are idle or partially utilize spectral resources, some portions of the allocated frequency spectrum are left unused or underutilized. Measurements indicate that traditional radio terminals lead to spectrum occupancy probabilities varying over time between 15% and 85% at a given geographical location (Akyildiz, Lee, Vuran, & Mohanty, 2006; Masonta, Mzyece, & Ntlatlapa, 2013; Shin, Kim, Min, & Kumar, 2010). From a technical viewpoint, the unused and underutilized frequency spectrum spaces are referred to as *white spaces* (Webb, 2012). Efficient utilization of these white spaces has the potential to

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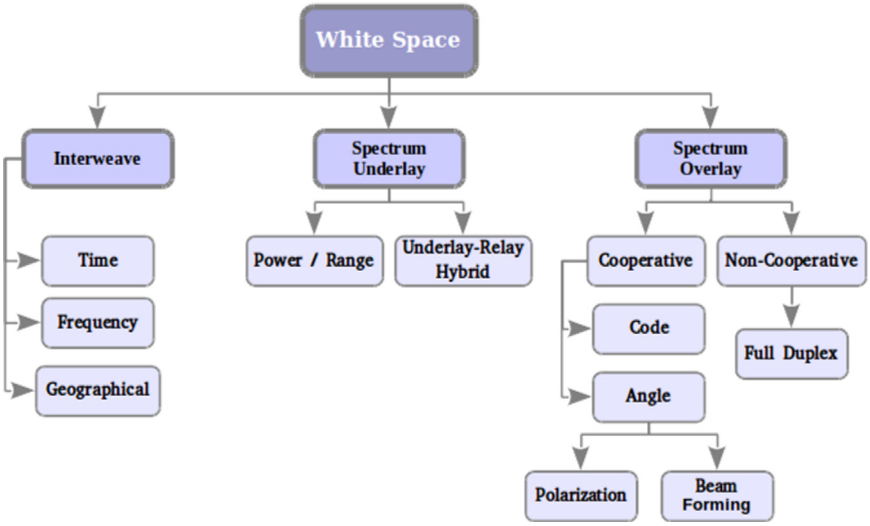

Fig. 1. Taxonomy of white spaces: The spectrum usage of cognitive radio (CR) users can be interwoven, underlaid, or overlayed with the spectrum usage by primary users (PUs).

mitigate spectrum shortages. Specifically, new approaches that either fully utilize the spectral resources or exploit white spaces without affecting current users can help us to improve the spectrum utilization.

A promising solution for exploiting these white spaces is to employ Dynamic Spectrum Access (DSA) techniques (Lu, Ping, Niyato, & Hossain, 2014; Zhao & Sadler, 2007). DSA techniques are the enabling technology of Cognitive Radio (CR) (Shin et al., 2010). Among several CR attributes, the sensing function is of critical importance—it senses the activity patterns of present users and determines potential white spaces for exploitation (Akyildiz, Won-Yeol, & Chowdhury, 2009b, 2011; Kocks et al., 2012; Yucek & Arslan, 2009). However, the potential of sensing white spaces for communication may presently be substantially underestimated due to the current narrow definitions of white spaces, which can be broadened as outlined in this paper.

In particular, the ongoing research on CR communication mainly focuses on the detection of white spaces in idle licensed frequency bands and within only a few signal space dimensions, specifically the dimensions representing time, frequency, and geographic (spatial) location. However, white spaces can be viewed more broadly: White spaces:

- do not necessarily exist only in an idle band,
- are not necessarily limited to specific dimensions of the signal space, and
- are not necessarily limited to licensed frequency bands.

The limiting narrow views of sensing of white spaces are mainly due to current definitions of white space, which considerably restrict the potential of CR communication. However, white space can be viewed from several different perspectives. These different perspectives need to be distinctly defined and jointly considered, as only considering a single definition may limit the potential of CR communication. Hence, it is of paramount importance to understand and differentiate various perspectives on white spaces. Fig. 1 illustrates a taxonomy of white spaces based on current research trends on the CR paradigm. Clarifying white space definitions may aid in overcoming current hurdles while facilitating wireless communication innovation.

This paper attempts to clarify the definitions of white space by differentiating the various definitional perspectives. We first provide background in Section 2 and then review current definitions and their scope in Section 3. Subsequently, we discuss the existence of white spaces based on current technological trends, i.e., white space in the interweave, underlay, and overlay paradigms in Sections 4, 5, and 6, respectively. Furthermore, we discuss white space from the licensing perspective is Section 7. Then, we provide a brief discussion of current issues and future possibilities for exploiting white spaces in future wireless systems in Section 8. We conclude the paper in Section 9.

2. Background

From a technical perspective, the radio spectrum is the part of the electromagnetic spectrum that corresponds to the wavelengths (and corresponding frequencies) used for radio communications. These wavelengths are used by a wide range of applications and are separated into chunks, i.e., corresponding frequency bands ranging from 9 KHz to 3000 GHz (Marcus,

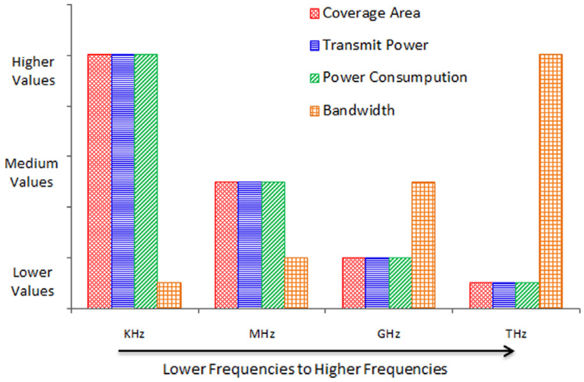

Fig. 2. Conceptual illustration of the behavior of the wireless radio spectrum in terms of bandwidth, coverage area, power consumption, and transmit power when progressing from lower frequencies to higher frequencies. In general, lower frequency signals can travel longer distances (larger coverage area with higher transmit power), but can carry only lower data rates. In contrast, higher frequency signals travel only shorter distances (smaller coverage area with correspondingly lower transmit power), but can carry higher data rates.

2013). The frequency employed has a direct impact on the trade-off between the propagation distance of the radio signal and data rate (bit/s) that the signal can carry. In general, lower frequencies signals can travel longer distances, but only carry lower data rates. In Fig. 2, we graphically illustrate the behavior of the wireless radio spectrum in terms of bandwidth, coverage area, power consumption, and transmit power, when progressing from lower frequencies to higher frequencies.

The frequency bands can be classified into two main categories, namely licensed frequency bands and unlicensed frequency bands. Licensed frequency bands require an individual to pay a licensing fee before they can be utilized. Licensing grants exclusive rights and ensures that there is no interference from other wireless entities (Marcus, 2014a). National regulatory authorities typically sell these licensed frequency bands at auctions for multi-billion dollar prices. Thus, it is impractical for an individual to utilize them for low-cost communication. For example, it would be absurd to employ a licensed band for a wireless router in a private home. In order to accommodate such low-cost communication applications, portions of radio frequency bands have internationally been excluded from sale (licensing). These portions of the spectrum are termed as unlicensed frequency bands. These bands do not require any permissions or licensing fees. However, a key trade-off is that they are vulnerable to interference due to the limited number of unlicensed bands and the large user base competing for bandwidth in unlicensed frequency bands.

A common misconception is that the escalating number of consumers and their rapidly growing usage of futuristic devices is causing a shortage of radio spectrum. This belief is further aggravated by intensifying competition among several entities over the occupancy of licensed and unlicensed spectral bands, especially for frequency ranges below 3 GHz, which have the desirable characteristics of long-range propagation combined with reasonably high channel capacity and readily available components. However, analyses of spectrum usage have revealed a different story. A major reason for spectrum scarcity is conventional static spectrum management, which utilizes the spectral resources inefficiently.

In order to overcome management inefficiencies, the concept of Cognitive Radio (CR) communication has been proposed (Mitola & Maguire Jr., 1999; Youssef, Ibrahim, Abdelatif, Lin, & Vasilakos, 2014). The International Telecommunications Union Radiocommunication sector (ITU-R, 2009, p. 3) defines a CR as an ambient environment aware system that can change its operating criterion based on the knowledge of the network. More precisely: "*A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.*"

In order to closely examine this definition, it is crucial to first become familiar with the terms "primary user" and "cognitive radio user" which represent central concepts in CR networks. Primary Users (PUs) are licensed users that have paid royalty fees to obtain exclusive rights for a part of the available spectrum. Such licensed bands are not fully utilized. On the other hand, a user employing CR technology to sense the ambient radio bands and to configure the transceiver parameters for opportunistically exploiting white spaces without causing harmful interference to PUs is referred to as a Cognitive Radio user (CR user). Cognitive radio communication has various emerging applications in a wide range of domains (Jianfeng, Ghosh, & Challapali, 2011). These applications include cognitive radio based smart grids (Althunibat, Wang, & Granelli, 2016; Gungor & Sahin, 2012; Khan, Rehmani, & Reisslein, 2016; Premarathne, Khalil, & Atiquzzaman, 2015; Yu et al., 2011), cognitive radio sensor networks (Akan, Karli, & Ergul, 2009; Bukhari, Rehmani, & Siraj, 2016; Ergul, Bicen, & Akan, 2016), and the use of cognitive radio technology in unmanned aerial vehicles (Saleem, Rehmani, & Zeadally, 2015).

3. Current definitions of white space and their scope

The definition of "white space" in a particular network determines the methods for quantifying and utilizing the "white", i.e., vacant spectral resources. White space has been defined by various researchers, organizations, and administrative authorities. Some prominent definitions in chronological order are:

(2001) The conventionally used definition from the U.S. Defense Advanced Research Project Agency (DARPA) (Kolodzy, 2001) describes white space as: "*a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area.*"

(2008) A European Conference of Postal and Telecommunications Administrations (CEPT) report (CEPT, 2008a, p. 4), characterizes white space as: "*a label indicating a part of the spectrum, which is available for a radio communication application (service, system) at a given time in a given geographical area on a non-interfering/non-protected basis with regard to other services with a higher priority on a national basis.*"

(2012) In an International Telecommunications Union (ITU) report (ITU, 2012, p. 41), white space is defined as: "*the portions of spectrum left unused by broadcasting, also referred to as interleaved spectrum. They may be used by other services on a secondary basis, i.e., on the condition of not disrupting broadcasting services and not claiming protection from them.*"

(2014) The U.S. Federal Communications Commission (FCC) (Yang, 2014, p. 5), states: "*White Spaces are the channels that are unused at any given location.*"

From these definitions, we can deduce the following characteristics of white space:

- A white space is an unused radio frequency.
- Its existence depends on time, frequency, and geographical location.
- Its utilization should not cause any harm to primary users.

These characteristics give rise to the so-called *interweave* paradigm in which CR users interweave their signals alongside the PUs' signals in the dimensions of time, frequency, and geographical location without fundamentally affecting the communication of the PUs (Goldsmith, Jafar, Maric, & Srinivasa, 2009). The interweave paradigm is the conventional CR communication model and is discussed in the following section.

Shortcomings of these definitions are that they do not consider conditions for licensed/unlicensed bands and neglect other viable dimensions of white space. Importantly, these conventional definitions do not incorporate perspectives arising from the productive usage of white space for CR communication by CR users. Rather, these conventional definitions are narrowly focused on the notion of PUs utilizing the licensed frequency bands, i.e., the frequency bands that are not white space. With the emergence of CR communications as a viable wireless communications paradigm, there is a need for broader definitions of white space that consider both PUs of the licensed frequency bands and CR users communicating over the white space. For example, how does a CR user behave in an unlicensed band or what if the three dimension are fully occupied? Operating a CR device based on a narrow set of definitions would clearly limit the potential of CR communication. This problem can not only be avoided but new opportunities for CR users can also be created by clearly defining white space from different perspectives. Note that there are three conventional white space paradigms, i.e., *interweave*, *underlay*, and *overlay*. Moreover, *hybrids* of these three conventional white space paradigms are possible (Sharma et al., 2015). We discuss these paradigms in detail in the following sections.

These new opportunities may also result in new applications, such as Internet of things (IoT), urban social networks, and enhance last mile connectivity in the areas where signals are not available by using Device to Device (D2D) communication networks. Moreover, by clearly defining the white space, the business and technical scenarios for white space usage can be clearly identified and their implementation will be simplified (Barrie, Delaere, Anker, & Ballon, 2012; Ballon, Lehr, & Delaere, 2013). Besides this, the decisions of regulatory bodies and telecommunications policy makers on spectrum auctions of particular spectrum bands require a thorough understanding and detailed definitions of white space (Parzy & Bogucka, 2013).

4. White space in interweave paradigm

In the interweave paradigm, CR users opportunistically exploit the unused white space in time, frequency, or space (geographic location) when PUs are idle (Wieruch, Pilz, & Jung, 2013). Fig. 3 illustrates the existence of white spaces in the interweave model. The dark shaded rectangles represent the communication activities by PUs. The white areas with dashed lines represent time periods when the respective frequency bands at the specific geographic locations are vacant, i.e., "white", and can be utilized for CR communication by CR users. If at some point during a CR user's transmission a PU becomes active and requires the same specific spectrum portion used by the CR user, then the CR user should switch to another idle band or terminate its transmission if no idle band is available. This happens because PUs access different channels at different times due to their mobility and varying use cases, making the availability of white spaces dynamic. CR users can achieve continuous communication by employing DSA techniques for spectrum hand-off from the currently used spectrum part to a new spectrum part while maintaining the quality of the transmission with minimum degradation during channel switching (Akyildiz, Won-Yeol, & Chowdhury, 2009a; Song, Xin, Zhao, & Cheng, 2012). We proceed to briefly discuss

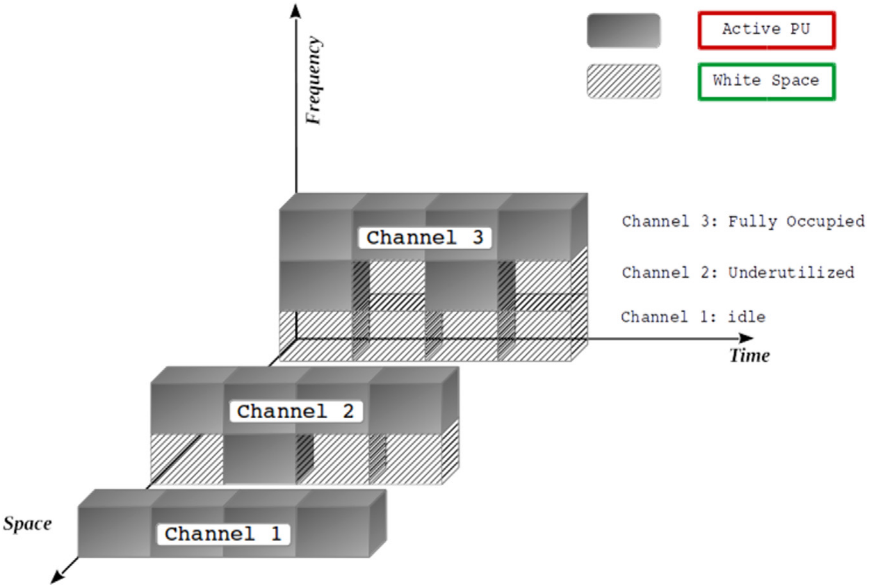

Fig. 3. White spaces in interweave paradigm are spaces along the dimensions of time, frequency, and space (geographic location) that are not occupied by PUs.

the characteristics of CR communication along the conventional dimensions of time, frequency, and space in the interweave paradigm.

4.1. Conventional time and frequency dimensions

A white space in time indicates the availability of a specific part of the radio frequency spectrum, i.e., a frequency band, for a particular time period for opportunistic usage. When considering the ongoing PU radio communication at a given time instant, some frequency bands may be idle, allowing for opportunistic usage by CR users (Rehmani, Viana, Khalife, & Fdida, 2011). Time and frequency are often considered jointly as the fundamental characteristics when analyzing a wireless network.

Based on the durations (time periods) of PU activity, a radio frequency band can be either fully occupied, idle, or underutilized as illustrated in Fig. 3. While current white space definitions use the terminology “idle bands', there are generally no well-accepted definitions of how long a channel needs to be idle to be considered “idle'. Once an idle band is detected, a CR user can exploit it until a PU arrives. Underutilized bands may be available for opportunistic reuse during specific time periods that can last for seconds, hours, or days depending on the duration and time granularity of the channel sensing (Saleem & Rehmani, 2014).

4.2. Time Frequency Resource Conversion

Technological advancements have led to the emergence of advanced user equipment which compared to traditional devices can support multitasking and enable the user to simultaneously run multiple applications. However, a user can at any given time typically focus on only one task. As a consequence, spectral resources are often wasted by applications running in background and may gain higher priority than the application in focus. For example, consider the case of video streaming. A user normally focuses on one video at a time but if multiple videos are simultaneously streamed, each stream consumes bandwidth. This may degrade the quality of the video in focus; in fact, the videos in the background may receive higher priority for spectral resources than the video in focus. This not only degrades network performance but also wastes precious bandwidth. Allocating radio resources according to the user behavior or context, i.e., knowing which applications have current user focus, could reduce spectrum usage.

With knowledge of the current user focus, a resource manager can apply Time Frequency Resource Conversion (TFRC) (Shan, Ni, Zhuang, Huang, & Wang, 2014), to manage resource allocation. TFRC revokes spectrum access for applications that are currently ignored by the user. This freeing up of frequency bands creates virtual spectrum holes that can be interpreted as white space. Depending on the user, these holes can last from seconds to hours and can be opportunistically accessed by CR users. Such a scheme requires a robust resource manager to thoroughly evaluate the context information including the knowledge of application type, request type, and user behaviors. Nevertheless, TFRC can play a vital role in enhancing spectrum utilization and quality of service.

Table 1
Operating features of wireless standards.

Wireless standard	Frequency band	Deployment	Application
AM	531–1611 kHz	Outdoors	Radio broadcast
IEEE 802.22	54–862 MHz	Outdoors and Indoors	Wireless regional area network
FM	66–108 MHz	Outdoors and Indoors	High quality audio over radio broadcast
GSM, CDMA, HSDPA, LTE	700–2600 MHz	Mostly Outdoors	Cellular Voice and Data
IEEE 802.15.4	868, 915, 2450 MHz	Outdoors and Indoors	Low-rate wireless personal area networks
ETSI HiperMAN	2–11 GHz	Outdoors	European alternative to WiMAX
WiBro	2.3–2.4 GHz	Outdoors and Indoors	Korean alternative to WiMAX
IEEE 802.16	2.3, 2.5, 3.5, 5.8–66 GHz	Outdoors	Wireless Broadband (WiMAX)
IEEE 802.15.1 (Bluetooth)	2.4–2.485 GHz	Mostly Indoors	Short range data communication, alternative to RS-232
IEEE 802.11	2.4, 3.7, 4, 5, 45, 60 GHz	Indoors and Campus wide	WLAN
IEEE 802.15.3	3.1–10.6, 24, 57–64 GHz	Outdoors and Indoors	High-rate wireless personal area networks
IEEE 802.20	3.5 GHz	Outdoors	Mobile Broadband

4.3. *Geographical location dimension*

Another dimension in white space definitions that is often considered in conjunction with time and frequency is the geographical region. The main reason for this consideration is that a frequency band that is occupied in a particular region may be available for opportunistic access in another region. CR users can take advantage of this by monitoring the power levels of various frequency bands in a given region. Low power levels may imply that frequency bands are idle; however, CR users need to be cautious to avoid hidden terminal scenarios (Tsertou & Laurenson, 2008).

Prior to wireless network deployment in a specific region, several radio propagation and communication characteristics are surveyed to prevent conflicts with surrounding networks. One of the surveyed characteristics is the range of frequencies used in the region. If the same or close frequencies are utilized in the vicinity, they may cause interference. Cellular network planning avoids such interference through a detailed frequency reuse policy (Paisana, Marchetti, & DaSilva, 2014). CR users can exploit this policy by keeping track of the radio frequencies used in the vicinity and shifting to unused bands. Thus, CR users should not be limited to detect only a few radio frequency bands, but rather be permitted to sense and potentially exploit the ubiquitously used frequency bands in Table 1.

Wide-band spectrum sensing can be very time consuming and complex for individual CR users (Fazeli-Dehkordy, Plataniotis, & Pasupathy, 2011; Hongjian, Nallanathan, Cheng-Xiang, & Yunfei, 2013). Thus, it may be preferable if a CR base station senses the spectrum and maintains a list of viable frequencies. Moreover, sensing of frequencies should be application dependent, i.e., should be based on the data rate requirements of the application. In this manner, only frequency bands that are capable of providing the required data rate are sensed. For example, low frequencies, such as AM frequencies, may not be viable for high data rate applications, but may be useful for other applications with low data rate requirements.

5. White space in underlay paradigm

In the underlay model, CR users transmit on licensed bands using low-power devices with a limited range. Underlay communication is possible irrespective of whether PUs are active or not. That is, PUs and CR users can transmit simultaneously as long as the interference to PUs is within acceptable limits. This type of white space in the underlay communication paradigm is also known as gray space utilization (Bedogni, Achtzehn, Petrova, & Mahonen, 2014; Macaluso, Forde, Dasilva, & Doyle, 2012; Peha, 2013).[1] Due to this simultaneous transmission property, underlay CR networks are gaining considerable traction and will likely play a significant role in future communications.

5.1. *Power/range*

In the underlay paradigm, the white space corresponds essentially to the power level beneath the noise threshold of the primary communication. In particular, in case the PU occupies a frequency band in a given geographic region for an indefinite period of time, a CR user can still communicate over the occupied frequency band. As illustrated in Fig. 4, licensed radio frequency bands can be utilized for secondary communication if the maximum transmission power of a CR user is kept below the PU's noise threshold. Underlay communication does not involve any sensing (Furtado et al., 2014) or opportunistic exploitation of unused spectrum; instead, underlay communication only requires certain precautions for avoiding harmful interference to PUs.

A currently practically feasible underlay communication technique is Ultra Wide Band (UWB) communication, which provides short range, high data rate communication (Zeng, McGrath, & Liu, 2014). UWB communication spreads the

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[1] In order to be consistent and to avoid confusion, we use the term “white space” throughout this paper.

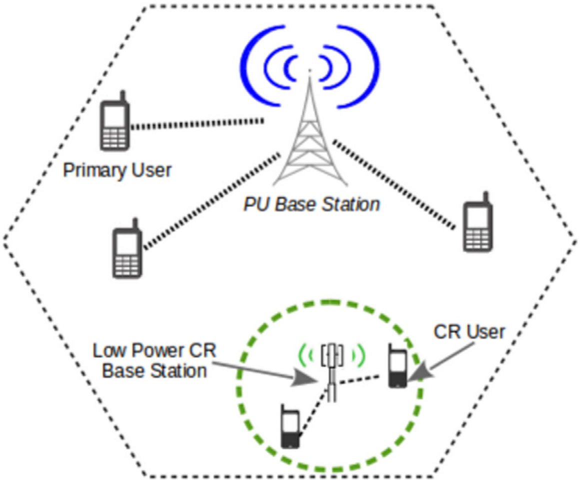

Fig. 4. Illustration of underlay communication: CR users communicate with low power underneath the noise threshold of PUs, i.e., the CR user communication does not interfere with the PU communication.

Table 2
Operating range and power for low-rate wireless communication standards.

Attributes	**UWB** (**IEEE 802.15.3**)	**Zigbee** (**IEEE 802.15.4**)	**Bluetooth**(**IEEE 802.15.1**)	**Wi-Fi** (**802.11**)
Power	Less than 1 mW	1–100 mW	1–100 mW	40–200 mW
Range	About 50 m	10–500 m	1–100 m	30–150 m
Frequency	3.1–10.6, 24, 57–64 GHz	868, 915, 2450 MHz	2.4–2.485 GHz	2.4, 3.7, 4, 5, 45, 60 GHz

transmission power over a wide frequency band; thus, licensed PUs communicating in narrow frequency bands can readily tolerate the minimal interference from CR users. However, the aggregate interference from several UWB devices may increase the noise level enough to affect PUs.

Apart from the UWB standard, three other protocol standards for short-range wireless communication with low power consumption can presently be considered for underlay communication. Table 2 compares the attribute for these potential underlay communication standards with UWB, which could be employed for underlay communication underneath the noise threshold of PU communication standards. However, extensive future research and standardization work is still required to make underlay communication with Zigbee, Bluetooth, or WiFi practical, e.g., by developing modified versions of these protocols with lower maximum transmission power. Generally, any future extensions of the protocol standards in Table 2 or any new low power CR protocol standards may share the frequency bands of the PU base station (see Fig. 4), when they transmit with low enough power following the underlay paradigm.

We proceed to briefly review two specific research directions for short-range communication with the underlay paradigm. The two directions explore very small cognitive femtocells as well as short-range device-to-device (D2D) or machine-to-machine (M2M) communication within the coverage region of a PU macro cell.

5.1.1. *Cognitive femtocells*

Interference in CR networks can be further reduced by exploiting cognitive femtocells (Gupta & Banerjee, 2011; Kpojime & Safdar, 2015). A femtocell is essentially a low-power, inexpensive, and compact base station used for enhancing indoor cellular capacity and coverage (Xenakis, Passas, Merakos, & Verikoukis, 2014). The femtocell devices can be equipped with cognitive capabilities for learning and reasoning. The femtocell devices thus enable opportunistic utilization of the spectrum space, while keeping the transmission power low enough to avoid any interference with the ambient PUs. Furthermore, CR enabled femtocells can not only adaptively allocate radio resources but can also contribute to mitigating co-channel interference and improving spatial reuse.

5.1.2. *Underlay approaches for D2D and M2M networks*

The underlay approach for small cell networks can outperform the interweave approach, as underlay can not only provide reliable connectivity but also provide significant capacity increases combined with low energy consumption. Furthermore, future Device-to-Device (D2D) (Liu, Peng, & Wang, 2013) and Machine-to-Machine (M2M) networks (Al-Karaki, Chen, Morabito, & Oliveira, 2014; Chen & Lien, 2014; Liu, Yang, Yu, Xiang, & Xie, 2015) are envisioned to operate in an underlay manner, co-existing with current and future cellular networks (Zaidi, McLernon, & Ghogho, 2014). In fact, the unlicensed access to narrow band frequencies is a way to extend the white space model and thus, highly suitable for M2M communications (Freyens, Loney, & Dissanayake, 2014).

5.2. Underlay–Relay Hybrid paradigm

The restriction of transmitting with limited power imposed on CR users in the underlay paradigm can be removed by compensating the PUs for the interference from CR user transmissions. White spaces whose exploitation would cause intermediate interference levels do not need to be neglected. Instead, CR users can transmit in the vicinity of PUs without worrying about transmit power limitations, if they assist the communication of the PUs, e.g., by relaying PU data. In this so-called Underlay–Relay Hybrid Paradigm (Kompella, Nguyen, Kam, Wieselthier, & Ephremides, 2014), CR users can simultaneously utilize the spectrum with the PUs as long as network stability is maintained. In order to compensate for interference caused during simultaneous transmission, when the CR user is idle, the CR users can collaborate with the PUs to relay some of the PU data packets to their intended destinations. In scenarios where no direct link is available or the direct link is weaker than the link between the PU and CR user, relaying by the CR user can increase the overall throughput of the network and create more white spaces.

5.3. Hybrid overlay/underlay paradigm

The hybrid overlay/underlay paradigm is another way to improve white space utilization. This hybrid paradigm combines the benefits of both the overlay and underlay techniques. More precisely, the hybrid overlay/underlay paradigm utilizes both the non-utilized and under-utilized spectra. A hybrid overlay/underlay paradigm has been used in Zou, Xiong, Wang, and Chen (2013) for cognitive radio based femtocell networks for urban and rural areas. The performance of cognitive femtocell networks is further improved through hybrid overlay/underlay paradigm in Ma, Cheung, Wong, and Huang (2015).

5.4. Spectrum mapping for underlay networks

Although white space exploitation using the underlay strategy has several advantages, it increases the complexity of CR networks, especially when multiple unregulated underlay networks are deployed in the vicinity of each other and substantially increase the interference. Traditionally, CR users consult geolocation databases for spectrum occupancy and related environment information. This database based scheme may fall short of yielding adequate data in a DSA network consisting of dynamic PUs that periodically refashion their network usage activities. The use of a Radio Environment Map (REM) (Yilmaz, Tugcu, Alagoz, & Bayhan, 2013) can help overcome this issue by efficiently characterizing the radio domain for CRs (Yilmaz et al., 2013). The REM establishes a detailed map by using multi-domain environmental data from geolocation databases, past experience, spectral regulations, and relevant policies (Khan, Khalil, & Mitschele-Thiel, 2011; Lin & Chen, 2014; Yu & Chen, 2011).

6. White space in overlay paradigm

In the overlay paradigm, CR users transmit simultaneously with PUs on licensed frequency bands by detecting the presence of PUs and appropriately changing the characteristics of the CR transmitted signal to avoid interference with PUs. The overlay strategy can be categorized into cooperative and non-cooperative approaches.

6.1. Cooperative

In the cooperative overlay approach, the conventional PUs acknowledge the presence of CR users, i.e., the CR users agree with PUs on the terms of spectrum usage (Chen, Chen, & Meng, 2014).

6.1.1. Code

In order to avoid any accidental or deliberate signal interference and interception in fixed frequency bands, many commercial communication devices employ spread spectrum (SS) techniques. One widely used SS technique is Frequency Hopping Spread Spectrum (FHSS), which uses multiple frequency bands for spreading the transmitted signal. Another widely used technique is Direct Sequence Spread Spectrum (DSSS), which uses only a single frequency band (channel) for spreading but the stream of information is divided into small chunks and combined with a bit sequence or code which specifies the user that the data is meant for. In both cases, a narrow-band signal is spread with a code sequence to fill a wider frequency band. SS techniques are the basis of Code Division Multiple Access (CDMA), a multiple channel access method, in which several PUs can send their data simultaneously over a single frequency channel. CDMA uses the coding scheme to distinguish the data streams for the different users and to protect the data.

The utilization level in an SS network due to PUs below the network's usual capacity can be viewed as a white space. CR users can communicate in such an underutilized network with low or no interference to PUs. However, due to privacy reasons, CR users cannot capture or use the codes of the primary network. To overcome this issue, CR users can use spreading codes that are (nearly) orthogonal with respect to the codes currently used by PUs and other CR users.

6.1.2. Angle

Polarization: An important planning parameter for the network deployment in a given geographic region is the polarization of the radio frequency (RF) antenna. Polarization affects the oscillation direction of the propagating radio signal. Antennas can only receive or transmit a signal with a specific polarization which is exclusively either vertical or horizontal. Thus, it is critical to match the polarization between the transmitter and the receiver. If there is a mismatch, then no signal is received. CR users can exploit the polarization angle dimension by transmitting in the opposite direction of the PU transmission.

Beamforming: Besides shaping the transmission angle range through directional antennas (Akyildiz & Wang, 2005; Vilzmann & Bettstetter, 2006), another emerging concept for shaping the transmission angle is beamforming. With beamforming, a transmitter can narrowly focus its signals towards an intended receiver instead of transmitting the signal omnidirectionally (Gang & Kishore, 2011; Winters, 2006). The narrow focus of the transmission angle limits the interference to neighboring receivers. Beamforming thus permits simultaneous transmissions to several spatially distributed devices (Doufexi, Armour, Nix, Karlsson, & Bull, 2004; Lun, Petropulu, & Poor, 2009).

However, beamforming requires multiple sophisticated directional antennas. Beamforming in CR networks can further enhance the performance for CR users while minimizing interference to licensed PUs (Gopalakrishnan & Sidiropoulos, 2015; Juan, Wei, Zhigang, & Zhang, 2012; Murray & Zaghloul, 2014; Park & Hwang, 2015; Ramamonjison, Haghnegahdar, & Bhargava, 2014; Zheng, Ma, Wong, & Ng, 2010).

6.2. Non-cooperative

In the non-cooperative overlay approach, CR users independently determine the availability of white spaces which do not cause interference to PUs when accessed.

6.2.1. Full duplex CR

Conventional CR users only utilize a part of the white space. This is because their traffic transmissions are usually slotted, whereby a given time slot is further partitioned into two sub-slots (Gao, Yin, & Han, 2015). Spectrum sensing is performed in the first sub-slot and data is transmitted in the second sub-slot. Spectrum sensing typically consumes a major portion of the white space, leaving the CR user with only a modest part of the white space for data communication. This half duplex data communication restricts the potential of CR users. This drawback can be removed by equipping CR users with multiple antennas for full duplex communication, i.e., simultaneous spectrum sensing and data transmission (Askari & Aissa, 2014; Liao, Song, Han, & Li, 2015). By employing this full duplex communication method, CR users can significantly increase their throughput. However, this technique is also fraught with challenges, such as increased cost, self-interference among multiple antennas (Zhao, Wang, & Chen, 2015), and increased energy consumption. It is worth noting that the use of full duplex CR is still in its infancy and is an open research topic with many challenging problems.

7. White space from the licensing perspective

From the licensing perspective, current white space definitions are limited in that they do not explicitly consider the type of spectrum license (Marcus, 2010). In particular, the current definitions only stipulate that CR users do not interfere with PUs, whereby PUs are assumed to operate in licensed frequency bands. Thus, the current white space definitions imply that white space is considered to exist only in licensed radio frequency bands. On the other hand, the current white space definitions imply that unlicensed bands are freely available without restrictions.

Technically speaking, CR users seek to exploit licensed bands due to their potential benefits, such as wide availability of licensed radio frequency bands and long-distance propagation. However, if there are no white space opportunities in licensed bands, then the CR users have to retract to unlicensed bands to continue radio communication. Generally, in unlicensed bands, all users are considered PUs as no entity is paying for these frequency bands. Nevertheless, in some scenarios, there may be priorities defined among users of unlicensed bands. Such priorities can impose limitations on the usage of unlicensed frequency bands. Consider, for instance, a hospital scenario where life monitoring and support systems utilize an unlicensed frequency band and require uninterrupted service with prescribed delay and error bounds. The life support systems will undoubtedly have the highest priority and should not be interfered with. A CR user entering the hospital can unintentionally cause harmful interference to sensitive incumbent communication devices if the existing priorities are not considered. Thus, it is crucial to not only define the presence of white spaces in unlicensed bands, but also the roles and responsibilities of the CR users.

The underutilized spectrum band of terrestrial TV bands, a.k.a., TV White Spaces (TVWSs), has been estimated through field trials and actual measurements (Beek, Riihijarvi, Achtzehn, & Mahonen, 2012; Chunyi & Harada, 2014; Holland, 2015; Mwangoka, Marques, & Rodriguez, 2013). These field measurements help us to maintain the geolocation databases of spectrum usage of TV incumbents (Saeed, Ibrahim, Harras, & Youssef, 2015). Recently, FCC regulations on TVWSs have

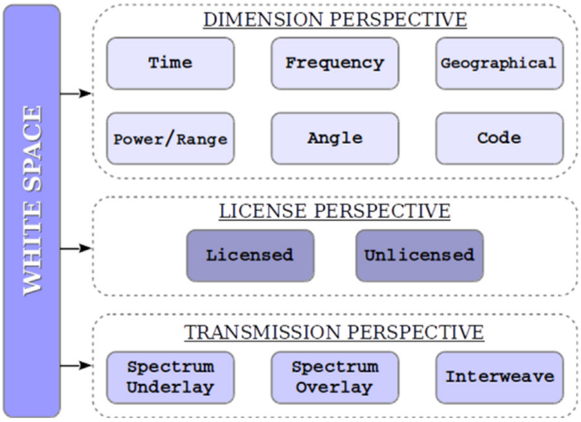

Fig. 5. Suggested expanded perspectives on defining white spaces: future cognitive radio communication may consider a combination of radio signal dimensions, licensing status, and transmission strategy.

opened the doors to new communication opportunities. Two standards for utilizing TVWSs are available in the literature: IEEE 802.11af (Flores at al., 2013) and IEEE 802.22 (Joshi, Acharya, & Kim, 2015; Stevenson et al., 2009). Cognitive radio networking is the enabling technology for effectively utilizing the TVWSs (Ghosh, Roy, & Cavalcanti, 2011; Kang & Park, 2014; Villardi, Abreu, & Harada, 2012). However, there is still a need for more efforts to standardize other licensed bands so that the white spaces in other licensed bands can be exploited in an efficient manner.

8. Discussion on definitional perspectives of white space

Current white space definitions only consider three dimensions of the spectrum space, namely time, frequency, and geographic region. Considering these three dimensions has been sufficient for conventional radio communication systems. However, restricting white space definitions to these three dimensions may limit the potential of CR. CEPT Report 24 (CEPT, 2008a) hints at a wider definition of white spaces. However, this report is limited to a preliminary review of the practicability of implementation of new/future applications within the white space spectrum in the 470–862 MHz band. Moreover, the report notes that there is a need to further investigate the possible use of guard bands and full duplex in the harmonized sub-band by other systems/services (cf. CEPT, 2008b for more details on the technical conditions of use). In this paper, we try to further emphasize and elaborate a wider definition of white spaces. This section outlines such possible future perspectives on white spaces.

In Fig. 5, we present an expanded view of white spaces that considers three perspectives. Present CR communication considers some combinations of these three perspectives. For instance, present CR communication approaches that dynamically sense the spectrum typically consider the radio signal dimensions, i.e., time and frequency, in licensed frequency bands and interweave CR user transmissions with PU transmissions.

Combinations of the three conventional paradigms (interweave, underlay, and overlay) can be constructed so as to combine their advantages, while mitigating their drawbacks. Combinations of the interweave and underlay paradigms have already been considered to some extent for maximizing channel capacity and optimizing spectrum efficiency (Goldsmith et al., 2009), while some combinations of the underlay and overlay paradigms have been considered in Section 5.3.

On the other hand, some combinations of the three perspectives have not yet been considered in technological research or standardization activities. That is, there are combinations of the three perspectives that are presently not possible, but future research may investigate these open areas. For instance, very recently, two new techniques have been proposed that represent novel mixtures of perspectives of white space exploitation: the Underlay–Relay Hybrid Paradigm (Kompella et al., 2014) (see Section 5.2) and TFRC (Shan et al., 2014) (see Section 4.2). For instance, the Underlay–Relay Hybrid Paradigm exploits the power/range radio signal dimension, while employing spectrum underlay transmission and operating in both licensed and unlicensed bands. Thus, any combination of these perspectives can be potentially considered and exploited as white spaces in future communication systems.

The time granularity of the white space is also an important aspect and may need to be quantified by regulatory bodies to facilitate suitable applications. To elaborate this further, the timescale of the white space availability, i.e., for how much time the white space is available to a CR node, may be considered in future communication systems. For instance, the study (Khalife, Malouch, & Fdida, 2009) noted that the white space can be on the time scales (durations) of hours, minutes, and seconds and one can select an application based on the time granularity of the white space. Statistical modeling of the durations of these white spaces has been conducted in Misic and Misic (2014).

White space in space–time dimensions can also be exploited to further improve the performance of future communication systems. For instance, three regions, i.e., the white region, the gray region, and the black region, have been proposed in the space–time dimension to efficiently utilize white spaces (Zhiqing, Zhiyong, Qixun, & Wei, 2015). In the black region, CRs are not allowed to operate, while in the gray region, CRs can opportunistically exploit the licensed temporal white spaces with the interweave paradigm. In the white region, CRs can take full advantage of being far away from the PUs, and thus may fully exploit white spaces without causing harmful interference to PUs. The classification of white spaces into these different regions may improve the overall capacity of future CR communication systems.

Clearly defining and identifying white spaces can not only facilitate advances of CR communications systems, but can also facilitate the development of new communication applications as well as spectrum sharing strategies among new applications. One example application area that can potentially benefit from clear comprehensive white space definitions is the communication with Unmanned Aerial Vehicles (UAVs), also referred to as “Drones” for diverse applications, such as agriculture, commercial transport, and movie making for sports and personal use (Marcus, 2014b; Saleem et al., 2015).

Carrier aggregation (CA) and channel bonding (CB) are other ways to efficiently utilize the dispersed white spaces in any of the white space paradigms. Channel bonding combines a set of contiguous non-overlapping wireless channels in order to create a single channel of higher bandwidth. Channel aggregation combines non-contiguous wireless channels to create a higher bandwidth channel (Bukhari et al., 2016). One such example is to perform carrier aggregation in the overlay paradigm, which has been studied in the context of carrier aggregation of white spaces in LTE-A systems in Kaltenberger et al. (2014).

9. Conclusion

Many complex technical issues and regulatory concerns can be mitigated by avoiding ambiguities and providing clear definitions for the basic development framework of an emerging technology. In the case of cognitive radio (CR) communication, the issues mainly relate to the exploitation of white spaces. Current white space definitions only consider a limited perspective of white space. These limited white space definitions may also limit the potential of cognitive radio (CR) communication. Since CR communication is based on the principle of exploiting white spaces, defining and exploiting every possible perspective of white spaces may contribute to improved CR communication. In this paper, we reviewed the shortcomings of current definitions of white space. We outlined a broadening of the definitions of white space to combinations of the three perspectives of radio signal dimension, license status, and transmission strategy. We believe that clarifying and expanding the definitions of white space will help in advancing wireless innovation.

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