A Comprehensive Survey on Networking over TV White Spaces

Mahbubur Rahman and Abusayeed Saifullah
Department of Computer Science, Wayne State University, Detroit, MI 48201
(r.mahbub, saifullah)@wayne.edu

Abstract—The 2008 Federal Communication Commission (FCC) ruling in the United States opened up new opportunities for unlicensed operation in the TV white space spectrum. Networking protocols over the TV white spaces promise to subdue the shortcomings of existing short-range multi-hop wireless architectures and protocols by offering more availability, wider bandwidth, and longer-range communication. The TV white space protocols are the enabling technologies for sensing and monitoring, Internet-of-Things (IoT), wireless broadband access, real-time, smart and connected community, and smart utility applications. In this paper, we perform a retrospective review of the protocols that have been built over the last decade and also the new challenges and the directions for future work. To the best of our knowledge, this is the first comprehensive survey to present and compare existing networking protocols over the TV white spaces.

1 INTRODUCTION
In a historic ruling in 2008, the Federal Communication Commission (FCC) in the United States opened up the TV white space spectrum for unlicensed secondary usage [1]. TV white spaces refer to the allocated but locally unused TV channels (between 54 MHz and 698 MHz in the US). Similar regulations have been adopted by several other countries including UK [2], Canada [3], Singapore [4], Malaysia [5], and South Africa [6]. Unlicensed secondary devices such as Wi-Fi [7], ZigBee [8], and Bluetooth [9] are allowed to access and operate over the TV white spaces without interfering the primary users, i.e., TV stations or other licensed users of the spectrum. To access TV white spaces, an unlicensed device can either query a cloud-hosted geo-location spectrum database or perform a sensing operation to determine the energy of the spectrum [1]. In 2010, FCC mandated that an unlicensed device must query a database to learn about the TV white spaces in its location [10]. Also, FCC kept the sensing technique as an optional choice for secondary users [10].

Due to their more availability, wider bandwidth, longer communication range, and capability to penetrate obstacles, TV white spaces show great promise to overcome several limitations in other wireless technologies. For example, Wi-Fi, Bluetooth, ZigBee, and other technologies that operate on unlicensed 2.4 GHz or 5 GHz bands greatly suffer from range limitations, complex network topologies and protocols (due to multi-hop nature) [11], inter-technology interference [1], [10], etc. In parallel, several other technologies are being developed targeting solely the TV white space spectrum, such as SNOW [11], [12], KNOWS [13], WhiteFi [14], WhiteNet [15], WISER [16], [17], WINET [18], SenseLess [19], FIWEX [20], V-Scope [21], Waldo [22], etc. These technologies include from real-time sensing prototype to full-fledged network architecture design. In fact, researchers have once again embraced this rare opportunity to develop networking architecture and protocols from the scratch.

TV white space technologies can enable several beneficiary applications including sensing and monitoring applications (e.g. Urban sensing [23], Wildlife habitat monitoring [24], [25], Volcano monitoring [26], [27], [28], Oil field monitoring [29], [30], [31], Civil infrastructure monitoring [32], agricultural Internet-of-Things (IoT) applications (e.g. Microsoft Farmbeats project [33], Climate Crop [34], Monsanto [35], AT&T project [36]), smart and connected community applications (e.g. Rural wireless broadband access [37], [38], Public safety [39]), real-time applications (e.g Industrial process control [40], Civil structure control [41], Data center power management [42], and smart utility applications (e.g. Advanced metering infrastructure [43]).

Despite all the benefits of TV white space networking, several key research challenges need to be addressed properly. First, the interference between primary (i.e., TV station) and secondary user (i.e., personal/portable device) plays a significant role in the design of TV white space networking protocols. Second, these protocols should be able to handle coexistence issues to facilitate homogeneous and heterogeneous applications. Third, TV white spaces are mostly fragmented (i.e., discontinuous in frequency spectrum) and pose significant challenges in seamless operation of these protocols. Fourth, the dynamic nature of TV white spaces due to both temporal and spatial variations make it challenging to adopt them in any protocol. Fifth, TV white spaces can be scarce in some places (mostly urban areas) and these protocols need to be adaptive to other frequency bands when needed. Sixth, these protocols should handle mobility due to spatial variation of TV white spaces. Seventh, proper security measures should be taken to ensure the communication safety in these protocols.

In this paper, we describe the challenges and the opportunities of the TV white space networking. Additionally, we provide a retrospective study and comparison between all the existing TV white space networking protocols. Furthermore, we identify the opportunities of the TV white space protocols for new application domains (i.e., IoT). To the best of our knowledge, this is the first survey that provides a comprehensive study, comparison, and opportunities of the TV white space networking protocols.

The rest of the paper is organized as follows. Section 2 provides regulatory insights on TV white spaces. Section 3 explores the characteristics of TV white space spectrum. Section 4 identifies the key research challenges and directions for networking over TV white spaces. Section 5 describes
and compares different network architectures and protocols that are proposed targeting TV white spaces. Section 6 describes the opportunities presented by TV white space networking. Finally, Section 7 concludes our survey paper.

2 Overview of TV White Space Regulation and Standardization

In this section, we formally introduce the TV white spaces, FCC regulations, and standardization efforts on TV white spaces. Table 1 summarizes all the regulatory parameters.

TV white spaces refer to allocated TV channels that are locally unused. The Federal Communication Commission (FCC) in the United States allowed the use of TV white spaces by fixed location or personal/portable unlicensed/secondary devices (e.g. Wi-Fi, Bluetooth, ZigBee, etc.) in 2008 [1], [10], but not to interfere in any way with the primary TV stations or licensed operations. Similar regulations are being adopted in many other countries including UK by Ofcom [2], Canada by Industry Canada Consultation [3], Singapore [4], Malaysia [5], Kenya [44], Namibia [45], South Africa by Independent Communications Authority of South Africa (ICASA) [6], Argentina by Communications Authority of Argentina (ENACOM) [47], Microsoft is also trying to open up TV white spaces in India [48]. In the United States, TV white spaces lie within the Very High Frequency (VHF) and lower Ultra High Frequency (UHF) (54-698 MHz) bands that correspond to TV channel index 2 to 51 (each with 6MHz channel spacing). To access/use TV white spaces in the United States, a fixed location secondary device can use TV channels with indexes 2-13 (54-216 MHz) in VHF frequency band, and 14-51 (470-698 MHz) in UHF frequency band except channels 3 (60-66 MHz), 4 (66-72 MHz), and 37 (608-614 MHz). Personal/portable devices may use TV channels with indexes 14-51 (470-698 MHz) in the UHF band, but not TV channels with indexes 20 (506-512 MHz), 37 (608-614 MHz) [49]. Similar regulations are being adopted by many other countries as well [50], [59].

2.1 Operational Regulations on TV White Spaces

In this subsection, we discuss the regulations mandated by FCC to operate on TV white spaces. The FFC ruling in 2008 [1] proposed that the low power devices may access and operate on TV white spaces either in licensed, unlicensed, or hybrid (both licensed and unlicensed) fashion as discussed below.

2.1.1 Licensed Operation

Licensed access to TV white spaces is mainly to enable the wireless broadband and mobile data services [11]. Specially, Qualcomm Inc. [51], Fiber Tower Corporation [52], the Rural Telecommunication Group (RTG) Inc. [53], Sprint Nextel Corporation [54], T-Mobile USA [55], etc. encouraged FCC to allow licensed TV white space operation, thus assuring that there will be no harmful interference from secondary or unlicensed users. Also, licensing would guarantee that all the innovations benefits would be only for the licensee and that will be a huge encouragement for the big companies to invest on TV white spaces.

2.1.2 Unlicensed Operation

On the other hand, unlicensed access to TV white spaces would also open up a whole new level of opportunities for low power secondary devices. Existing unlicensed bands (e.g. 2.4 and 5 GHz) are already being used for a huge number of innovative products (e.g. Wi-Fi, ZigBee, BLE, etc.) due to almost no barriers in accessing unlicensed bands. Thus, unlicensed use of TV white space will definitely flourish the innovations. Unlicensed use of TV white spaces would also definitely increase the chances of providing wireless broadband access to rural and Native American tribal areas due to its lower costs compared to the cost associated with the infrastructure investments in licensed operation.

2.1.3 Hybrid Operation

FCC, encouraged by Wireless Internet Service Providers Association (WISPA) [56], allows accessing TV white spaces with hybrid or light licensing models, similar to the licensing rules in 3650-3700 MHz band. As a viable alternative to exclusively licensed and/or unlicensed operation, hybrid or light licensing allows fixed base stations (e.g. Cellular towers, etc) to be registered in a database and clients (e.g. personal/portable devices) not to use TV white space spectrum exclusively. A database approach (discussed in Section 2.2.2) in hybrid operation model will definitely reduce the chances of interference while operating on TV white spaces.

2.2 Access Regulations on TV White Spaces

Now we elaborate on the plans for unlicensed use of the TV white spaces. In the following, we first classify the unlicensed devices according to FCC [1], [10] and then discuss on the methods of accessing the TV white spaces by unlicensed devices.

2.2.1 Unlicensed Device Classification

To operate on unlicensed TV white spaces, devices are functionally categorized into two types: fixed and personal/portable. By conforming to TV white space regulations (i.e. not interfering the primary TV stations and licensed users), both fixed and personal/portable devices are allowed to send and receive broadband and other types of communication data. We give a brief functional description of this two types of unlicensed devices below.

Fixed Device. The fixed category consists of fixed unlicensed devices that can transmit with higher power and generally placed in outdoor locations. It is assumed that locations of these devices will not change. Fixed category devices are allowed to communicate with other fixed category devices and personal/portable devices. Also, after acquiring a TV white space channel, a fixed category device has to send automatic periodic messages identifying itself to avoid interference with other TV white space devices. Functionally, they will provide commercial and/or non-commercial services to the clients. With higher transmission powers, these devices may cover a geographical area of several kilometers.

Personal/portable Device. Personal/portable devices will operate with comparatively lower power and could be mobile and change locations. They can be installed as Wi-Fi like cards in cell phones, laptop, computer, wireless in-home Local Area Network (LAN) devices, etc. Personal/portable...
devices have two operational modes: (i) controlled by a fixed category device or a personal/portable category device that has already determined its usable TV white spaces (Mode I), (2) independent, where a personal/portable device determines the usable TV white spaces in its own location (Mode II). Personal/portable category devices are allowed to communicate with both fixed category and other personal/portable category devices.

2.2.2 Determining Occupied and Unoccupied TV White Spaces

Initially, in 2008, FCC thought of three TV white space determination methods that may be adopted by unlicensed devices. In the following, we first talk about these three methods and then give a reasoning about practical choices (out of three methods) for unlicensed devices.

Geo-location Database Approach. In this method, an unlicensed device will first learn about its geo-location via a professional device installer or some existing geo-location technology, such as GPS. A GPS device is easy to mount on an unlicensed device. After determining the geo-location, the unlicensed device will contact a licensed geo-location database, hosted on the cloud (Internet), to determine the existing TV white spaces at its location. However, an analysis has to be done for each TV white space channel to determine whether that device’s location is not in the interfering zone of other primary TV stations or licensed users.

Control Signal Approach. This method incorporates TV white spaces information in a control signal generated by an external source. An external source can be a fixed TV or radio broadcast station, a Commercial Mobile Radio Service (CMRS) base station, a Private Land Mobile Service (PLMRS) base station, or another unlicensed transmitter. An unlicensed device will listen to the control signals transmitted by the external source and decide on its TV white spaces. Also, in this method, an unlicensed device is only allowed to transmit on a TV white space channel after it gets a positive identification of available TV white space channels from the control signals generated from a single or multiple sources as mentioned above.

Spectrum Listening/Sensing Approach. If an unlicensed device has the capability of sensing or listening to the radio spectrum on its own, it can sense and determine the available TV white space channels in its geo-location. An unlicensed transmitter can always attach an antenna and receiver radio module with the capability of detecting TV signals. However, certain rules are in effect by FCC and unlicensed devices have to be compliant with them during the spectrum sensing. For example, FCC mandates a TV channel is to be considered free (thus, a TV white space) if the energy level (e.g. signal power) is under certain threshold values (see Table 1). This threshold values may also vary based on different physical attributes (i.e. device type, TV channel index, etc).

FCC in their first order in 2008 mandated that an unlicensed fixed TV white space device has to follow both geo-location database approach for detecting TV white space channels and spectrum sensing/listening to confirm that no other unlicensed device is currently transmitting on those channels. An unlicensed personal/portable device has to employ one of the two following approaches: (i) it has to be under the control of a fixed device or another personal/portable device with the capability of determining the geo-location and accessing the geo-location database, (ii) it has to be able to determine its own geo-location, access the geo-location database, and spectrum sensing. However, in FCC second order in 2010, mandatory spectrum sensing/listening for fixed or personal/portable devices has been lifted and kept as an optional choice.

2.3 Standardization Efforts

Since the adoption of TV white spaces, various communication protocols are being developed in parallel for wireless networks. As such, various standards bodies started leveraging TV white spaces. In the following, we give a brief overview of different standards that are being targeted to enable communication over TV white spaces.

2.3.1 IEEE 802.22 Wireless Regional Area Networks

Conforming to FCC orders, IEEE 802.22, standard body provided a draft to FCC for consideration. IEEE 802.22 had the focus of providing cognitive Medium Access Control (MAC) and physical layer (PHY) specifications to establish Wireless Regional Area Networks (WRANs) over TV white spaces. This standard mainly focused on developing different cognitive MAC solutions to deal with the coexistence (discussed in Section 4.2) problem in TV white space operations. However, the status of the draft is currently inactive.

2.3.2 IEEE 802.11af Wireless Local Area Networks

IEEE 802.11af focuses on developing MAC and physical layer specifications for Wireless Local Area Networks (WLANs) over TV white spaces. Recently, the governing body standardized the Wi-Fi like connectivity over TV white spaces.

2.3.3 IEEE 802.15.4m Low-Rate Wireless Personal Area Networks

IEEE 802.15.4m is trying to adopt TV white spaces and provide MAC and physical layer specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). While this standard is currently under development, it shows great promises for Internet-of-Things (IoT) applications with limited resources (e.g. energy, latency, etc.).

2.3.4 IEEE 802.19.1 Wireless Coexistence Group

IEEE 802.19.1 group focuses on developing methods for coexistence of different unlicensed TV white space devices/networks. More specifically, the task group specifies methods for coexistence in TV white spaces that are independent of any radio technologies.

2.3.5 IEEE 1900.4a, 1900.4.1 Heterogeneous Mobile Wireless Networks

IEEE 1900.4a proposed its amendments to enable mobile wireless services in TV white spaces. More specifically, it aims to provide architectural building blocks with optimized radio resources to enable distributed heterogeneous wireless access networks. Alongside, IEEE 1900.4.1 task group provides a detailed description of the building blocks for IEEE 1900.4a.
| Technical Attributes     | Fixed Device | Personal/portable Device | Wireless Microphone |
|--------------------------|--------------|--------------------------|---------------------|
|                          |              | Mode I (Client mode)     | Mode II (Independent mod) |             |
| Geo-location             | Necessary    | Not necessary            | Necessary          | Necessary  |
| Database Access          | Not necessary| Not necessary            | Not necessary       | Not necessary |
| Spectrum Sensing/Listening |             |                          |                     |            |
| Allowed TV               | 2-35 (53 - 602 MHz), except 3, 4 | 21-35                  | 21-35               | 2-35 (53 - 602 MHz), except 3, 4 |
| White Space Channels     | -84 dBm per 6 MHz | -114 dBm per 6 MHz      | -114 dBm per 6 MHz  | -114 dBm per 6 MHz |
| Sensing Threshold        | 1 Watt (30 dBm) | 100 mWatt (20 dBm), 40 mWatt (16 dBm) (Near protected Areas) | 100 mWatt (20 dBm), 40 mWatt (16 dBm) (Near protected Areas) | 100 mWatt (20 dBm), 40 mWatt (16 dBm) (Near protected Areas) |
| Transmission Power       | <6 dBi (Mounted outdoor) | N/A                     | N/A                 | N/A |
| Device Antenna Height    | <30 meters (Mounted outdoor) | N/A                     | N/A                 | N/A |
| Antenna Gain             | 0 dBi        | 0 dBi                    | N/A                 |            |
| Out-of-Band Emission Limits (EIRP) | 4 Watt       | 100 mWatt                | 100 mWatt           | Non interfering |

**TABLE 1**

Technical Attributes of TV White Space Devices

### 2.3.6 IEEE 1900.7 Radio Interface for Dynamic TV White Space Access

IEEE 1900.7[^63] aims to develop a radio interface that incorporates MAC layer and physical layer for dynamic access of TV white spaces for both fixed and personal/portable devices. It also takes the harmful interference to incumbent users into account in their design.

### 3 Characteristics of TV white spaces

In this section, we discuss various characteristics of the TV white spaces that can enable diverse types of wireless applications.

#### 3.1 Spectrum Availability

TV white spaces provide a large number of channels for both licensed and unlicensed devices compared to other wireless spectrum bands such as on which IEEE 802.11[^7], IEEE 802.15.4[^8], etc usually operate on. Basically, TV channels with indexes from 2 to 51 are considered as TV white spaces, if unoccupied locally. The corresponding physical frequencies are in VHF and lower UHF bands, such as those in between 54 MHz to 698 MHz. Thus, with few restrictions (i.e. channel 37 is only for medical use, two more designated channels are for wireless microphones, etc.) from FCC[^1][^10], TV white spaces offer almost 47 TV channels. Each of the TV channels corresponds to a 6 MHz of bandwidth. Depending on the geo-locations, a various subset of those 47 channels may be found as vacant TV channels and can be utilized in wireless communications. For example, rural and suburban areas usually offer a larger set of TV white spaces due to very few official TV stations[^11]. Urban areas also offer sufficient amount of TV white space channels, but lesser in number compared to the rural or suburban areas. Rural area TV white spaces could be utilized in already existing applications such as habitat monitoring[^25], volcano monitoring[^23], environmental monitoring[^64], etc. We will provide a detailed scope of applications in TV white spaces in Section 5. On the other hand, TV white spaces may be utilized for real-time data center management[^65], urban sensing[^23], etc. in metropolitan city areas. To emphasize on the availability of TV white spaces, Figure[1] shows TV white space availability in a different number of counties (out of 3142) in the United States, with data collected from Spectrum Bridge database[^66].

#### 3.2 Higher Bandwidth

TV white space spectrum provides diverse choices on the bandwidth that can be used in wireless communications. Typically, the bandwidth of a TV channel is 6 MHz. Being able to operate on more than one TV white space channels (say, N) gives a bandwidth increase in the multitude of N. Such diverse bandwidth selection may benefit many existing wireless technologies. In traditional wireless sensor networks (WSNs) such as those based on IEEE 802.15.4 (e.g. Zigbee[^8], Bluetooth[^9], WirelessHART[^67], etc.), the maximum allowable bit rate is 250 kbps. Such standards suffer to provide stringent requirements of several critical applications that require more bandwidth. For example, volcano monitoring[^23],[^27],[^28] applications require data being sent over wireless medium from seismometers and microphones at a very high sampling rate of 100 kHz.
they require a resolution of 24 bits per sample during transmissions. While it’s seemingly infeasible by IEEE 802.15.4 based networks to provide such great deal of bandwidth, TV white spaces show great promises instead. A single TV channel may provide a bandwidth up to 21 Mbps [14]. This bandwidth can be boosted up by a magnitude of $N$ just by simply operating on $N$ TV white space channels. Thus, TV white spaces can enable applications that demand high bandwidth data transactions over the wireless medium.

### 3.3 Propagational Characteristics

Being in the VHF and lower UHF physical spectrum bands, TV white spaces have several important propagational characteristics. Below, we discuss the long communication range and obstacle penetration capabilities of TV white space spectrum.

#### 3.3.1 Longer Communication Range

Due to the lower frequencies (54 MHz to 698 MHz), wireless signals transmitted over TV white spaces can reach longer distances. While wireless communication range critically depends on the transmission power, lower frequencies of TV white spaces add an extra beneficial factor to that. Looking at Friis’ Transmission Equation [68] below we can verify that:

$$P_{rx} = P_{tx}G_{tx}G_{rx}(\frac{c}{4\pi D_f})^2$$

where, $P_{rx}$ and $G_{rx}$ are the receiver power and gain, respectively. $P_{tx}$ and $G_{tx}$ are the transmitter power and gain, respectively. $c$ is the speed of light. $D_f$ is the distance between transmitter and receiver and $f$ is the frequency that is used for communication. If we look closely at Friis’ transmission equation, we can see that the distance is inversely proportional to the frequency. Thus, confirming the relationship between lower frequencies and longer distances in wireless communication. In practice, an effective single hop communication range using TV white spaces can be up to 8 km with a transmission power of 100 mWatt (20 dBm) [12].

Such communication range can benefit several WSN applications. To cover several hundreds of meters, an IEEE 802.15.4 based network usually forms multi-hop mesh topology, increasing both structural and operational complexities of the network. By adopting TV white spaces WSN applications can be effectively benefited by reducing time synchronization overhead between multiple sensor nodes, in-network communication latencies (e.g. convergecast, broadcast, multi-cast, etc.), and energy consumption of the battery-powered resource-constrained devices.

#### 3.3.2 Obstacle Penetration

TV white spaces have great obstacle penetration properties. Due to their lower frequencies, they have longer wavelengths. A signal transmitted on a TV white space channel yields a wavelength that ranges between 43 cm to 59 cm. Signals with such wavelengths can easily penetrate permanent obstacles such as concrete building walls, trees, etc. Thus, TV white space channels can be comfortably used for non-line-of-sight communication over long distances. Protocols (e.g. Wi-Fi [7], Zigbee [8], Bluetooth [9], etc.) that use spectrum bands of 2.4 GHz or 5 GHz can hardly penetrate obstacles and cannot provide better quality of services in terms of good signal-to-noise-ratio (SNR), packet reception rate (PRR), etc. Using a similar transmission power, a signal sent over TV white spaces can penetrate through larger set of physical obstacles compared to that signal being sent over 2.4 GHz or 5 GHz bands. In fact, obstacle penetration is very severe in industrial settings. Industrial WSN protocols such as WirelessHART [67] depend on higher degree of redundancy (e.g. several retransmission, or data being sent via multiple wireless channels). Such requirements drastically decrease the scalability of a network. In contrast, using TV white spaces for sensor networking [11], [12] can reduce such redundant allocations and can become highly scalable. It has been found that a TV white space spectrum at 550 MHz can easily penetrate 7 or more 12-inch concrete walls with a packet reception rate of more than 99.95% with just 0 dBm of transmission power. Thus, TV white spaces show great opportunity for both indoor and outdoor WSN applications.

### 4 Research Challenges and Directions for TV White Space Networking

Different characteristics of TV white spaces come in handy in different network situations. However, TV white spaces also pose significant challenges that are associated with its wide availability, diverse bandwidth, and longer communication range. In the following, we talk about intrinsic challenges that needs to be addressed while adopting TV white spaces. Also, we provide future directions for networking over TV white spaces.

#### 4.1 Interference Between Primary and Secondary Users

While longer communication range eases the complexity of traditional wireless network (i.e. WSNs) topology and architecture, it also poses significant challenge in terms of interference toward the licensed users and primary TV stations. If unlicensed fixed or personal/portable devices are not careful enough during their operation in TV white spaces, it may lead to complete shutdown of any other nearby licensed services operating on the same set of TV white space channels. Although, accessing the TV white space spectrum database or spectrum sensing operation are adopted by unlicensed devices, it may not be enough while targeting applications that involve longer range communications. Also, limiting the output power [1], [10] of unlicensed fixed or personal/portable devices might be too much conservative for applications that require longer range communication. Hence, it demands the protocols be developed that can balance between transmission power and communication range, while completely avoiding interference between primary, licensed, and unlicensed users.

#### 4.2 Coexistence of Homogeneous and Heterogeneous Applications

TV white spaces have the potential to host numerous benefiting applications targeted for common people with lower costs. It has been envisioned by FCC [1] that unlicensed
operation in TV white space will surplis the development of protocols and applications that are currently available in unlicensed 2.4 GHz or 5 GHz bands. Very recently, Sensor Network Over White Spaces (SNOW) [11], [12] is proposed and encouraged the research community to embrace TV white spaces for Low-Power Wide-Area Networks (LP-WANs), thus enhancing the chances to enable IoT applications in great scale. In future, there will be multiple network architecture and protocols like SNOW. It’s obvious that to survive in TV white space spectrum, all the protocols will need to respect each other and coexist. Coexistence issues may not only appear in heterogeneous networks but also in homogeneous networks. Figure 2 shows the possibility of multiple SNOW networks operating on adjacent locality. Thus, it’s important to develop protocols that will resolve coexistence issues in both homogeneous and heterogeneous network scenarios, along with primary TV stations and licensed users.

4.3 Fragmentation of TV White Spaces

With the advent of analog to digital TV broadcasting system, a TV channel bandwidth is narrowed down to a fixed 6 MHz width in the United States [1] and other countries. While digital TV channels are relocated, depending on the geo-location and licensed/unlicensed usage, TV white spaces have naturally become fragmented. This fragmentation poses a significant challenge to the applications that are adopting TV white spaces. Depending on bandwidth requirements, different applications will need a different number of TV white space channels. Hence, both hardware and software protocols of those applications will need to be able to use fragmented TV white space spectrum. Currently, SNOW [11], [12] and few other protocols [14], [15] aim to address that. However, they lack proper handling of fragmented TV white spaces. While operating on TV white spaces, adopting protocols need to respect the communications of primary/licensed/unlicensed devices that are already happening in between the fragmented spectrum. Thus, it will require protocols to adapt to variable transmission powers in different parts of TV white space spectrum in the same application. This is a huge challenge for any protocol. Also, traditional hardware limitations (i.e. sampling rate, antenna directions, etc.) may reduce adoption of fragmented TV white space spectrum, hence limiting the scalability of the applications due to cost and form factors.

4.4 Dynamic Nature of TV White Spaces

Depending on the geo-location and the nature of usage by primary/secondary users, availability of TV white spaces may vary significantly over time. For example, a TV channel might be considered as a TV white space during a particular time of a day/week and occupied (thus, not a TV white space) rest of the time. Hence, protocols that adopt those TV white spaces may have to relocate themselves into other white space channels, when needed. Such dynamic behavior of TV white spaces require the adopting protocols to be able to dynamically change their spectrum. This might hinder seamless operation of those protocols and drastically change energy and latency requirements of the benefiting applications. Also, applications that have stringent real-time requirements may not even get a chance to relocate themselves in other TV white space channels in time. Hence, compromising the quality of service of those applications. To survive in dynamic TV white spaces, appropriate cognitive radio mechanisms should be developed and it’s an open area of research.

4.5 Scarcity and Future Adaptation

A huge number of TV white space channels are available in rural or suburban areas. However, this might not be the case for applications that are hosted in urban areas. For example, the city of Los Angeles, Chicago, etc. has very less number of vacant TV channels that can be used for white space networking. [55] Thus, it may become very challenging to acquire a piece of TV white spaces and continue operations uninterruptedly. Also in future, both in rural/suburban or urban areas, TV white spaces could be mandated to be used only by primary and licensed users. Such scenarios will make it impossible for applications to be hosted on TV white spaces. Thus, devices/protocols that wish to operate on TV white spaces should be highly configurable and adaptable to relocate at any point of time on other unlicensed frequency bands, such as sub-GHz (902 MHz - 928 MHz), 2.4 GHz, and/or 5 GHz. Although, few protocols can interchangeably operate on 2.4 GHz and 5 GHz (e.g. Wi-Fi), it’s a huge challenge for devices that will operate on TV white spaces. Thus, proper research focus should be on developing highly configurable software and hardware protocols for TV white spaces.

4.6 Antenna Design

Due to the lower frequencies of TV white spaces, communication between two devices can span up to tens of kilometers [1]. However, such benefits come with a cost. From the perspective of physical form factor, to operate on lower frequencies, a device need to mount a larger antenna. For efficient/correct reception, an antenna have to be on the order of one-tenth or more of the wavelength of the signal transmitted [69]. Wavelength (say, \( \lambda \)) of a signal is inversely proportional to the frequency of the signal [69]. This
scenario becomes even worse when protocols/applications require multiple antennas for desired quality of service. In that case, the antennas need to be placed apart with a physical gap of at least $\lambda/2$. In lower frequencies, it's intrinsically difficult. It becomes more challenging when a small sensor device needs to mount larger and several antennas depending on application requirements. Thus, to operate on TV white spaces, research is due on efficient antenna design that is very energy efficient and takes less physical space.

4.7 Mobility

Mobility is a huge challenge in every wireless domain. Depending on the mobility pattern and requirements, different protocols adopt different techniques. It also poses great challenges while operating on TV white spaces. Interestingly, none of the existing techniques can be adopted directly to TV white space protocols. As discussed earlier, based on a geo-location, the availability of the TV white space channels may vary. Thus, a mobile device operating on a TV white space channel may not be able to use the same channel in a different location. Also, FCC mandates that each time a TV white space device (e.g. personal/portable) changes its location by 100 meters, it must contact the geo-location database or perform other techniques to determine the TV white spaces in its new location. Device mobility in TV white spaces raises interesting and important challenges that need to be addressed properly to support applications that need mobility (e.g. Vehicle-to-vehicle communications).

4.8 Security

Intrinsically, wireless communication is highly susceptible to security threats. The level of security threats may differ from protocol to protocol depending on its communication ranges. For example, practically a Bluetooth communication range is between 5-10 meters. Near field communication (NFC) has a practical range of few centimeters. Thus, making them naturally resistant to sniffing, spoofing, man-in-the-middle, etc. attack to some extent. Wi-Fi and Zigbee incorporates several techniques to avoid security threats as well. TV white space protocols are currently being developed and lack proper security measures. Security threats become greater when the communication range increases. Thus, research on security for protocols in TV white spaces are significantly important as new threats will emerge due to longer communication range and possible isolation of devices in remote areas.

5 TV White Space Networking Protocols

In this section, we provide a comprehensive study on different protocols that are proposed and developed targeting solely the TV white space spectrum. We divide the protocols into four major categories: Spectrum Sensing Protocols, Geo-location Based Protocols, Wireless Broadband Protocols, and Network Architecture Designs. Also in Table 2 we provide a comparative study between those protocols based on several attributes.
5.1 Spectrum Sensing Protocols

5.1.1 Waldo

The work in [22] incorporates two viable techniques to design a system called white space adaptive local detector or Waldo, for low-cost devices to detect and opportunistically use TV white space spectrum. First, Waldo demonstrates that spectrum monitoring (low-cost) devices has “good enough” sensing capabilities. Second, Waldo provides a detection technique based on locally measured signal features and location. In short, Waldo takes advantages of crowd-sourced local spectrum measurements data from multiple low-cost sensing devices. A central repository is created where location and corresponding spectrum characteristics are stored and TV white space availability is constructed. Thus, in general Waldo is a centralized TV white space access approach just like traditional database approach mandated by FCC [11, 10]. Later on, a white space device consults with the local repository by providing its location and corresponding signal characteristics (sensed by that device) to decide on the availability of the TV white spaces. In the following, we provide detailed design characteristics of Waldo.

The design of Waldo incorporates two basic components. The first component is the centralized database. The second component consists of a collection of white space devices. Waldo also has two operational phases: offline and online [22]. The flow of operation is shown in Figure 3. In offline phase, the central database component collects spectrum characteristics and associated locations from crowd-sourcing or low-cost dedicated sensing devices. Spectrum information from a various number of devices is fused together to construct local models for the availability of TV white spaces at distinct locations. In online phase, TV white space devices (persona/portable) collect location-specific model information from the database and correlate with their locally captured spectrum characteristics. Based on the correlation, it decides on the available TV white spaces for opportunistic usage. The TV white space devices also feedback their local spectrum information to the database. Thus, improving the location-based model information as well as for later uses by other devices. In the database component, there’s a model constructor module that uses a binary classifier to indicate whether a TV channel is usable as white space or not [22]. A model updater keeps modifying the location-based model information by integrating latest spectrum data to provide improved future usage of the database [22].

5.1.2 In-band Spectrum Sensing in Cognitive Radio Networks

To properly model the coexistence between primary and secondary users in cognitive radio networks, the work in [26] proposed an efficient and effective in-band spectrum sensing scheduling technique. In-band spectrum sensing is essential in the context of cognitive radio networks which can be adopted by fixed or personal/portable devices while operating on TV white spaces. It’s important to meet the two seconds detectability and latency (to leave a channel by a secondary user) requirements imposed by IEEE 802.22 [57]. The work in [76] presents a periodic in-band spectrum sensing that optimizes both the sensing interval and latency and minimizes sensing overhead while taking into false positive and false negative factors into account. In the following, we provide few insights about the in-band sensing scheduling technique.

In-band sensing scheduling algorithm incorporates either fast sensing or fine sensing while minimizing the overall sensing overhead. In fast sensing, it takes the minimum amount of time. However, fast sensing is highly vulnerable to channel noise or co-channel interference. On the other hand, fine sensing needs relatively long time compared to fast sensing and provides a higher degree of sensing accuracy. Depending on sensing frequency and quality of services at different times, the in-band sensing scheduling algorithm will employ them separately. However, the main purpose of the in-band sensing scheduling algorithm is to minimize the sensing overhead, while also conforming to the regulations from FCC and IEEE 802.22 [57] work group.

5.1.3 A TV White Space Spectrum Sensing Prototype

The work in [77] presents a real-time TV white space spectrum sensing prototype that can be used to detect signals from ATSC (Advanced Television Systems Committee) digital TV devices, NTSC (National Television Systems Committee) analog TV devices, and wireless microphones in a single integrated platform. To solve the fading channel problem in ATSC and NTSC sensing, [77] proposes a spatial diversity technique. To deal with the weaker signals from wireless microphones, [77] proposes an advanced microphone sensing system that takes the surrounding noises into account. Overall, the proposed prototype minimizes the false negative rates for detecting ATSC, NTSC, and wireless microphone signals in TV spectrum band. In the following, we provide a description of the TV white space spectrum sensing prototype.
The prototype incorporates two configurable receiver antennas for spatial diversity. Any single antenna or both of them can be used for sensing purpose. However, the prototype has a single RF receiver chain. Thus, in diversity mode, the receiver interchanges between antennas with a time interval, called **quiet time**. A quite time is set up generally in two ways: long Quite time or sequence of shorter quite times. This prototype especially uses a sequence of shorter quiet times, each approximately 7 ms. After receiving the baseband samples, the prototype applies a Fast Fourier Transform (FFT) and decides on the spectrum availability at different parts of the spectrum. The absolute squared output from FFT algorithm is scaled, accumulated, and sent to ATSC, NTSC, and wireless microphone sensors integrated on the prototype. Based on processing from those specific sensors, the prototype decides on the received/sensed signal whether it’s from ATSC, NTSC, or wireless microphone.

### 5.1.4 FIWEX

Compressive sensing based cost-efficient indoor white space exploration (FIWEX) has been proposed in [20]. Based on indoor TV white space exploration inside a building, FIWEX study the temporal and spatial features of the spectrum. A comprehensive sensing prototype has been built utilizing the study of temporal and spatial features from a limited number of RF-sensors deployed inside the building. Thus, FIWEX is able to provide highly accurate indoor white space availability with low cost. In the following, we provide the working principles of FIWEX.

FIWEX determines whether a TV channel is vacant or not by comparing the received signal strength in that channel with a threshold value. Thus, if the received signal strength in a TV channel is higher than the threshold value, that TV channel is deemed locally occupied, otherwise not. In fact, FIWEX can operate with the devices that can support a threshold level of -114 dBm as mandated by FCC [1], [10]. Mainly, FIWEX mechanism is two folded: **long-time** and **short-time** sensing. In long-time sensing phase, FIWEX listens to specific locations altogether (a receiver for each location) for a longer period of time. In contrast, FIWEX chooses few candidate locations in short-time sensing and move a single receiver to gather signal strength information. Based on long-time and short-time sensing data, FIWEX finds the strong TV channels that are mostly occupied and white space channels that are available at different times at different locations. The prototype of FIWEX is composed of two parts: **central server** and a **real-time sensing** module. The central server utilizes the data from real-time sensing modules (e.g., RF sensors) and maintains historical records of TV channels and their relative location-based white space competency information. The system architecture of FIWEX is depicted in Figure 4.

### 5.2 Geo-location Based Protocols

#### 5.2.1 SenseLess

A database-driven white spaces network [19] has been proposed to safely and efficiently operate a network on TV white spaces. Taking the up-to-date database inputs about the TV channel incumbents, TV channel signal propagation modeling, and a content dissemination process into account, SenseLess ensures interference-free scalable white space networking. The network architecture of SenseLess comprises several base stations (BSs) and client devices. Each client is associated with a BS. In the following, we provide the architectural design of SenseLess and describe its services.

![Fig. 5. The SenseLess system architecture [19]](image-url)

The design of SenseLess is infrastructure based, as shown in Figure 5(a). The BSs are logically connected to a **SenseLess service**. Thus, SenseLess is logically centralized. In short, given a specific location, the SenseLess service determines which TV white space channels are available to use in that location. Both the BSs and client devices do not do any spectrum sensing and solely depend on the SenseLess service to know about the TV white space channels at their desired locations. SenseLess service provides a subset of APIs where the input is the location (latitude, longitude) provided by a BS or client node. Thus, SenseLess service can provide a bitmap of TV white space availability for a
given location. SenseLess service operates in two different modes: sole location input mode or publish-subscribe mode. The first mode has already been discussed where the service provides with the TV white spaces information for a given location. In the second mode, a BS or client node can subscribe to the service and SenseLess service will track the changes of TV white spaces at their locations. If the TV white spaces change in a subscribed location, the SenseLess service will fire an event to the BS of a client node or a BS itself. Thus, BSs are always connected to the SenseLess service.

A SenseLess service has two components: a back-end store and a SenseLess engine, as shown in Figure 5(b). The back-end store maintains the signal propagation models and data about incumbent users. The SenseLess engine computes the white space availability of given location. Again, the back-end store has a database and a terrain servers component. The database stores all the information (e.g. location, channel, height, transmit power, etc) about all the TV stations, wireless microphone, BSs/client nodes that are being serviced by the SenseLess service. The terrain server provides terrain elevation data at any given point on the device's location. On the other hand, SenseLess engine accurately determines the white space availability by computing the attenuation of signals at different locations by taking all the related location-parameters that are available on database into account. Using the above-mentioned components, SenseLess provides an accurate and efficient way of TV white space networking.

5.2.2 V-Scope
The work in [21] presents a Vehicular Spectrum Scope (V-Scope), a vehicle-based measurement framework that enhances the performance of traditional database approaches for accessing TV white spaces. Depending only on white space database can result in underutilization of TV white spaces and thus, requires spectrum sensing-aided data to improve already existing white space databases. V-Scope proposes to attach RF sensors on vehicles and collect and analyze data from those sensors to better estimate the white space availability in a location. The system architecture of V-Scope is shown in Figure 6. In the following, we provide insights on V-Scope's design and operation.

V-Scope comprises following five workarounds that contribute to enhancing the traditional TV white space database with measurements from sensor nodes mounted on moving vehicles. First, it detects the primary and secondary users based on sampled measurements on different TV channels. Second, all the measurements are clustered into different groups after being sent to a central server. Third, each TV channel propagation models are refined. Fourth, secondary devices are localized if their locations are not already registered into the database. Fifth, V-Scope models the power leakage to estimate TV white spaces that are adjacent to primary TV channels.

5.2.3 HySIM
The work in [28] presents a game theoretic hybrid spectrum and information market (HySIM) for a TV white space network that incorporates interactions between database operator, spectrum licensee, and unlicensed users. HySIM has a three-layer hierarchical architecture. At higher layer, the database and licensee negotiate the commission fee that licensee pays for spectrum market usage. In middle layer, database and licensee compete to sell information about TV white spaces or TV channels to unlicensed users. In the lower layer, the secondary users decide whether they should buy exclusive access to channels from the licensee or the information about actual TV white space channels from the database. We do not elaborate further on the work in [28].

5.2.4 WISER
The work in [16], [17] presents an indoor TV white space exploration system called White-space Indoor Spectrum Enhancer (WISER). Devices/users under this architecture do not need to do any spectrum sensing. Traditional spectrum database approach is usually very conservative and misses out to open/identify a significant portion of TV white spaces that are available in indoors (e.g. buildings, etc). To enable those undiscovered TV white spaces in indoors, WISER proposes different techniques that are cost-effective. As such, WISER outperforms the techniques those based on the outdoor-sensing-only, one-time-profiling-only, and sensor-all-over-the-place methodologies [16], [17]. In the following, we provide detail architectural design and operations of WISER.

WISER consists of three modules: a real-time sensing module, a white space database, and an indoor positioning module, as shown in Figure 7. In short, the real-time sensing module does both indoor and outdoor spectrum sensing and reports the availability of white spaces to the white space database. Any device/user that wants to access/use the TV white spaces will first determine its location using indoor positioning module, and then query the white space database to learn about the available white space channels. Thus, the real-time sensing module is mostly responsible for the correctness of WISER. We describe three modules of WISER below.

The real-time indoor sensing module performs the following tasks to report the availability of TV white spaces to the white space database. It first conducts one-time spectrum profiling by sensing at sufficient positions of the indoor location and building a correlation between TV
channels and the locations. The location that is not profiled is assumed to have the same correlation as the nearest profiled location. After profiling, TV channels are grouped into two categories: strong and weak-to-normal. The grouping also includes the permanent TV white space channels from cloud-hosted white space database. Intuition is that weak-to-normal channels have the higher chances to be considered as TV white spaces. The profiling data also helps to build a channel-location clustering. Finally, based on this channel-location clustering, indoor sensors are positioned to contribute to WISER database later. As mentioned earlier, a user needs to know its location to be able to query the database. Thus, one of the traditional indoor localization technique is adopted in WISER.

5.3 Wireless Broadband Protocols

5.3.1 Toward enabling broadband for a billion plus population with TV white spaces

The work in [38] presents a broadband access-network topology using TV white spaces in rural India. While India has the second largest telecommunication infrastructure [35], the majority of the rural areas in India lack network (especially, Internet) connectivity by any means. To provide wireless broadband Internet, multiple Wi-Fi clusters, covering several rural areas, connects to a fiber network over TV white spaces. In the following, we provide more details about the work in [35].

A broadband access network may be possible in rural India by lengthening the Internet coverage from a rural PoP (Point of presence), provided by BharatNet [38]. To extend the Internet reachability, TV white spaces are utilized to connect a PoP with an optical fiber point to Wi-Fi access points. Using TV white spaces, non-line-of-sight and long-distance communication are possible. According to [35], rural people can connect to the Wi-Fi access points via 2.4 GHz band. Each Wi-Fi access point will be mounted with a UHF band device. This UHF node will be used to backhaul data to/from Wi-Fi mesh network. Thus, enabling wireless broadband Internet via TV white spaces.

5.3.2 WhiteFi

The work in [14] presents WhiteFi, where Wi-Fi like connectivity is enabled by TV white space spectrum. However, providing such connectivity is non-trivial and needs to address temporal variation, spatial variation, and fragmented spectrum of TV white spaces, or UHF band. [14] provides an extensive characterization of temporal variation, spatial variation, and spectrum fragmentation of TV white spaces, while also comparing with the regular Wi-Fi band (2.4 GHz). Based on rigorous analysis and experiments, [14] proposes WhiteFi that is built on KNOWS (described in Section 5.4.2) platform. In the following, we provide a detailed architectural design of WhiteFi.

WhiteFi architecture has three basic components: a spectrum assignment algorithm, a signal interpretation before Fourier Transform (SIFT) technique, and a chirping protocol. The spectrum assignment algorithm handles the spatial diversity and fragmentation of TV white spaces and provides WhiteFi with the information of what channel to use for Wi-Fi operations. The spectrum assignment algorithm is highly adaptive to dynamics of TV white spaces and can assign variable bandwidth channels to the clients (5, 10, 20 MHz, etc). The SIFT is used to perform time-domain signal analysis on TV white space spectrum. SIFT facilitate the Wi-Fi access point discovery, center frequency of the Wi-Fi access point/channel. The chirping protocol of WhiteFi deals with the client’s disconnection from the Wi-Fi access point due to unavailability of the TV white space channel at some instance of time. Chirp protocol reserves a separate 5 MHz of a backup channel (broadcast with the Wi-Fi beacon) to facilitate client disconnections.

5.3.3 WhiteNet

The work in [15] presents a database-assisted multi-AP TV white space network architecture called WhiteNet. This architecture is very similar to WhiteFi [14] and differs mostly in the number of AP used to provide Wi-Fi like connectivity in a larger area. Due to the adoption of multiple APs, WhiteNet is subject to inter-AP interference and spectrum allocation problem between the APs. Since different TV spectrum has different levels of interference, the inter-AP interference problem become nontrivial. Also, depending on time, location, and white space fragmentation, the spectrum allocation between multiple AP needs significant effort. From the WhiteNet user perspective, WhiteNet proposes an AP discovery method that helps the user to efficiently identify the center frequency and spectrum usage of the corresponding AP. In the following, describe the WhiteNet architecture and its protocols that deal with inter-AP interference and white space spectrum management.

The WhiteNet architecture comprises three key modules: A WhiteNet local database, B-SAFE, and AP discovery. The WhiteNet local database conforms to the FCC database requirements [10]. Apart from providing the available TV white space information, the WhiteNet local database also stores each AP location, spectrum allocation information for each AP, interference of each TV white space channel on each AP, inter-AP interference relationships, etc. The WhiteNet local database has a submodule called Contention Database that resolves the TV white space channel contention between APs. WhiteNet proposes a protocol called
B-SAF: distributed spectrum allocation for white spaces to help each AP determine its own spectrum allocation in a distributed fashion. In each AP, B-SAFE takes into account several constraints such as the interference of each TV white space channel on that AP, the corresponding inter-AP interference, spectrum fragmentation, and the area of coverage. The novel AP discovery module is directly associated with the WhiteNet users that helps them to effectively and quickly identify the surrounding AP’s center frequency and operational bandwidth. To do so, WhiteNet assumes that each AP sends a periodic beacon message on the leftmost chunk of its acquired spectrum and encode its center frequency and bandwidth information. Each WhiteNet user will have to listen to those beacon messages to discover each AP. A user performs a Discovery and Cancellation action where it discovers one AP after another. After discovering all the APs, the WhiteNet user connects with the AP that can provide maximum overall utilization in terms of bitrate, SINR, etc. The overall system implementation overview of WhiteNet is shown in Figure 8.

5.3.4 Performance Analysis of a Wi-Fi Like Network Operating in TVWS

The work in [80] presents a quantitative analysis of Wi-Fi like networks those operate in TV white spaces to provide wireless broadband access. Considering the inter-AP interference and dynamics of TV white spaces in urban and rural areas, [80] analyzes the achievable range and downlink throughput of Wi-Fi like networks. In the following, we provide the findings of [80] based on its network architecture, propagation model, and inter-AP interference models.

Performance analysis has been done in three scenarios: outdoor urban, indoor urban, and outdoor rural areas, with a coverage area of (2x2) sq. km, (0.5x0.5) sq. km, and (5x5) sq. km, respectively. In each scenario, the location of the APs is modeled using homogeneous Poisson Point Process [81]. The density of the process is set to 12.5 APs/sq. km, 0.25APs/sq. km, and 125 APs/sq. km for outdoor urban, indoor urban, and outdoor rural, respectively. The propagational models used for different scenarios are similar to [82]. To coexist, multiple Wi-Fi APs adopt the CSMA/CA medium access control protocol. Based on all those models, [80] quantitatively showed that the range difference between traditional Wi-Fi AP operating on a 24 MHz wide TV white space channel in the outdoor urban area stays between 67 m to 130 m. However, the downlink data rate can be reduced by 23% even when using a 20% wider bandwidth than traditional Wi-Fi settings. For indoor urban scenario, the range limit can be extended up to 10 m - 20 m, while a similar downlink rate as traditional Wi-Fi network can be provided. The Outdoor rural scenario shows similar characteristics as the indoor urban scenario because of the lesser number of interference issues compared to outdoor urban.

5.4 Network Architecture Designs

5.4.1 SNOW

Sensor Network Over White Spaces (SNOW) [11], [12], [83], [84] has been proposed to utilize TV white spaces for wireless sensor networking. Moreover, it shows great promise to be an enabling technology for Low-Power Wide-Area Networks (LPWANs). In contrast to traditional multi-hop complex wireless sensor networks such as those based on IEEE 802.15.4 [8], SNOW can facilitate long-range single-hop architecture using TV white spaces. Also, SNOW has the capability to enable concurrent bi-directional parallel communications between a BS and several nodes associated with it. It has been possible by a set of novel protocols proposed by SNOW. To best of our knowledge, SNOW is the first complete network architecture that was built targeting the TV white space spectrum to enable large-scale wide-area IoT applications. In the following, we describe the SNOW architecture and its novel protocols.

SNOW has a star topology architecture as shown in Figure 9(a). In the heart of the star, there is a BS. The BS has Internet connectivity and can access the TV white
space spectrum database. Thus, the BS can get the white spaces in its network location. The BS is computationally powerful and is directly connected to a power source. On the other hand, SNOW nodes are battery-powered and directly connected to BS with a single hop. Thus, its a star topology. Due to long communication range, while operating on TV white spaces, a single SNOW network can connect several kilometers [11], [12]. A SNOW node does not do any spectrum sensing or database access. Thus, it totally depends on the BS to learn about its white spaces. A BS can concurrently receive from a set of SNOW nodes without any interference with a single half-duplex radio. The BS can also send concurrent different data streams to a set of nodes without interference using a single half-duplex radio. Below, we describe how such communication paradigm has been achieved.

To enable concurrent bi-directional parallel communication without any interference in SNOW, a novel physical layer protocol has been proposed. After getting the available TV white spaces in its location, a BS splits the spectrum into multiple orthogonal subcarriers. SNOW is inherently capable of using fragmented TV white space spectrum. Each node is assigned a subcarrier. To concurrently receive from multiple nodes, the BS adopts a Distributed implementation of Orthogonal Frequency Division Multiplexing, called D-OFDM. D-OFDM is different from traditional OFDM based multi-user access [11], [12]. In D-OFDM, nodes do not need to synchronize (i.e. time and frequency) with each other. Nodes send data through their assigned subcarriers. At the receiver, the BS applies a Fast Fourier Transform (FFT) to decode parallel data stream from several orthogonal subcarriers. Similarly, to send different data to different nodes, the BS applies Inverse FFT or IFFT on different orthogonal subcarriers and send a single composite time domain signal. Different nodes receive on their corresponding subcarriers. To make the upward and downward communication concurrent, SNOW adopts a dual-radio approach at the BS as shown in Figure 9(b). Since the BS is aware of whereabouts of all the subcarriers, the two radios of the BS do not interfere with each other. In the following, we describe the lightweight Medium Access Control protocol employed in SNOW to facilitate spectrum sharing between multiple nodes.

If the number of nodes is greater than the number of available subcarriers at the BS, one subcarrier may be shared by multiple nodes. Since the BS knows about the locations of the nodes, it tries to assign a subcarrier to multiple nodes such that the hidden terminals effect is minimized. A node adopts a lightweight CSMA/CA protocol with a static-interval random back-off [35] for transmission. Thus, there is no interference on any shared subcarrier. For each transmission, an acknowledgment (ACK) is sent to the sender (either BS or node) and hence the communication in SNOW is reliable. Finally, SNOW can support thousands of nodes (i.e sensors) and connect a greater area due to its highly flexible protocols and design [86], [87].

5.4.2 KNOWS
The work in [13] presents a cognitive radio network over TV white spaces, called KNOWS. Since TV white spaces can be fragmented and the availability can be changed over time, KNOWS proposed a new hardware platform and a spectrum aware MAC protocol to deal with those dynamics. Such design of KNOWS effectively can increase the overall throughput of the network compared to others that try to operate in TV white spaces using the same network architecture and protocols that were actually built for other frequency spectra. Conforming to FCC regulations [1], [10], KNOWS proposed a robust TV white space detection scheme where the unlicensed secondary devices do not interfere the operation of the licensed primary TV users. Also, KNOWS MAC protocol allows unlicensed secondary devices to opportunistically access and share variable bandwidth TV white space spectrum. In the following, we describe the physical layer and MAC layer of KNOWS.

![Fig. 10. Overview of KNOWS' system components [13].](image.png)
KOBS MAC layer has two main functions: collaborative sensing and spectrum reservation. All the one-hop neighboring devices collectively learn about their surrounding TV white space channels by sending periodic beacon messages every 100-200 ms. A beacon message contains its local white space information. Thus, KOBS MAC layer employs a collaborative sensing technique. To transfer data, sender and receiver nodes contact each other via the control channel and decide on the TV white space channel and desirable bandwidth to use by a three-way handshaking. Both sender and receiver contend for the control channel using CSMA/CA with a random back-off. Before starting the data transmission, the sender node reserves that TV white space channel by sending a spectrum reservation command packet, called Data Transmission Reservation (DTS). After sending the DTS, the sender and receiver initiate the exchange of data without any back-offs. A node in the network can build a log of the usage of the TV white spaces channels by listening to DTS commands from its neighbors.

5.4.3 WINET

The work in [18] presents the first indoor multi-AP white space network design, called WINET. WINET takes into account the TV white space spectrum fragmentation, temporal variation, and spatial variation and optimizes the AP locations, AP association, and spectrum allocation in the network. Such design of WINET can increase the coverage area, overall system throughput, and the fairness among the WINET users. In the following, we describe the infrastructure based WINET system architecture and the associated design challenges.

![System architecture of WINET](image)

As shown in Figure 11, the WINET architecture has three key components: an indoor white space identification system (WISER [16]), APs, and the demand locations. The WISER architecture has been explained in Section 5.2.2. WINET adopts WISER since it can provide with more TV white spaces in indoor location than the traditional database approach. In WINET, each AP and the client device has multiple cognitive radios. Any demand location of WINET can have multiple client devices. Each of those client devices can simultaneously contact with multiple APs using their multiple cognitive radios. Thus, multiple APs are deployed to cover all the demand location. All the APs and client devices adopt the CSMA/CA MAC protocol.

WINET addresses several key challenges to enable the multi-AP based indoor white space networking. First, it provides a way to optimize the total number and placements of the APs that can maximize the system throughput and fairness between client devices. Second, WINET compensates for the dynamic nature of TV white spaces, such as fragmented spectrum, temporal variation, and spatial variation. Third, the association between APs can be significantly challenging since client devices may need to simultaneously contact with multiple APs. As such, WINET formulates two optimization problems called Maximizing the average Demand Fairness problem (MDF) and Spectrum Allocation and AP association problem (SAP). MDF deals with the fairness between clients and SAP deals with AP's spectrum allocation and association. WINET provides a polynomial time solution for MDF and proves that SAP is NP-complete. However, it does not provide any polynomial time heuristic or approximation algorithm for SAP.

5.4.4 A Cognitive Radio System (CR-S)

Using the IEEE 802.11a MAC, [88] presents a cognitive radio network architecture over the UHF TV white spaces. The proposed cognitive radio network comprises a cognitive AP and various cognitive mobile stations. Although this network design is proposed using IEEE 802.11a MAC, it can be adopted on top of any other MAC layer or physical layer. Such flexibility is achieved by incorporating an abstraction layer in between the protocols of this cognitive radio network and the MAC layer. For detecting TV white spaces, CR-S adopts both geo-location based and sensing based approaches. Such hybrid approach provides more protection against the incumbents and other unlicensed secondary users. In the following, we describe the proposed protocols of CR-S.

The cognitive AP solely decides on the available TV white spaces to operate on and lets the cognitive mobile stations know via multiple control channels. To facilitate network management and control, in-band signaling is adopted. The cognitive AP is equipped with two transceivers: one is for dedicated sensing of TV channels and the other is for dedicated communications between AP and cognitive mobile stations. The AP consists of several functioning modules: a policy engine, geo-location module, CE-UMAC interface, sensing engine, AP cognition controller, sensing information manager, and a graphical user interface (GUI). While most of the modules are self-describing, we will provide functioning details of few of them in the following. The AP communicates with the IEEE 802.11a MAC via a set of abstractions provided by the CE-UMAC interface module. The AP cognition controller is responsible for selecting the TV white space channel to operate on, keeping a rank of the TV white space channels, detecting and recovering from the in-band incumbents and other secondary users, assessing the link qualities, etc. On the other hand, the cognitive mobile stations are equipped with a single transceiver. A cognitive mobile station consists of a mobile station cognitive controller and a CE-UMAC
6 Opportunities of TV White Space Networking

Protocols that are adopting or being developed on TV white spaces can host a multitude of applications utilizing its availability and longer communication range. In this section, we provide a detailed application scope of TV white space networking. Figure 12 depicts such various kinds of application domains.

6.1 Sensing and Monitoring Applications

A great deal of wide-area sensing and monitoring applications can be realized with lesser network and protocol complexities in TV white space spectrum. In practice, wide-area sensing and monitoring applications are hosted on top of IEEE 802.15.4 [8] and IEEE 802.11 [7] protocol stacks. However, due to their shorter communication range (e.g., 30-40 meters in a single hop), they create complex multi-hop networks to cover larger geo-location area. Few examples are as follows. First, to cover the 1280 meters (the main span) of the Golden Gate Bridge at San Francisco, CA, a WSN needs to be deployed with at least 46 hops [32] and it takes nearly 10 hours to collect data from all the sensors. Second, to track Zebras in an area of approximately 200,000 sq. meters, ZebraNet [59] offers a delay-tolerant WSN since sensors on Zebras get disconnected due to their shorter communication range. Third, East Texas Oil is filed is about 74x8 sq. kilometers and will require an uncountable number of sensors to monitor the whole area [31]. Figure 13 shows a complex multi-hop mesh network architecture that will possibly be required in case of any of the example above. Intrinsically, protocols for such network will be very complicated, energy and time-consuming. Thus, it demands that those applications should adopt some new protocols. Recently, such sensing and monitoring applications started adopting LPWAN technologies [75] that operate on the sub-1GHz band (902-928 MHz) and reduce them to single hop networks. Similar to the sub-1GHz band, TV white spaces have the capability to do the same. Moreover, depending on the geo-location, TV white spaces can offer 5-10 times more free spectrum for operation. Thus, making it possible to host a great deal of wide-area sensing and monitoring applications including Urban sensing [23], Wildlife, Environment, and Habitat Monitoring [30], [31], [90], Volcano monitoring [26], [27], [28], Oil field Monitoring [29], [30], [31], Civil infrastructure monitoring [32], etc.

6.2 Agricultural IoT Applications

Agricultural IoT applications [91] demand reliable communication between numerous sensors deployed in crop fields and farmers warehouse. It has been envisioned by the United Nations to double the food production by 2050 to meet the future demand by growing population of the earth [92]. To efficiently and effectively farming, farmers should be able to decide on the important and critical environmental factors and crop requirements on demand. As such, soil nutrients, effective fertilizers, water level in soil, seeds planted, temperature of stored food and materials should be monitored exclusively, all the time. To this extent, numerous sensors should be deployed and data should be collected to take effective data-driven decisions. The communication protocols between sensors can be built on TV white spaces to confirm longer range communication, higher bandwidth, less interference, and energy efficiency as discussed in Section 3. Several companies have already started adopting TV white spaces for building communication protocols of agricultural IoT applications. For example, Microsoft Farmbeats project [33], Climate Crop [34], agricultural projects, Monsanto project [35], AT&T project [36], etc.

6.3 Applications for Smart and Connected Communities

Protocols can be built on TV white spaces to enable applications that can enhance sustainability, quality of life, health, safety, and economic prosperity of communities in both urban and rural areas [93]. The smart and connected community applications are envisioned to address the needs of past, present, and future of the community. Thus, ensuring the preservation and revitalization, livability, and sustainability of the community [94]. To realize the idea of smart and connected community, it’s inevitable to enable technologies that are broadly available and accessible. TV white spaces can proudly represent and host such enabling technologies. As such, different attempts have already been made to enable wireless broadband access for rural areas [37], [95], enterprise, campus, municipal, and public safety [96], etc.

6.4 Real-Time Applications

TV white spaces have the potential to support large-scale wireless cyber-physical systems (CPS) applications. Real-time CPS incorporates feedback control loops that depend on hard/soft real-time wireless communications between sensors to controllers and controllers to actuators. In contrast to traditional WSNs such as those based on IEEE 802.15.4 [8], CPS applications aim to achieve a best-effort communication paradigm. Following the demand of CPS, industrial sensor network protocols such as WirelessHART [67] have evolved over time. However, to meet the escalating demands of industrial Process control [40], Civil structure control [41], Data center power management [42] applications, thousands of sensor nodes will need to connect to the controller via gateways [96]. Following the WirelessHART [67] standard, to connect thousands of sensors in an industrial setting will require several gateways with physical wires and thus losing the benefits of wireless. Also, due to the time synchronization requirements in the nodes and centralized network architecture, future real-time CPS applications will suffer from several scalability problems. Attempts have been made to develop highly scalable wireless communication protocol [11], [12] utilizing the TV white spaces. Thus, real-time CPS applications can be benefited greatly by adopting those protocols.
6.5 Smart Utility Applications

The ubiquitous smart utility network (SUN) for efficient management of electricity, natural gas, water, and sewage can be hugely benefited by adopting protocols built on TV white spaces. One of the key enabling features of SUN is the advanced metering infrastructure (AMI) [43]. The benefits of AMI is twofold: (i) it provides monitoring, command, and control for the service providers, (ii) it helps in measurement, data collection, and analysis at consumers end. AMI tools at the service provider and consumer ends are usually far apart from each other and need to exchange control messages and metering data. Such messaging requires efficient and inexpensive communication protocols that are highly scalable. Typically, SUN operates in unlicensed sub-1GHz (902-928 MHz) in the United States. With several other LPWAN technologies (e.g. LoRa [97], Sigfox [98], etc.) being developed and targeted for IoT applications in the sub-1GHz band, it’s only a matter of time that band gets overly congested and prone to severe inter-technology interference [75]. Thus, by adopting protocols built on TV white spaces will greatly benefit SUN applications. At the same, the communication range between the service provider and consumers can be significantly increased.
CONCLUSION

The 2008 FCC ruling in the United States on TV white space spectrum has opened up new opportunities for unlicensed operation in the TV band. TV white spaces’ availability, diverse bandwidth, and excellent propagational characteristics make them suitable for long range, low-power, and large area applications such as sensing and monitoring applications, agricultural IoT applications, wireless broadband access, real-time applications, smart and connected communities, smart utility applications, etc. Several new network architectures and protocols have been proposed solely targeting the TV white space spectrum as well. However, TV white space fragmentation, temporal diversity, and spatial diversity make it challenging to adopt them directly due to interference and coexistence issues. In this paper, we have investigated these key research challenges and provided future directions. We have then provided key insights and comparison between several protocols built on top of TV white spaces. Also, we have presented the opportunities of TV white space protocols in great details.

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