IEEE 802.11af: A Standard for TV White Space Spectrum Sharing

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ABSTRACT

Spectrum today is allocated in frequency blocks that serve either licensed or unlicensed services. This static spectrum allocation has limited resources to support the exponential increase in wireless devices. In this article, we present the IEEE 802.11af standard, which defines international specifications for spectrum sharing among unlicensed white space devices (WSDs) and licensed services in the TV white space band. Spectrum sharing is conducted through the regulation of unlicensed WSDs by a geolocation database (GDB), the implementation of which differs among regulatory domains. The main difference between regulatory domains is the timescale in which WSDs are controlled by the GDB, resulting in different TVWS availability and WSD operating parameters. The IEEE 802.11af standard provides a common operating architecture and mechanisms for WSDs to satisfy multiple regulatory domains. This standard opens a new approach to treat spectrum as a single entity shared seamlessly by heterogeneous services.

INTRODUCTION

White spaces are unused spectrum resources at specific times and locations that can be exploited through spectrum sharing. TV white space (TVWS) exists in the broadcast TV operating frequencies known as the VHF/UHF band, specifically ranging from 470–790 MHz in Europe [1, 2] and non-continuous 54–698 MHz in the United States [3]. The existence of TVWS enables spectrum sharing among unlicensed white space devices (WSDs) and licensed protected users of the TVWS band. The TVWS band is currently used by a large variety of licensed protected services, such as terrestrial TV broadcast services, and program making and special event (PMSE) users. Some of the licensed services have resided in this band for nearly 100 years [4]. Licensing protects the incumbent users of the TVWS band from interference within their service area. Therefore, WSDs operating in the TVWS band are not permitted to interfere with any protected incumbent user in their specified operating area.

Propagation characteristics of the TVWS band make it a desirable and convenient spectrum for many wireless transmission services [5]. First, because this band resides under the 1 GHz frequency, material obstruction is less harmful than at higher frequencies, allowing non-line-of-sight coverage [6]. The difference in signal attenuation between a variety of materials and frequencies is shown in Table 1 [7], where differences of up to 50 dB are found between 570 MHz and 5.7 GHz. Second, the TVWS band presents a path loss advantage over unlicensed industrial, scientific, and medical (ISM) bands (2.4 and 5.7 GHz) due only to operating frequency. For example, TV channel 2 (54–60 MHz) has 20 dB less path-loss than TV channel 30 (566–572 MHz), which itself holds a 20 dB gain over the unlicensed band at 5.7 GHz.

The superior propagation factors of the TVWS band are demonstrated in Fig. 1. The capacity and distance components are compared for low transmission-power TVWS mobile devices, 2.4 GHz devices and 5.5 GHz devices, as well as high power TVWS-fixed devices. Wider channels in the high frequency bands, such as the 80 MHz channels used in the 5 GHz ISM band, provide higher capacity over a short range, but require more infrastructure to achieve wide-area coverage. In contrast, the 6-MHz-wide 4 W white space signal is more robust and propagates longer distances with a significant capacity. The calculations for Fig. 1 assume free-space propagation using the Friis transmission equation [8] in order to demonstrate relative performance with characteristic system parameters.

The excellent propagation characteristics of the TVWS band coupled with underutilization in many locations present desirable potential spectrum sharing opportunities. To achieve sharing among WSDs and licensed TV broadcasters and PMSE users, many challenges must be addressed by a common standard. One of the main challenges is guaranteeing the protection of incumbent users of the TVWS band from interference in their operating region. WSDs are required to operate in unoccupied spectrum, which can vary in size, location, and time. This means WSDs must support different channel widths and be able to learn from an approved geolocation database which channels are available and for

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Materials	0.57 GHz (dB)	1 GHz (dB)	2 GHz (dB)	5.7 GHz (dB)	0.57 to 5.7 GHz (ΔdB)
Brick 89 mm	–1.5	–3.5	–5.4	–15	13.5
Brick 267 mm	–4.8	–7	–10.5	–38	33.2
Composite Brick 90 mm/ Concrete Wall 102 mm	–12	–14	–18	–42	30
Composite Brick 90 mm/ Concrete Wall 203 mm	–21.5	–25	–33	–71.5	50
Masonry 203 mm	–9.5	–11.5	–11	–12.75	3.25
Masonry 610 mm	–26.5	–27.5	–30	–46.5	20
Glass 6 mm	–0.4	–0.8	–1.4	–1.1	0.7
Glass 19 mm	–2.5	–3.1	–3.9	–0.4	–2.1
Plywood (dry) 6 mm	–0.15	–0.49	–0.9	–0.1	–0.05
Plywood (dry) 32 mm	–0.85	–1.4	–2	–0.9	0.05
Reinforced concrete 203 mm/ 1% steel	–23.5	–27.5	–31	–56.5	33
Reinforced concrete 203 mm/ 2% steel	–27.5	–30	–36.5	–60	32.5

Table 1. *Received signal magnitude gain in dB (0.0 dB = no attenuation) [7].*

The primary element and what mainly differentiates the IEEE 802.11af operation to other 802.11 standards is the GDB. The GDB is a database that stores by geographic location the permissible frequencies and operating parameters for WSDs to fulfill regulatory requirements.

what time duration. Once operating in an available channel, WSDs are required not to interfere with incumbent devices in neighboring channels. Finally, WSDs are required to immediately cease transmissions when the database informs them to stop.

To address these challenges, the IEEE 802.11af standard provides an international framework that adapts to the different WSD operating parameters and regulatory domains around the world. In this article, we present the standard framework defined by IEEE 802.11af; then we discuss how this framework can be applied to the two main regulatory approaches. Because the standard is still in the letter ballot draft process as of June 2013, we focus our discussion on high-level architecture and applications.

Standard Framework

In this section we describe the primitives and main mechanisms of the IEEE 802.11af standard. We present the key architecture components, the communication flow and mechanisms utilized by the standard to satisfy different international regulations and finally we present the physical layer operation.

Components of the IEEE 802.11af Architecture

In this section we introduce the entities that form an 802.11af network and present the non-regulatory specific roles these elements execute.

Geolocation Database — The primary element, and what mainly differentiates the IEEE 802.11af operation from other 802.11 standards, is the geolocation database (GDB). The GDB is a database that stores, by geographic location, the permissible frequencies and operating parameters for WSDs to fulfill regulatory requirements. GDBs are authorized and administrated by regulatory authorities; therefore, a GDB's operation depends on the security and time requirements of the applied regulatory domain [9].

Registered Location Secure Server — The next architectural element in an IEEE 802.11af network is the registered location secure server (RLSS). This entity operates as a local database that contains the geographic location and operating parameters for a small number of basic service sets (BSSs). The RLSS distributes the permitted operation parameters to the access points (APs) and stations (STAs) within the BSSs under the RLSS's control [9].

Just as the operation of the GDB depends on the security and time requirements of regulatory domains, the role the RLSS plays in the network varies across regulatory domains and is explained in detail later in the regulatory framework.

Geolocation-Database-Dependent Entities — The remainder elements in the IEEE 802.11af network are referenced by the term geolocation database-dependent (GDD), which specifies that their operation is controlled by an authorized GDB, which ensures these satisfy regulation requirements [9].

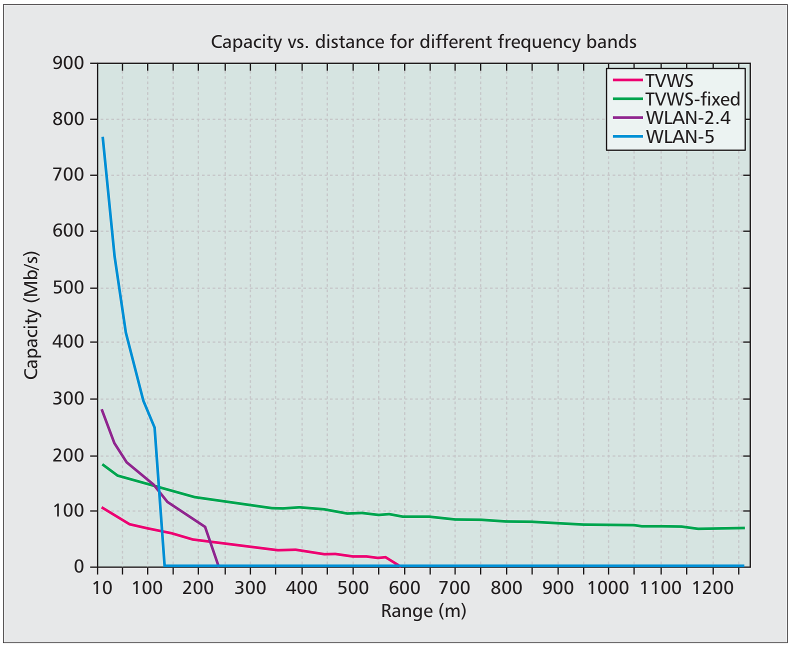

Figure 1. *Capacity vs. distance comparison for different wireless systems calculated with the parameters shown in Table 2.*

GDD-Enabling Station — The GDD-enabling station is the equivalent of the entity commonly known as the AP. However, in the 802.11af standard this entity controls the operation of the STAs in its serving BSS. The GDD-enabling STA can securely access the GDB to attain the operating frequencies and parameters permitted in its coverage region. With this information the GDD-enabling STA has the authority to enable and control the operation of the STAs under its service, identified as GDD-dependent STAs. Specifically, the parameters obtained from the GDB are represented through a white space map (WSM). The GDD-enabling STA ensures the maintenance and distribution of a valid WSM. Additionally, the GDD-enabling STA transmits a contact verification signal (CVS) for GDD-dependent STAs to check validity of the WSM [9].

GDD-Dependent Station — The GDD-dependent station can be identified as the STAs in the BSS architecture. However, the 802.11af standard specifies that the operation of the STAs is controlled by the serving GDD-enabling STAs. The GDD-dependent STAs obtain the permitted operating frequencies and parameters in a form of a WSM from either the GDD-enabling STA or RLSS. The validity of the WSM is confirmed through the CVS transmitted by the GDD-enabling STA [9].

Registered Location Query Protocol — The Registered Location Query Protocol (RLQP) serves as the communication protocol between GDD-enabling and GDD-dependent STAs to share WSM and channel utilization [9]. This protocol enables the operation of the main mechanisms used in the IEEE 802.11af standard. Through this communication the STAs can effectively select spectrum, power, and bandwidth allowed by their regulation domain.

Communication Flow between Entities

The 802.11af standard defines the communication protocol between the GDD-dependent STAs, GDD-enabling STAs, and RLSS. However, the communication flow between the GDB and the high-level entities (RLSS and GDD-enabling STAs) is outside the scope of the 802.11af protocol. The standard's mechanisms are independent of how this communication is performed, allowing regulators to select the communication protocol over the Internet's infrastructure.

Figure 2 illustrates two infrastructure BSSs containing all the components of the IEEE 802.11af architecture introduced. As shown in Fig. 2, the RLSS and GDD-enabling STAs obtain white space availability through the Internet.[1] Within the 802.11af scope, the RLSS only communicates with the GDD-enabling STAs through infrastructure and operates bidirectionally. Finally, the GDD-dependent STAs perform bidirectional over-the-air communication with GDD-enabling STAs, within either the TVWS band or other ISM bands.

802.11af Mechanisms

In this section we present the mechanisms defined in the 802.11af standard and logical messages passed between the architecture entities to satisfy regulatory requirements.

Channel Availability Query — Through the channel availability query (CAQ) procedure, STAs obtain the available radio frequencies that allow operation in their location in the form of a white space map (WSM). In the CAQ process the RLSS grants the WSM to the CAQ requesting STA. However, in some regulatory domains the RLSS is required to access the GDB to obtain the channel availability information. The CAQ request may contain multiple device locations. The CAQ responding STA must restrict the WSM validity to either a unique device location or a bounded area of multiple locations [9].

The GDD-dependent STA performs a CAQ request to a GDD enabling STA in three different cases: first, to remain in the GDD enable state after enablement times out; second, when a change in channel availability is indicated by the GDD-enabling STA through a CVS; third, if the GDD-dependent STA has moved beyond the regulatory permitted distance [9].

Channel Schedule Management — The GDD-enabling STAs use the channel schedule management (CSM) procedure to query an RLSS or other GDD-enabling STAs to obtain white space channel schedule information. The channel schedule indicates a schedule change and consists of the start and ending times for the requested channels [9].

The GDD-dependent STAs do not perform CSM requests. However, the GDD-enabling STAs can transmit a CSM request to an RLSS or other GDD-enabling STA (with GDB or RLSS access) to query the schedule information for white space channels in either TV channels or WLAN channels.

[1] *The Google database of white space availability in the United States appears at http://www.google.org/spectrum/whitespace/channel/*

Contact Verification Signal — The contact verification signal (CVS) is sent by a GDD-enabling STA to serve two purposes. First, the transmission of the CVS establishes which GDD-dependent STAs are within the reception range of a GDD-enabling STA. Second, the CVS helps the GDD-dependent STAs ensure operation under a valid white space map (WSM) and that it corresponds to the serving GDD enabling STA [9].

To validate operation under a correct WSM, the GDD-dependent STAs utilize the map ID field in the CVS frame. If the map ID value in the CVS frame is equal to its existing WSM, the GDD dependent STA assumes the operating WSM is valid and resets its enablement validation timer [9]. However, if the map ID is different from the existing WSM ID, the GDD-dependent STA transmits a Channel Availability Query request to obtain the valid WSM in the CAQ response. If the GDD-dependent STA does not obtain the valid WSM, it stops transmission after the enablement validation timer is expired [9].

GDD Enablement — The GDD Enablement procedure allows a GDD-enabling STA to form a network, satisfying regulation requirements under the control of a GDB [9]. A GDD-enabling beacon signal is transmitted on available channels in the TVWS band by a GDD-enabling STA to offer GDD enablement service. A GDD-dependent STA, upon receiving the GDD-enabling signal, can attempt enablement with the GDD Enablement Response frame. However, some regulatory domains require that, prior to enablement the GDD-enabling STA identifies with a GDB that the requesting GDD dependent STA is authorized to operate in the location-selected frequencies.

The GDD-dependent STAs have three GDD enablement states: *Unenabled*, *Attempting GDD Enablement*, and *GDD Enabled*. When in *unenabled* state, the GDD-dependent STA cannot transmit any frames; instead it passively scans channels for an enabling signal from a GDD-enabling STA to join their network. The GDD-dependent STA enters the *Attempting GDD Enablement* state when it receives a GDD-enabling signal that allows it to only transmit the GDD enabling response frame after GDB authentication, if required by regulation. The *GDD Enabled* state is reached when the GDD-dependent STA receives a successful GDD Enablement Response, which causes the GDD enablement validity timer to begin.

Once the GDD-dependent STA is enabled for operation, its state can be changed to **unenabled** by two main causes. First, when the GDD enablement validity timer is expired, considering the timer modifications performed by the WSM, CVS, and CAQ procedures. Second, a GDD-dependent STA is required to cease transmission if it receives from the GDD-enabling STA who enabled its operation an unexpected GDD enablement response frame with "Authorization Deenabled" [9].

Network Channel Control — Network channel control (NCC) is a two-message procedure that controls the frequency usage in the TVWS band. The NCC requesting STA petitions for usage of selected frequencies from its WSM by providing its spectrum mask. The NCC responding STA allows operation in the requested frequencies if available by providing the valid network channels and related transmit power constraints in an NCC response frame. The NCC procedure is commonly performed between the STAs, the GDD-dependent STA as the NCC requesting STA and the GDD enabling STA as the NCC responding STA. It is possible for the NCC responding STA to forward the NCC request to the RLSS, which constructs the NCC response frame and sends it via the NCC responding STA. An STA is allowed to perform a new NCC request whenever the WSM is changed.

White Space Map — The WSM is a list of identified available white space channels and corresponding power limitations provided by the GDB.

A GDD-enabling STA is required to obtain

Parameter	TVWS-fixed	TVWS	WLAN 2.4	WLAN 5
TX power (mW)	4000	40	40	40
Frequency (MHz)	192	518	2437	550
Bandwidth (MHz)	5.33	5.33	20	80
Minimum SNR (dB)	8	8	8	8
TX antenna gain (dBi)	0	0	0	0
RX antenna gain (dBi)	12	–3	0	0
Path loss exponent	4	4	4	4

Table 2. *Calculation parameters assuming free-space propagation.*

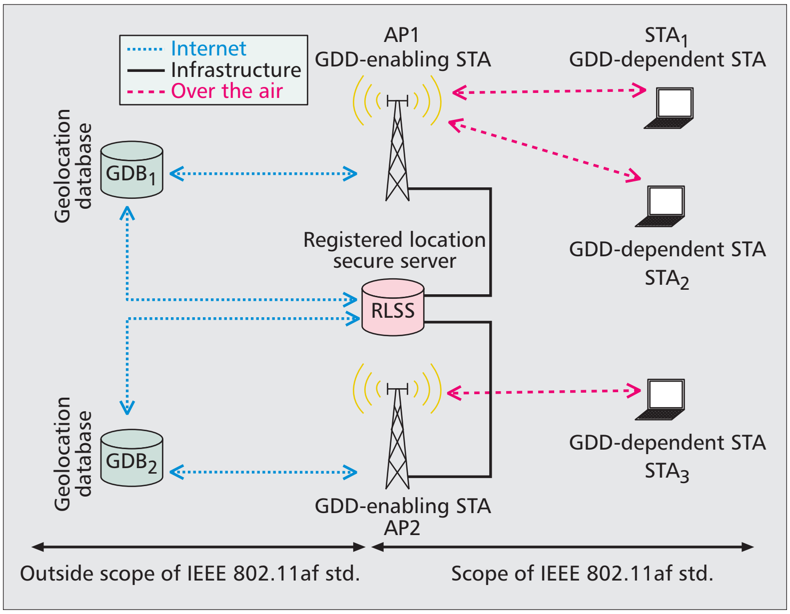

Figure 2. *Example TVWS network including all 802.11af architecture entities [9].*

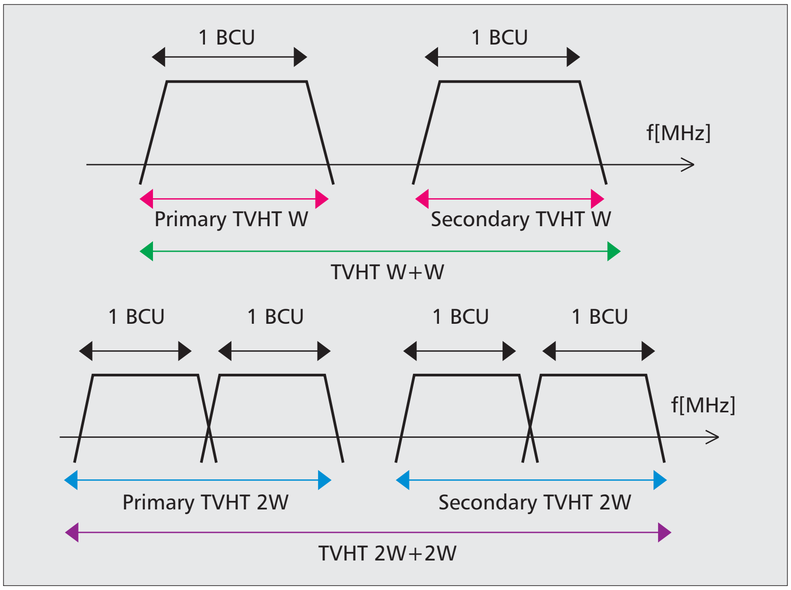

Figure 3. *TVHT PHY channel configurations: TVHT W, 2W, W+W, and 2W+2W*

the permitted frequencies and operating parameters before it begins transmissions. Based on the obtained GDB information, the GDD enabling STA generates the WSM to transmit to the GDD-dependent STAs under its operating region. The WSM is transmitted by the GDD enabling STA within the GDD Enablement response frame, CAQ response frame and WSM Announcement frame. The transmission power limitation in a WSM when the channel bandwidth consists of multiple white space channels is constrained by the minimum power level found on the multiple channels [9].

It is important to note that the GDD-dependent STAs can only transmit on the available channels assigned in their valid WSM. The WSM may be updated by the GDB as channel availability changes. Whenever a GDD-dependent STA receives an updated WSM from its GDD-enabling STA, it is obligated to move channels if operating in a channel marked as unavailable in the updated WSM [9].

A final important aspect of the WSM is that these are country-specific due to the difference in regulatory operations of GDBs across regulatory domains. The 802.11af standard provides a general format for the WSM element that can be applied to any regulatory domain. Inside the WSM element the field WSM information, which specifies the available channel information for the TVWS, adapts to the requirements of any regulation [9].

Physical Layer

In the IEEE 802.11af standard the TV high throughput (TVHT) physical layer (PHY) specification replaces the HT (20 MHz orthogonal frequency-division multiplex, OFDM) and VHT (20, 40, 80, 80+80, 160 MHz OFDM) PHY specifications in WSD devices when operating in TVWS bands. A TVHT device has support for single-channel bandwidths or basic channel unit (BCU) W of 6, 7, and 8 MHz depending on the regulatory domain, as shown in Fig. 3. Additional bonded or non-contiguous bandwidths of 2W, 4W, W+W, and 2W+2W are possible, as illustrated in Fig. 3. Only single-channel bandwidth W and a single spatial stream is mandatory, although multiple-input multiple-output (MIMO) transmissions with 4x space-time block coding (STBC) and 4x multi-user (MU) diversity are supported [9].

The TVHT transmission format is similar to that of a 40 MHz VHT transmission. It currently defines 144 OFDM subcarriers for 6 and 8 MHz channels and 168 for 7 MHz channels, so 6 and 7 MHz transmissions are spectrally identical. For all W, data is sent on subcarrier indices –58 to –2 and 2 to 58, with index 0 at DC and 6 pilot tones inserted at indices ±11, ±25, and ±53. In the case of multiple frequency segments (2W, W+W, etc.), this subcarrier assignment is duplicated [9].

Regulatory Framework

In this section we present the regulatory essentials for spectrum sharing adopted by IEEE 802.11af. We introduce the different control and monitoring operations used by the two main approaches to GDB implementation and how the 802.11af standard adapts to different regulatory time requirements.

Incumbent Protection

WSDs' spectrum access in the TVWS band is based on the regulatory requirement of non-interference to protected licensed devices. Incumbent users include both broadcast services such as digital terrestrial television (DTT) and PMSE users that include wireless microphones, among other services [1, 10]. To avoid interfering with protected devices, a WSD is required to be aware of the operating frequency and region of all protected devices. A WSD has limited capabilities and therefore obtains this information from a regulated GDB. This approach is adopted by most regulators because it guarantees reliable and precise information from a centralized, secure, and verified entity [1, 10].

A detailed interference analysis showing how regulations on device protection impact white space availability is presented by Webb in [10]. However, in this section we present the currently deployed regulations and how the 802.11af standard adapts to these.

Regulatory Implementation of the GDB

The two main methods of operating with the GDB are reflected in the operation constraints each approach enforces on their unlicensed white space users.

Open-Loop GDD

GDB Operation — The first approach is an open-loop GDD system, in which the database grants operation to unlicensed devices on a daily basis on channels indicated as available in that timeframe [3]. The main drawback to this approach is that interference is treated as a binary event. Instead, interference should be treated as a function of the devices and their emissions footprint.

Usage — An open-loop GDD system is implemented by the United States regulator, the Federal Communications Commission (FCC). Under this regulation, TVWS operation is allowed in 6 MHz channels within the frequencies 54–698 MHz in TV channels 2, 5, 6, 14–35, and 38–51 [3]. The WSDs follow an up to 48-hour schedule that provides the list of available channels in this time period, under which a static set of maximum transmit power rules are followed [3].

Under this regulation WSDs have a flexible operating region because these authenticate with the GDB once a day. However, fixed and conservative transmit power is required due to the large timescale of the feedback, leading to rigid or binary operation of channel availability.

Parameter Regulation — In the open-loop system, to ensure protection of incumbent users the maximum permitted transmission power is conservative, especially at neighboring channels. For portable WSDs, the FCC allows a maximum effective isotropic radiated power (EIRP) of 100 mW (20 dBm) per 6 MHz bandwidth on unoccupied channels. And only a maximum EIRP of 40 mW (16 dBm) for the first channel adjacent to any primary user. Fixed WSDs are limited to a maximum power delivered to the antenna of 1 W (30 dBm) and no greater than 4 W (36 dBm) EIRP from any attached antenna per each 6 MHz channel. These power regulations can be generalized as 12.6 dBm EIRP permitted per any 100 kHz [3].

The downside of such rigid power regulation is that 80 percent of the potential white space channels become unavailable, limiting white space implementation to rural areas and minimizing the development of spectrum-sharing technologies [11].

Closed-Loop GDD

GDB Operation — The second approach is a closed-loop GDD, in which frequent interaction between the GDB and the WSDs allows flexible operating parameters that apply to a specific device characteristics and location. In this method, the unlicensed user is under tight control by the database, a command-and-control system that is possible through constant feedback [1, 2].

Usage — A closed-loop GDD system is followed by the European (European Telecommunications Standards Institute, ETSI) and United Kingdom (Ofcom) regulators. WSDs' operation is permitted in 8 MHz channels within the frequencies 470–790 MHz [1, 2].

The WSD is required to perform a GDB discovery procedure in a time interval relevant to its operating location [2], commonly every two hours. Once an approved GDB is located, the WSD requests the *operational parameters* of its specific operating region, and in response provides the GDB with its *device parameters*. The operational parameters sent to the WSD have time validity and only apply to the specific reported location. Upon time expiration or 50 m movement from the last reported position, the WSD must request new operation parameters [2].

The operational parameters transmitted by a GDB contain the upper and lower DTT channel frequency, the maximum power spectral density per 100 kHz within allowed channels, and the time validity of such operation parameters and sensing levels for PMSE and DTT for future implementation of spectrum sensing [1]. The WSD sends to the GDB the intended *channel usage parameters*, which include the intended frequencies and the corresponding transmission power for each 100 kHz. These parameters are required to be acknowledged by the GDB before a WSD operates in the TVWS band [1].

Parameter Regulation — Unlike the static parameter regulation of the open-loop system, the closed-loop approach has granular parameter regulations that apply to a specific device and location. This allows WSDs to have flexible permitted transmission power dependent on location, frequency, and time. This translates into higher average transmission power when the WSD is at a greater distance from the incumbent user, and further apart in frequency to avoid adjacent channel interference.

The tight feedback and granular parameter specification allow the GDB to modify the WSD operation at any instant. A closed-loop system has the advantage of being able to enforce time-sensitive regulations. For example, the GDD enabling STA (AP) is required to stop transmission within 60 s when instructed by the GDB. Similarly, a GDD-dependent STA is required to stop transmissions within 1 s when requested by the GDD-enabling STA and within 5 s if communication is broken [1, 2].

802.11AF AND REGULATORY DOMAINS

Architecture Roles — The roles of the architecture entities presented earlier depend on the applied regulatory domain, and their security and timeline constraints [9]. In Table 3 we present the main differences these entities perform.

The WSDs or GDD-dependent STAs operate under different *transmit power limitations*. Under an open-loop system the WSD has fixed power limitations for in-channel and adjacent channel transmissions; however, under a closed-loop domain the WSDs have flexible power limits that depend on the operating frequency, location, and time. Next, the GDB licensing period in a closed-loop system is non-interactive and operates WSM on a timescale of one to two days [9]. However, in a closed-loop system the GDB is able to control the WSDs typically in a two-hour licensing period or by defining a specific WSM validation time; closed-loop licensing methods require the intended location and emission footprint of the WSD [9]. The RLSS in an open-loop domain only performs as an informative entity that forwards the WSM from the GDB to the GDD-enabling STAs. On the contrary, the RLSS in a closed-loop system performs authoritative commands where it can calculate WSM for the BSSs under its control. Finally, and most important, the tight control of a closed-loop domain allows the system to stop WSD transmis-

Under a regulation WSDs have a flexible operating region because these authenticate with the GDB once a day. However, fixed and conservative transmit power is required due to the large time scale of the feedback, leading to rigid or binary operation of channel availability.

Current regulation limits interference at the transmitter by imposing power constraints, guard bands and physical separation requirements. However, a receiver's design also strongly affects the interference impact of a given secondary transmitter.

	Open loop GDD system (FCC)	Closed loop GDD system (ETSI, Ofcom)
WSD Tx power limits	• 1 W for fixed devices Portable devices: • 100 mW per 6 MHz • 40 mW adjacent channel	***Flexible***, dependent on distance in *frequency* and *location* from incumbent
GDB licensing period	• Daily with a 48-hour schedule • Non-interactive	• WSM validity defined by GDB • Typically two-hour period • Demand and control • Tight feedback
RLSS role	• Informative • Forward WSM to WSDs	• Normative • Authoritative operation • Calculation of operating parameters
Time response to licensed service appearance	• Not defined	Stop transmissions: • AP WSD within 60 s • STA WSD within 1 s

Table 3. *Key operating distinctions between the open and closed loop systems.*

sions in a short time span due to the appearance of a licensed service.

Mechanisms — The use of the 802.11af mechanisms presented depends on the timescale requirements of the applied regulatory domain [9]. In Table 4 we present how these mechanisms are used to satisfy the different regulatory time requirements in a day, hour, and minute time span [9].

The CAQ is the procedure in which WSDs request the available radio frequencies for operation. This is an informative mechanism that applies to both daily and hourly consultation, used by open and closed-loop systems, respectively. Similarly, the CSM is an informative procedure in both daily (open-loop) and hourly (closed-loop) consultation that is used by WSD to obtain white space channel schedule information. In the same way, the NCC procedure controls the frequency usage in both daily and hourly consultation. None of these mechanisms are applied in a minute responsiveness for either open or closed-loop regulators.

Next, the CVS procedure is used to ensure WSD operation in available frequencies. The CVS usage in a daily consultation by open-loop regulators is required to be secure because WSMs are broadcast to all WSDs in a defined area. However, CVS is not required to be secure in an hourly consultation because the closed-loop regulators use a unique WSM per client or group of clients. The minute time span is used if a WSD misses consecutive signals from the GDD-enabling STA, and indicates that a change in channel frequency has occurred.

Finally, GDD enablement is used by GDD-dependent STAs to join a network, and therefore is required in a daily, hourly and minute time span, but used in the feedback time of the applied regulatory domain. Similarly, the WSM is required in all timescales by the GDD-enabling STAs to ensure that GDD-dependent STAs (under its control) satisfy regulations.

Possible Future Directions for Spectrum Sharing

A proposal for spectrum sharing has recently been published by the President's Council of Advisors on Science and Technology (PCAST) [12]. In this report, the authors highlight the potential for rapid economic stimulus and growth by making underutilized government-held spectrum available for secondary users via spectrum sharing. The PCAST presents spectrum as a road analogy, where they propose usage of spectrum like a "wide multi-lane superhighway, where lanes are continuously shared by many cars, trucks, and other vehicles" [12]. Essentially, different wireless services share spectrum and move across lanes, depending on their usage requirements. Meeting the vision of efficient spectrum sharing will require a number of additional innovations discussed in the report and solutions to the following open problems.

Minimum Receiver Performance Requirements

Interference in adjacent channels can be mitigated at the transmitter, the receiver, or both. Current regulation limits interference at the transmitter by imposing power constraints, guard bands, and physical separation requirements. However, a receiver's design also strongly affects the interference impact of a given secondary transmitter [12]. Current DTV receiver hardware costs have been reduced by using lower-quality digital filters, making them more sensitive to energy in neighboring bands. Secondary transmitters run the risk of saturating adjacent-band receiver analog-to-digital converters (ADCs) even in the case of perfect transmission filtering. For example, the U.S. nationwide Long Term Evolution (LTE) network planned by Light Squared was recently prevented from being deployed because GPS receivers are not designed to tolerate any adjacent-spectrum interference. There is no standard for characterizing

Mechanism	Daily consultation required (FCC)	Hourly consultation required (ETSI, OFCOM)	Minute responsiveness (NONE)
Channel availability query (CAQ)	Informative	Informative	Not applicable
Channel schedule management (CSM)	Informative	Informative	Not applicable
Network channel control (NCC)	Informative	Informative	Not applicable
Contact verification signal (CVS)	Required to be secure	May be secure	Loss of consecutive signals requires action
GDD enablement	Required	Required	Required
White space map (WSM)	Required for enabling STA, might be translated for dependent STA		

Table 4. *GDD mechanisms and applied timescales [9].*

Some of the largest unresolved issues with spectrum sharing depend on the space, time, frequency, and power granularity devices are granted spectrum access.

and specifying receiver behavior across spectrum sharing device classes, limiting spectrum allocation and making adjacent-channel interference a major cause of spectrum scarcity. This results in a severe reduction of the number of channels available and the allowable transmit power of secondary devices. Therefore, regulations to characterize and guarantee minimum receiver performance in the presence of interference are required to enable efficient utilization of the spectrum band.

Operational Feedback Granularity

Some of the largest unresolved issues with spectrum sharing depend on the space, time, frequency, and power granularity devices are granted spectrum access. The margin of protection for primary users will limit the spectrum availability for secondary users. Tighter sensing and reporting feedback loops could reduce those margins while maintaining protection. In addition, the mobility of the primary and secondary devices also influences these decisions. A 40 mW WSD that is mobile may be allowed to use the same channels as a 4 W fixed device under FCC regulations, but the transmit power restriction could be eased if it provided more timely geolocation updates.

While geolocation databases were initially proposed to solve the problem of hidden terminals in cognitive radio networks, it is expected that a centralized system could contain full knowledge of the location of all radio devices using the band and their characteristics. This allows several key networking issues to be resolved, such as congestion and frequency planning on large timescales, or even transmission scheduling over short timescales. A centralized controller can be used to assign services to appropriate frequency bands and adapt to their ever changing usage. For example, spectrum that is not available for high-power secondary use can be provided to low-power secondary radios to form short-range or low-rate networks [12].

The 802.11af standard does not directly address these issues, as they remain to be settled by regulatory authorities. However, the mechanisms presented in the standard are designed to be flexible and adapt to changing spectrum sharing approaches.

Conclusion

Spectrum sharing illustrates the potential of underutilized spectrum, enabling increased performance across a broad range of devices and services. We present the 802.11af standard, which permits white space devices to harmoniously share the TV white space band with incumbent services, such as TV broadcast and PMSE devices. Spectrum sharing in the TVWS band is achieved by the use of a geolocation database that contains full knowledge of licensed and unlicensed usage of the band. We discuss and compare the two approaches to implement the GDB: open and closed-loop systems. These approaches mainly differ in the timescale in which monitoring operations occur, which leads to large differences in white space availability and WSD operation. The IEEE 802.11af standard provides a common architecture, a communication scheme, and a control structure that allows standardization across both open and closed-loop approaches. Finally, we present how receiver tolerance to interference and the control feedback granularity influence the innovation and performance of spectrum sharing technologies.

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