First Cognitive Radio Networking Standard for Personal/Portable Devices in TV White Spaces

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Abstract— **Recent FCC rules allowing unlicensed use on a secondary basis of the Television White Spaces (TVWS) promise a whole new set of possible applications. The first step towards realizing these applications is the creation and adoption of industry standards. In this paper we present the first such standard for personal/portable devices in the TVWS that complies fully with the existing FCC rules while retaining flexibility for use with other regulatory domains. We describe the physical (PHY) and medium access control (MAC) layers specified in the standard and present performance results to demonstrate the robustness and spectral efficiency of the proposed protocols.**

Keywords- white spaces, cognitive radio, wireless standard

I. INTRODUCTION

It is well known that although all of the spectrum under 3 GHz is allocated, much of it is not used at any given place at any given time, as evidenced in the US by [3]. In a recent study, the economic potential for the TV white spaces was estimated at $100 billion [4]. The realization of underutilization of the spectrum, publication of Notice of Proposed RuleMaking (NPRM) by the Federal Communications Commission (FCC) in 2004 [5] and, subsequent activities by regulatory agencies worldwide, have spurred significant interest in the research and development of technological solutions for better utilization of the spectrum.

The next step in this evolution is the development of wireless communications standards. In this paper we discuss the first cognitive radio networking standard for personal/portable devices utilizing TV white spaces being developed by Ecma-International [1]. The IEEE 802.22 draft standard [11] addresses fixed-access devices and targets rural area applications. This work is ongoing. The Ecma standard discussed in this paper addresses fixed and portable devices and targets in-home, in-building and neighborhood-area applications. The first edition of this standard is nearing completion.

In this paper, we present a brief overview of the current status of policy discussions regarding spectrum management in regulatory agencies worldwide, and a detailed description of the Ecma standard for personal/portable devices, including the architecture, the design of the physical (PHY) and medium access control (MAC) layers, rationale for choices made in terms of use cases, and performance evaluation. We also present an overview of other activities in TV white spaces in the industry such as the White Space Database Group and CogNeA, and how they relate to each other.

A. *CogNeA and Ecma TC48-TG1 standard*

A group of companies came together about two years ago to develop a specification for white spaces. This group later came to be known as Cognitive Networking Alliance (CogNeA) [2], and issued its first public statement in the form of a press release in December 2008. The group started its work with the development of marketing and technical requirement documents, and later a draft/early specification which was subsequently transferred to the Technical Committee 48 – Task Group 1 (TC48-TG1) within Ecma-International for further development in March 2009.

The scope of the Ecma TC48-TG1 standard (referred to in this paper as Ecma white spaces standard, for short) is to develop a specification that comprises the PHY and MAC layers that can be utilized in the white space spectrum. The Ecma standard aims to serve a broad range of applications, including multi-media distribution and internet access. The first edition of the standard is scheduled to be released to the public by the end of 2009. The scope of CogNeA is the development of the ecosystem necessary for the promotion of the Ecma white spaces standard.

B. *Related work*

Besides CogNeA, some of the other activities in TV white spaces include IEEE 802.22, IEEE 802.19 and IEEE SCC 41, which are discussed in this section. The White Spaces Database Group is discussed in Section IIA.

1) IEEE 802.22

In November 2004, the IEEE 802 Standards Committee started their standardization activity for a Wireless Regional Area Network (WRAN) in the TVWS, known as IEEE 802.22 for fixed wireless data services in sparsely populated rural areas. It is the first standards Working Group (WG) to develop a communication standard for TV white spaces using cognitive radio technology. This standard includes cognitive capability functions such as spectrum management, sensing interface, and geo-location and database access in addition to PHY and MAC layer protocols.

The capacity of each WRAN CPE (Consumer Premises Equipment) is expected to be up to 1.5 Mbps in the downstream and 384 Kbps in the upstream. The IEEE 802.22 standard is designed to provide broadband wireless access services in a large area (typically 33 km radius) which has less than 255 terminals to be served per TV channel (assuming the oversubscription ratio of 40:1). The operating frequency range for the standard is 54~862 MHz but only frequencies below 698 MHz will be allowed by the FCC regulations in the US.

2) *IEEE 802.19 and IEEE SCC 41 standards*

The focus of IEEE 802.19 standard is the development of mechanisms for coexistence amongst potentially dissimilar networks that will operate in a common TV white space channel. The activities in this group may include development of mechanisms for the discovery of other networks. IEEE SCC 41 defines higher (than MAC and PHY) layer standards for dynamic spectrum access networks, and is thus complementary to the other standards.

The rest of the paper is organized as follows: Section II describes the system model and technical requirements of the Ecma specification, Section III presents an overview of the architecture and some key design objectives of the standard, Sections IV and V respectively describe the PHY and MAC layers in some detail while Section VI presents performance simulation results. Finally, conclusions are presented in Section VII.

II. SYSTEM MODEL AND REQUIREMENTS

In this section we will briefly review the worldwide regulatory scenario, describe some applications and use cases and present the technical requirements of the Ecma specification.

A. *Regulation*

The major worldwide regulatory agencies involved in developing rules for the unlicensed use of TV white spaces are the FCC in the US, Office of Communications (Ofcom) in the UK and the Electronic Communications Committee (ECC) of CEPT in Europe. In this section we will briefly review the current status of each of these agencies and briefly describe the activities on the key protection mechanisms of geolocation/databases and sensing.

On February 17, 2009, the FCC released the final rules for "Unlicensed Operation in the TV Broadcast Bands" [6]. This was the culmination of many years of deliberations on the subject, starting with the first NPRM in May 2004 [5] and followed by laboratory and field testing of sensing devices through 2007 [7] and 2008 [8]. The main features of the rules as set forth in this order are as follows:

- TV Band Devices (TVBDs) are divided into two categories: fixed and personal/portable. Fixed TVBDs operate from a known, fixed location and can use a transmit power of upto 4 W EIRP. They are required to have a geolocation capability, capability to retrieve list of available channels from an authorized database, and a spectrum sensing capability. TVBDs can only operate on channels that are not adjacent to an incumbent TV signal in any channel between 2 and 51 except channels 3, 4, and 37. Personal/portable devices are restricted to channels 21 – 51 (except Channel 37) and are allowed a maximum EIRP of 100 mW on non-adjacent channels and 40 mW on adjacent channels and are further divided into 2 types: Mode I and Mode II. Mode I devices do not need geolocation capability or access to a database but must have sensing capability. Mode II devices, like fixed devices, must have geolocation, database access and sensing.
- Sensing is a mandatory function that all TVBDs must implement. ATSC, NTSC and wireless microphone signals have to be detected at a level of -114 dBm. A channel must be sensed for 30 seconds before determining if it is available for use by a TVBD. If a wireless microphone is not detected during this time and the database indicates that there is no TV signal present, then the channel is available for use. In the event that the sensing indicates the presence of a TV signal, but the database indicates otherwise, the sensing result must be communicated to the user who has the option of removing this channel from the available channels list. Once operation has started on a channel, sensing must be done at least once every 60 seconds and if a wireless microphone is detected the channel must be vacated within 2 seconds.
- Geolocation means must be present in all fixed and Mode II devices, with an accuracy of +/- 50 meters. This position information is used to query a database for a list of available channels that can be used for TVBD operation. The database will include information on all TV signals and may also have information on wireless microphone usage.
- Safe harbor channels for wireless microphone usage are defined in the 13 major metropolitan markets to be the first available channel on either side of Channel 37. TVBDs cannot operate on these channels.

Meanwhile, Ofcom, the regulatory body in the UK has also made significant progress in developing regulations for the TV white spaces with a first consultation released on February 16, 2009, and a further statement in July 2009 [9]. The detailed rules have yet to be released but a first indication is that TVBDs will require either sensing or gelocation/database access unlike the FCC rules which required a combination of both protection mechanisms. The sensing levels being proposed for sensing-only devices are -120 dBm for digital TV and –126 dBm for wireless microphones.

The ECC has just begun working on cognitive radio in the TV bands within its newly created group SE 43 [10] which is tasked with defining the technical and operational requirements of operating in the TV white spaces with a first report on the subject due in May 2010.

1) *White Spaces Database Group*

For operation in the US, the FCC rules mandate that TVBDs access a database to obtain a list of available channels for their use. Such a database that includes information on all incumbent services, including digital and analog TV signals and wireless microphones does not exist yet. To this end, an industry group called the "White Spaces Database Group" was started to develop an architecture, protocols and security mechanisms for a database that would satisfy the FCC requirements. This work is ongoing.

2) *Sensing algorithms*

The topic of sensing has been central to the white spaces proceeding from the very beginning. The early work in this area focused on the simple energy detection methods and their limitations [18][19]. Most of the work in defining the requirements specific to the white spaces was done in IEEE 802.22 where a simulation methodology was developed to test various algorithms with captured signals [20]. In addition to the energy detector, feature detectors based on sensing the ATSC pilot, cyclostationarity and higher order statistics have been proposed and evaluated. Prototypes have also been tested in lab and field setting to verify that sensing at the levels required by the FCC rules is indeed possible with simple hardware [21].

B. *Applications and Use Cases*

Users will benefit from the newly available TVWS spectrum. The primary benefit of TVWS comes from the better propagation characteristics and therefore increased range and robustness, in comparison to higher frequencies. The ability to operate at lower power-levels for a given range would result in better energy efficiencies. Additional spectrum in the TVWS helps deal with overcrowding of ISM bands. In addition, ready availability of hardware components such as radio frequency tuners, makes these frequency bands especially appealing.

Example applications supported by this standard are:

(1) Robust delivery of high definition video inside home and across multiple walls.

(2) Robust coverage inside buildings and across campuses for wireless data applications such as wireless VoIP and mobile unified communications.

(3) Enhanced range for municipality, community and rural internet access without sufficient line of coverage.

(4) Enhanced coverage for smart service and remote machine-to-machine and RFID deployments such as smart grid, smart metering, transportation, industrial automation, supply chain automation, asset tracking and environmental monitoring.

(5) New interactive applications for TV broadcasters, such as weather and news updates, upcoming program previews, interactive advertisements and games and web access.

(6) Most importantly, TVWS can provide enhanced range, robustness and quality for emergency-response and public service communication networks.

C. *Technical Requirements*

The technical requirements for the design of PHY and MAC are driven by the need to support the above mentioned applications, and by the regulatory requirements. Since one of the challenging applications for this standard is robust in-home streaming of video, the parameters have to be chosen appropriately for the environment. In this section we will discuss some of these key requirements.

1) *Channel model*

There have been various measurement and analytic studies on the nature of propagation in UHF channels [11][13][14][15][16]. It is clear from these that in addition to path loss and losses due to wall absorption, multipath is an important feature of the indoor channel. The measured data indicates that the multipath RMS delay spread is between 50 to 100 nanoseconds. This would imply that the physical layer should be able to accommodate a maximum delay spread of about 1 microsecond. Since the actual delay spread can vary depending on the environment, the standard allows a range of cyclic prefixes from 1 to 2 microseconds. In order to simulate performance with multipath, an exponential fading Rayleigh multipath channel model was chosen in which the channel taps are independent complex Gaussian random variables with an average power profile that decays exponentially with delay.

2) *Data rate, range*

TABLE 1 shows the link margin values for the lowest and the highest data rate modes targeted by this standard. Assuming a transmit power of 20 dBm and a path loss exponent of 2, the link margin at a range of 1000 m for the 4.75 Mbps data rate mode is 6.09 dB (in support of enhanced range applications, such as II.B 3 to 6). The link margin at a range of 100 m for the 23.74 Mbps data rate mode is 9.74 dB (in support of applications II.B 1 and 2).

TABLE 1 LINK MARGIN

Parameter	Value	Value
Data Rate	4.75 Mbps	23.74 Mbps
Average transmit power	20 dBm	20 dBm
Total path loss (600 MHz)	88 dB (at 1000 m)	68 dB (at 100 m)
Received power/bit	-68 dBm	-48 dBm
Total noise power/bit (with 6 dB Noise Figure)	-101.20 dBm	-94.25 dBm
Required E_b/N_o (BER of 1.0e-6)	3.1 dB	12.52
Fading margin	10 dB	10 dB
Implementation & other losses	14 dB	14 dB
Link Margin	6.09 dB	9.74 dB

3) *QoS requirements*

This standard aims to support four categories of services: background, best effort, video, and voice. Among those applications, HDTV streaming poses the most significant design challenges. Specifically, the throughput on a per 6MHz channel basis must be sufficient to support a maximum high definition stream bit rate of 19.3 Mbps with sufficient excess bandwidth; and a nominal delay of 50 millisecond.

III. STANDARD OVERVIEW AND KEY DESIGN OBJECTIVES

The Ecma white spaces standard specifies the PHY and MAC layers for cognitive radio networking for personal/portable devices operating in TV white spaces. In this section we present an overview of network topology, device types and key design objectives for the standard.

This standard supports flexible network formation with three types of devices: master devices, slave devices, and peer devices. A network can be formed as master-slave or peer-to-peer, as illustrated in Figure 1, or as a mesh-network. In a master-slave network, a device is designated as master and others are associated with the master as slaves. The master coordinates Dynamic Frequency Selection (DFS), Transmit Power Control (TPC), and channel measurement on behalf of slave devices.

A peer-to-peer network comprises of peer devices. Peer devices coordinate DFS, TPC, and channel measurement in a distributed fashion. A peer device is able to directly communicate with any other peer device as long as it is within the range of the other peer device. In other words, a peer-to-peer network can be ad hoc, self-organizing, and self-healing.

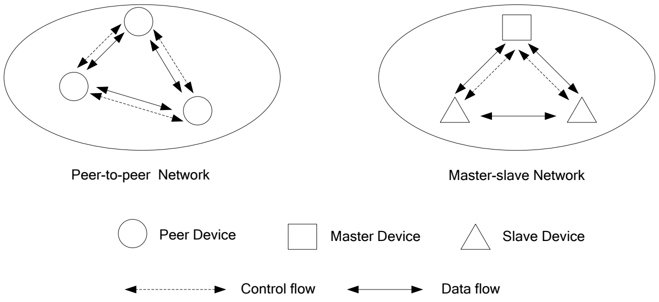


Figure 1 Basic Network Formation

The interoperability of the three device types is built-in due to the fact that all devices follow the same beaconing and channel access protocols. Two or more networks can share the same channel and are also able to communicate with each other. As a result, a number of networks may form a large-scale network such as a mesh-network or a cluster-tree network using a single channel or multiple channels. While not explicitly addressed by the standard, additional support from higher layers will allow multi-hop routing of messages from any device to any other device in the extended network.

A. *Adaption to worldwide regulatory requirements*

As discussed in Section II.A, regulations require the protection of incumbent users in order to operate in TV white spaces. These incumbent protection regulations may vary from one region to another. This standard takes a toolbox approach and specifies a number of incumbent protection mechanisms including DFS, TPC, and spectrum sensing, that may be adapted based on the regulatory requirements of a particular region. While geo-location/database access is treated as a higher layer function, and therefore out of the scope of this standard, the standard facilitates the use of information so obtained (e.g. available channel list) by the devices to protect incumbents.

As an example, for networks operating in the US under the FCC rules [6], a master device as defined in this standard will meet the requirements of the FCC defined Mode II device by including a geolocation (and sensing) function and periodically obtaining available channels list from an authorized spectrum database via the internet. All slave devices (with sensing function) associated with such a master device will comply with the requirements of an FCC defined Mode I device. A peer device without access to an authorized spectrum database can act as a FCC defined sensing-only device. In addition, a peer device that includes the geolocation (and sensing) function and periodically obtains the available channels list from an authorized spectrum database can act as an FCC defined Mode II device, also enabling other sensing capable devices as Mode I devices.

B. *Robust support for real-time traffic*

Protocol efficiency and QoS provisioning is another key design objective of this standard. To support one full HDTV stream over a TV channel, the effective throughput at the MAC Service Access Point (SAP) shall be at least 19.3 Mbps. Let us suppose that the maximum physical rate is 23.76 Mbps assuming the highest achievable spectral efficiency is 3.96 bit/s/Hz on a 6 MHz channel. As a result, the protocol overhead including PHY and MAC layer has to be about 19% or less. In addition to effective throughput, the delay jitter and packet loss rate have to be low for real-time video streaming. Besides supporting high effective throughput, the protocol is designed to remain very efficient even for longer range internet access applications.

Robust incumbent protection and strict QoS provisioning impose significant design challenges and shape the design choices. In the following sections, we describe some PHY and MAC design features and the rationale behind them.

IV. PHYSICAL LAYER DESIGN

The PHY design is based on a 128-fft orthogonal frequency division multiplexing (OFDM) structure. This size was chosen as the best compromise between overhead and complexity. In this section we briefly discuss the data frame structure, the OFDM parameters and some key differentiators.

A. *PPDU frame structure*

The PPDU frame format is shown in Figure 2. Each frame contains the PLCP preamble, the PLCP header, and the payload. The payload includes the PSDU, the tail bits, and the pad bits, if needed.

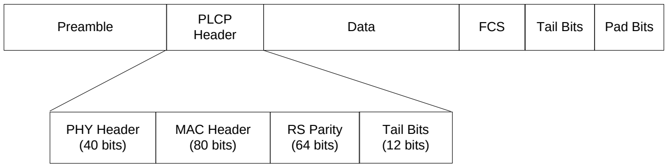


Figure 2 PPDU frame format

1) *PLCP preamble*

The PLCP preamble is used by the receiver for frequency and time synchronization and channel estimation. Two types of PLCP preambles are defined: normal PLCP preamble and burst PLCP preamble. The normal PLCP preamble is used for all the packets in normal mode and for the first packet in streaming mode, while the burst PLCP preamble is used for the second and the subsequent packets in the streaming mode. The format of the normal PLCP preamble is shown in Figure 3. The normal PLCP preamble is three symbols in duration and consists of a short preamble and a long preamble. The short preamble may be used for AGC tuning, coarse frequency offset estimation and timing synchronization. The long preamble may be used for channel and fine frequency offset estimation. The short preamble consists of nine repetitions of a short training sequence while the long preamble consists of two repetitions of a long training sequence.

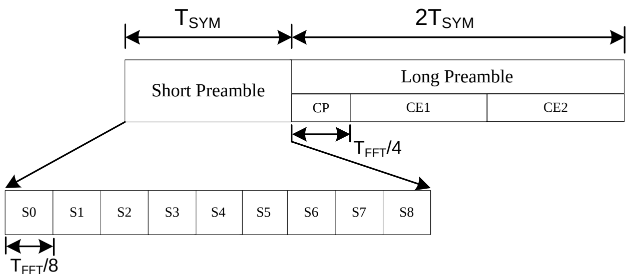


Figure 3 Normal PLCP preamble format

The format of the burst PLCP preamble is shown in Figure 4. The burst PLCP preamble is one symbol in duration and consists of two repetitions of a burst training sequence. The burst PLCP preamble may be used for channel and fine frequency offset estimation. The PLCP preamble is modulated using BPSK, and preceded by a cyclic prefix of length 1/8.

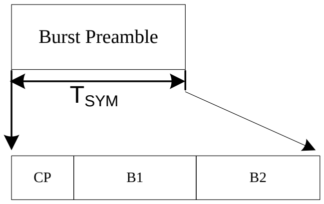


Figure 4 Burst PLCP preamble format

2) *PLCP header*

The PLCP header includes the PHY header, MAC header, tail bits and the parity bytes, as shown in Figure 2. The numbers in parenthesis represent the number of bits allocated for that field. The PHY header contains cyclic prefix mode (1/32, 1/16, or 1/8), transmission mode (normal or burst), data rate, multiple antenna mode, PSDU length (0 to 4095 bytes), scrambler initialization seed, interleaver parameters and relative transmit power. It also includes a number of reserved bits that may be used to define additional modes in future revisions. The reserved bits are set to 0. The MAC header consists of frame control, address, sequence control, and access control information. The MAC header field received from the MAC is incorporated into the PLCP header without any modifications. The PLCP header is Reed-Solomon (RS) encoded using a systematic (23, 15, 4) RS encoder, convolutionally encoded with a code rate of R=1/2, bit interleaved, and modulated using QPSK. The resultant 196 constellation points vector is then split into two OFDM symbols. The cyclic prefix of each header OFDM symbol is 1/8.

3) *Payload*

The payload field contains the PSDU, the tail bits, and the pad bits, if needed. The PSDU is scrambled using the pseudo-random binary sequence (PRBS). The scrambled bits are input to a FEC block, which includes a RS encoder, convolutional encoder, puncture, and pad bits inserter. If the total number of coded bits is not multiple of the number of coded bits in one OFDM symbol, the pad bits shall be added at the end of the encoded message. All encoded bits shall be interleaved by a block interleaver using two-step permutation. The output of bit interleaver is entered serially to the constellation mapper. The input data to the mapper is first divided into groups of the number of coded bits per subcarrier (2, 4 or 6) and then converted into complex numbers representing QPSK, 16-QAM or 64-QAM constellation points. The mapping is done according to Gray-coded constellation mapping. The complex valued number is scaled by a modulation dependent normalization factor to achieve constant average power.

B. *OFDM parameters*

TABLE 2 shows the OFDM parameters and corresponding values for each channel bandwidth. The system is based on a 128-point FFT. The subcarriers are classified as four types of subcarriers which are data, pilot, guard, and DC.

TABLE 2 OFDM PARAMETERS

TV channel bandwidth (MHz)	6	7	8
Total number of subcarriers, NFFT	128		
Number of guard subcarriers, NG (L,DC,R)	26 (13,1,12)		
Number of used subcarriers, NT=ND+NP	102		
Number of data subcarriers, ND	98		
Number of pilot subcarriers, N_P	4		
Sampling frequency (MHz)	48/7	8	64/7
FFT period, T_{FFT} (us)	18.667	16	14
Subcarrier spacing, ΔF (KHz)	53.571	62.5	71.429
Signal bandwidth (MHz)	5.518	6.438	7.357

In all OFDM symbol following the PLCP preamble, 98 subcarriers among 102 used subcarriers are used for data transmission. These data subcarriers carry the complex constellation points. A group of complex constellations are sequentially mapped to the IFFT inputs from -51 to 51, excluding the IFFT inputs for pilot and DC subcarriers. In all OFDM symbols following the PLCP preamble, four of the subcarriers are allocated for pilot signals in order to facilitate coherent detection and to provide robustness of the transmission system against frequency offsets and phase noise. These pilot signals shall be inserted in subcarriers for 13 OFDM symbols, as shown in TABLE 3. The pilot insertion pattern is repeated per every 13 OFDM symbols. The pilot signals shall be BPSK modulated by a pseudo random binary sequence to avoid the generation of line spectral frequencies.

TABLE 3 PILOT SUBCARRIER INDEX DURING 13 OFDM SYMBOLS

Symbol Index modulo 13	Subcarrier Index			
0	-51	-25	1	27
1	-39	-13	13	39
2	-31	-5	21	47
3	-45	-19	7	33
4	-35	-9	17	43
5	-27	-1	25	51
6	-49	-23	3	29
7	-41	-15	11	37
8	-33	-7	19	45
9	-47	-21	5	31
10	-29	-3	23	49
11	-37	-11	15	41
12	-43	-17	9	35

NOTE: The first OFDM symbol starts after the long preamble from 0.

Null subcarriers include the DC subcarrier and the guard subcarriers. No power is allocated to the null subcarriers. For each OFDM symbol, 25 subcarriers are allocated as guard subcarriers. These guard subcarriers are located on either edge of the OFDM symbol. The 13 and 12 subcarriers are used as left and right guard subcarriers, respectively.

C. Some features: RS coding, retransmission strategy, multiple antennae support

The standard draws heavily from well-known OFDM based standards such as 802.11a. However, some key differentiators have been included in order to improve performance, such as Reed Solomon (RS) coding, an improved retransmission scheme and multiple antenna support. In this section, we briefly describe these enhancements.

RS Coding: A (245, 255) RS code over GF(256) has been included in order to improve the packet error rate performance. The polynomial used is $p(x) = x^8 + x^4 + x^3 + x^2 + 1$. The same code is punctured and truncated to form a systematic (15, 23) code that is used to encode the PLCP header. Thus, a single RS decoder can be used to decode both the PLCP header and the data.

Retransmission strategy: In the IEEE 802.11 standard, a retransmitted packet is sent with the same interleaver as the original packet, but with a different scrambler seed, and generally receivers do not soft-combine the original and retransmitted packet. This gives a performance gain when it is assumed that the channel on the retransmission is uncorrelated from the original transmission channel. However, if the multipath channel does not change between the original and retransmitted packet, there is no performance gain in the packet error rate performance with retransmission since there is no diversity in the retransmission. However, there is an opportunity to exploit the existing frequency diversity in the channel by using a different interleaver on the retransmission, with optional soft-combining at the receiver of the original and retransmitted packets. The original interleaver used has 14 columns and 7 rows. Simulation results show that an interleaver with 7 columns and 14 rows performs equally well and when soft-combined with an original packet with an interleaver with 14 columns can give up to 7 dB of additional gain as shown in Figure 13. If the receiver does not choose to implement soft-combining, the performance is no worse than that obtained by retransmitting with the same interleaver but different scrambler. Hence, this feature allows differentiation at the receiver.

Multiple Antennae support: The use of multiple transmit antennae is optional. However, it is recognized that future enhancements that would require either additional range or higher data rate might benefit from the use of multiple transmit and/or receive antennae by implementing either Space Time Block Coding (STBC) for increased range or Spatial Multiplexing (SM) for higher throughput. Due to the antenna size at UHF, the number of transmit antennae is limited to 2. In order to avoid issues with backward compatibility in the future, the standard includes “hooks” that would allow devices in the future to implement multiple antennae options without sacrificing throughput due to increased preamble and header length. This is accomplished as follows:

(1) If a transmitter uses two transmit antennae, it transmits a defined short preamble sequence that is orthogonal to the one used when it transmits on only one antenna. All receivers shall be capable of detecting which short preamble was transmitted by correlation. Thus, receivers are capable of distinguishing a single antenna transmission from a dual antenna one without any additional signaling.

(2) When using two transmit antennae, a different long preamble is transmitted that is frequency interleaved over the two antennae, i.e. Antenna 1 transmits only over even frequencies and Antenna 2 over odd frequencies. Again, receivers shall be able to derive the channel estimated from such a preamble.

(3) A transmit diversity scheme called Frequency Interleaved Transmit Diversity (FITD) is defined where after coding, interleaving and modulation, the symbols are frequency interleaved over the two antennae as described above. Since receiving such a signal does not require additional complexity, unlike STBC, all receivers shall be able to receive such a signal. When a transmitter uses two antennae the PLCP header is always transmitted using FITD so that all receivers are capable of receiving it.

(4) Assigned bits in the PLCP header indicate what form of transmit diversity is being used by the transmitter for the data: FITD, STBC or SM.

The above mechanism allows the transmitter to use either a single or dual transmit antenna scheme without any additional overhead requirement on preambles and headers, while maintaining compatibility between devices that use single and dual antenna.

V. MAC LAYER DESIGN

The fundamental building blocks for MAC are beaconing protocols and channel access protocols.

Channel reservation access is necessary to achieve high protocol efficiency and strict QoS provisioning. Channel reservation access is also essential for establishment of well-protected Quiet Period (QP). Pure contention based protocol would not work due to low protocol efficiency, high delay jitter and hidden terminal problem, among others.

The periodical beaconing is the only reliable way to maintain channel reservation for data transfer and channel measurement. To be detailed later, the beaconing protocol supported by this standard is based on multi-device beaconing instead of the single-device beaconing method used in traditional MAC protocols. The single-device beaconing cannot effectively support channel reservation for QoS provisioning and the establishment of extended quiet zone for reliable sensing, especially in personal/portable environments. The biggest problem for single-device beaconing is the potential interference between adjacent networks. As illustrated in Figure 5, suppose AP 1 is the only beaconing device in network A and AP 2 is the only beaconing device in network B. AP 1 and AP 2 broadcast channel reservation and QP schedule through their beacons. Since client A is beyond the transmission range of AP 2 and the client C is beyond the transmission range of AP 1, client A and client C becomes hidden terminal to each other. As a result, the channel reservation and QP scheduled for client A and Client C will be disrupted. To overcome such a problem, this standard incorporates multi-device beaconing. Using the same example as above, by beaconing Client A and Client C devices exchange channel reservation information and QP schedule across network A and network B periodically. Therefore, collision on channel reservation and QP is minimized.

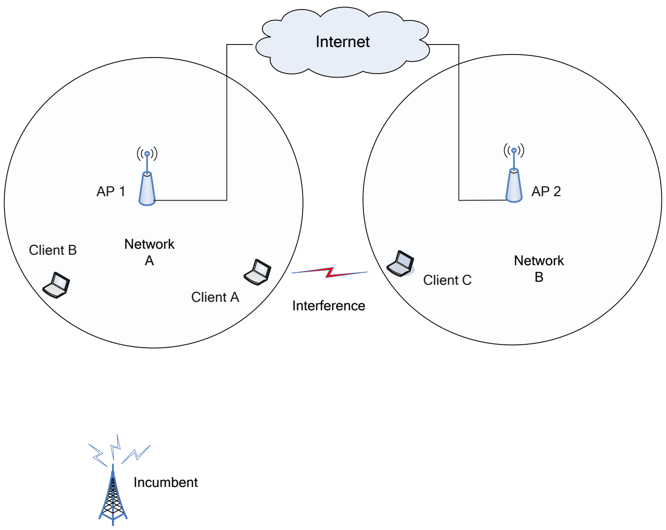


Figure 5 Potential interference between adjacent networks

The list of key MAC design features are summarized in TABLE 4. In the following subsections, we further explain some key design features.

TABLE 4 FEATURES TO SUPPORT KEY FUNCTIONALITIES

Functionality	**Features**
Network formation	Peer to peer, master-to-slave, mesh
Beaconing	Scalable multi-device beaconing
Channel access	High efficient reservation access with overlay support of prioritized contention access
Frame processing	Frame aggregation and burst transmission with block ACK
Spectrum sensing	Synchronized Quiet Period and Extended Quiet Zone
Self-coexistence	Full interoperability between different device types. Support channel reservation and QP schedule across neighboring networks.
Spectrum agility	Proactive channel selection, fast channel evacuation and connection re-establishment
TPC	Wide-range TPC based on link quality and incumbent status
Device discovery	Auto discovery
Power management	Traffic indication MAP, Hibernate and sleep modes

A. *Superframe structure and beaconing*

The basic timing structure for frame exchange is a superframe. The superframe is composed of 256 Medium Access Slots (MASs). A recurring superframe consists of a Beacon Period (BP), Data Transfer Period (DTP) and a Contention Signaling Window (CSW). A Reservation-based Signaling Window (RSW) could be appended right after the BP to support signaling between a master and slave devices in a master-slave network. RSW is not needed for a peer-to-peer network. The signaling windows and beacon period are used for sending and receiving critical information for management of network and channel.

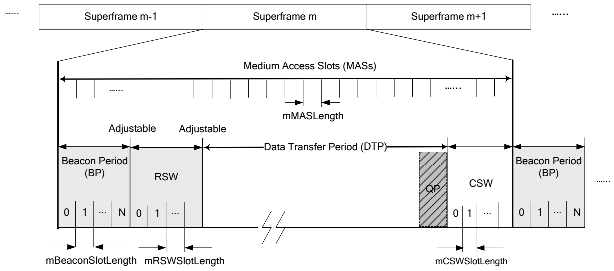


Figure 6 MAC Superframe structure

The BP length is adjustable and depends on how many regular beaconing devices participate in the same BP. A device is defined as a beaconing device if it owns a beacon slot in BP and regularly transmits beacons. A peer device or a master device is by default a beaconing device. A slave device is normally a non-beaconing device unless promoted to be a beaconing device. A non-beaconing device can be promoted to beaconing device to facilitate self-coexistence across neighboring networks, as discussed earlier. A beaconing protocol is specified in this standard to resolve collision among beaconing devices and keep them synchronized. Each device protects its own BP and its neighbours' BPs. Multiple beacon periods, one from each neighbor network, merge into one BP to enable efficient sharing of radio resources and establishment of extended quiet zone across neighboring networks.

A beacon packet contains important information for network operation including device identification, beacon slot occupation, medium reservation, TIM (Traffic Indication Map), quiet period (QP) schedule, and channel management. Periodical transmission of network and channel management information by using multi-device beaconing scheme described above enables easy device discovery, slot reservation, channel measurement and evacuation. Moreover, since the beaconing status of a slave device can be changed on demand, the beaconing overhead can be tailored.

B. *Channel access*

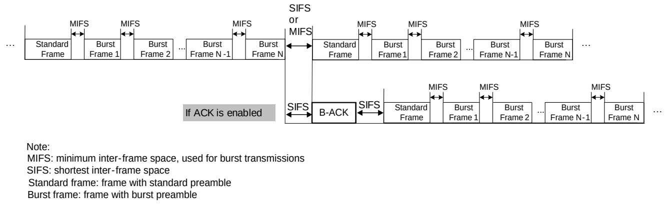
This standard supports both Channel Reservation Access (CRA) and Prioritized Contention Access (PCA) during DTP.

To guarantee Quality of Service (QoS), Ecma white spaces standard supports various channel reservation types as summarized in TABLE 5. Basically, each connection is established using reservation based time slot (i.e., Medium Access Slot : MAS) negotiation. A device may reserve MASs via explicit negotiation or implicit negotiation, by including Channel Reservation Protocol (CRP) IE via beacon or control message, respectively. The reservation status of MASs is exchanged among devices via beacons regularly whereby reservation collision can be avoided, or discovered and resolved.

TABLE 5 RESERVATION TYPES

Reservation Type	Description
Alien BP	Prevents transmission during MASs occupied by an alien BP.
Hard	Provides exclusive access to the medium for the reservation owner and target; unused time should be released for PCA
Soft	Permits PCA, but the reservation owner has preferential access.
Private	Provides exclusive access to the medium for the reservation owner and target. Channel access methods and frame exchange sequences are out of scope of this specification; unused time should be released for PCA.
PCA	Reserves time for PCA. No device has preferential access.

A device with reservation of consecutive MASs may make the best of burst transmission and block-acknowledgement (B-ACK) to improve channel efficiency, as illustrated in Figure 7.



Note:
MIFS: minimum inter-frame space, used for burst transmissions
SIFS: shortest inter-frame space
Standard frame: frame with standard preamble
Burst frame: frame with burst preamble

Figure 7 An illustration of burst transmission

All unreserved MASs in the DTP may be used for PCA. The PCA mechanism provides differentiated, distributed contention access to the medium for four Access Categories (ACs) of frames, from low priority to high, background (BC), best effort (BE), video (VO) and voice (VI), as summarized in TABLE 6. A device employs a prioritized contention procedure for each AC to obtain a Transmission Opportunity (TXOP) for the frames belonging to that AC using the PCA parameters associated with that AC. PCA parameters include Arbitration Interframe Space (AIFS), Contention Window (CW), and TXOP limit. To assist a device operating in the power-saving mode to transmit and receive PCA traffic, this standard defines Traffic Indication Map (TIM) IE and PCA Availability IE. A device may use TIM IE to indicate target receivers that the device has data buffered for transmission via PCA. On the other hand, the PCA Availability IE identifies the MASs in which a device will be available to receive PCA traffic and transmit the required response.

TABLE 6 USER PRIORITY TO ACCESS CATEGORY MAPPINGS

Priority	User Priority	802.1D Designation	AC	Designation (Informative)
Lowest	1	BK	AC_BK	Background
	2	-	AC_BK	Background
	0	BE	AC_BE	Best effort
	3	EE	AC_BE	Best effort
↓	4	CL	AC_VI	Video
	5	VI	AC_VI	Video
	6	VO	AC_VO	Voice
Highest	7	NC	AC_VO	Voice

In contrast to contention-based channel access, channel-reservation-based access allows a stream to maintain steady data bandwidth resource, as well as, ensure low packet delay jitter. Moreover, it improves spectrum efficiency, since it avoids the overhead of collisions in contention-based access.

C. *Incumbent protection and frequency agility*

This standard provides the following incumbent protection and recovery mechanisms: a) reliable channel measurement; b) effective transmit power control; and c) fast channel evacuation and connection re-establishment.

1) *Reliable channel measurement*

Sensing is required by the FCC for every unlicensed TV band device. A key challenge of sensing is the requirement to detect incumbents reliably under very low signal level, e.g. -114 dBm. That makes sensing highly susceptible to interference from other unlicensed TVBDs [22]. To prevent such interference, a key idea is to set up synchronized and extended quiet zone such that all unlicensed devices can remain quiet while some of them perform sensing. This standard allows the establishment of the extended quiet zone using over-the-air multi-device beaconing, network synchronization, and reservation based channel access.

Both regular QP schedule and on-demand QP schedule are supported in this standard. Regular QP is mandatory and scheduled for predetermined duration right before CSW once every predetermined number of superframes. Each device synchronizes its regular QP with its neighbors and broadcasts the regular QP schedule in its beacon periodically. Since the QP schedule is fixed and broadcasted periodically, every device including newly joined devices can quickly converge to the same regular QP schedule. Regular QP schedule helps in the establishment of extended quiet zones. As illustrated in Figure 8, Client A and Client C will now avoid hidden terminal problem illustrated in Figure 5 by regular broadcast of QP schedule through beaconing.

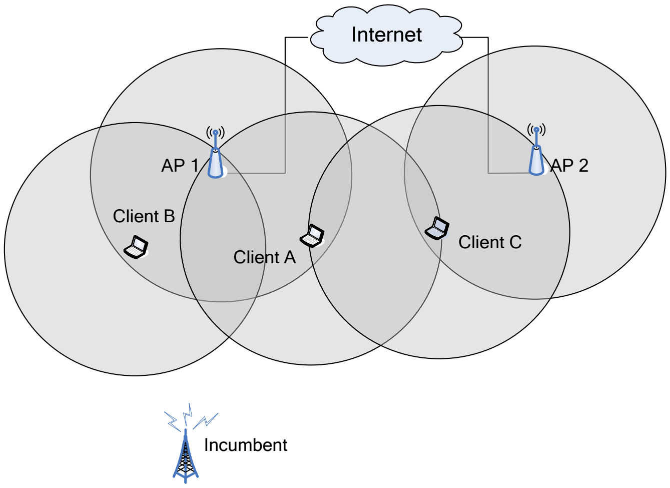


Figure 8 Extended quiet zone

On-demand QP schedule provides additional flexibility and intelligence for a device to have early detection of incumbents. For example, while waiting for next regular QP, a device can trigger on-demand QP schedule once an abnormal channel activity is detected. A device may use some of its reserved MASs for on-demand QP purpose thus saving the time and overhead to set up on-demand QP.

2) *Fast transmit power control*

Traditionally, TPC is used to maintain quality of a link with the right level of transmit power. As a result, transmit power is finely tuned for smooth operation. Moreover, traditional TPC is mainly based on receiver's link feedback such as the signal-to-noise-ratio, received signal strength, frame error ratio or other parameters.

In TV white spaces, TPC needs to take incumbent protection into account. For example, the operating channel status could change from non-adjacent to adjacent suddenly. As a result, the transmission power limit shall be reduced from 100mW down to 40mW. In addition, TPC in such case is based on incumbent detection rather than receiver link quality. In a master-slave network, where a slave device may not be able to determine channel status, a master controls the transmission power limit for each slave device.

This standard supports both fine TPC and fast TPC based on link quality feedback and incumbent status.

3) *Fast channel evacuation and connection re-establishment*

One challenge for operation in TV white spaces is to maintain smooth operation during and after incumbent detection. Upon discovery of an incumbent, a device shall suspend data communication and transmit only management messages up to certain time, e.g., 200 milliseconds as per the FCC rules, before evacuating the channel within a very limited time, e.g., 2 seconds.

The time for a group of devices to resume transmission in a new channel can be broken down into two parts: a) channel scan; and b) device re-associate and re-establish channel reservation. Each part may take significant time due to either regulation requirements or network initialization procedures. For instance, a TV band unlicensed device is allowed to start operating on a new TV channel if no incumbent signals above the specified threshold are detected for a minimum time interval of 30 seconds. In other words, to identify the channel availability it may take at least 30 seconds if starting de novo. For the second part, device association (including device discovery) and re-establishment of channel reservations could take seconds to minutes if devices are not coordinated in selecting the new operating channel and network re-entry.

To save time to identify a new channel for operation, this standard proactively maintains at least one backup channel. A backup channel will be checked regularly to make sure it is available and ready for use as soon as needed. To reduce time for the second part, this standard supports copy of network settings such as beaconing status, channel reservation and security establishment from the old channel to the new channel. Therefore, devices do not have to go through every step to joining beacon group, performing authentication, and establishing channel reservation again in the new channel. Certain conditions for using channel copy operation may apply. For example, the new channel is not being used by other networks in order to copy the same channel reservations from the old channel to the new channel.

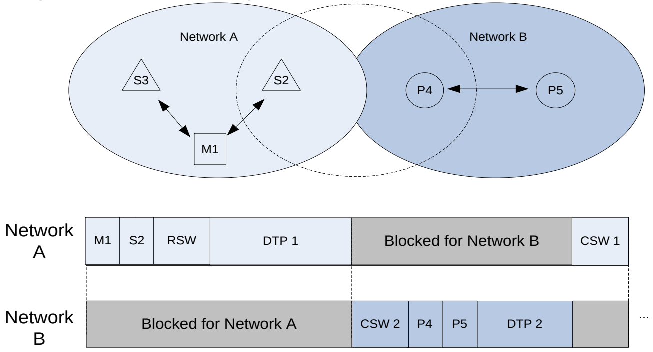
In a master-slave network, the master coordinates channel evacuation. While in a peer-to-peer network, any peer device may initiate channel evacuation with the new channel setup parameters pre-agreed.

In case that the incumbent signal is too strong to allow devices to exchange beacon/control message for evacuation, the device shall move to the pre-agreed backup channel after a specified time-out period.

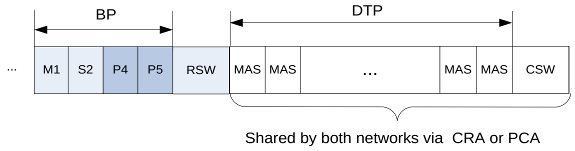
D. *Inter-network coexistence*

Two networks may be closely located or come into range due to mobility. A device discovers an alien network by detecting alien beacons. The alien beacon period shall be protected once detected. If the master device or peer device detects an alien BP, the master device or peer device can initiate the BP merge process to allow the two BPs to merge into one BP and share the same superframe. If a slave device detects an alien BP it may first promote itself as the regular beaconing device to facilitate closer inter-network coordination. The slave device now beaconing regularly can help its network and neighbor network merge into one superframe and fully share the channel resources.

The advantage of merging superframe as compared to non-merging is described as follows. As illustrated in the Case 1 of Figure 9, two neighboring networks, network A and network B, may alternate the use of a channel for certain duration (static contiguous time block). Although this approach is straightforward, QoS provisioning will be a major issue, especially for delay-sensitive applications. For example, the packet delay jitter will increase significantly since no transmission is allowed during the periods blocked for the other network. Moreover, pseudo-static access-time allocation is inefficient in terms of channel sharing between the neighboring networks. Now if network A and network B merge into one superframe as shown in case 2 of Figure 9, the two neighboring networks can fully share the entire DTP on demand, thus improving channel efficiency and reducing delay jitter. The CSWs and QPs of the two networks can be also merged, further reducing overhead.



Case 1: Non-merged Superframe



Case 2: Merged Superframe

Figure 9 Beaconing promotion and superframe merge

Note that two neighboring networks can continue to operate as independent networks for channel management and security management. One network can freely move to another channel without disrupting the operation of the other network. Network association and device authentication are also controlled within each network.

VI. PERFORMANCE EVALUATION

A. *PHY performance*

The standard defines 10 possible data rates with different combinations of coding-rate and modulation. The performance of these modes is shown in both AWGN (Figure 10) and Rayleigh fading multipath channel with an rms delay spread of 100 ns (Figure 11). These simulations are with 8 RS codewords per packet (1960 data bytes) and no other impairments are considered besides multipath.

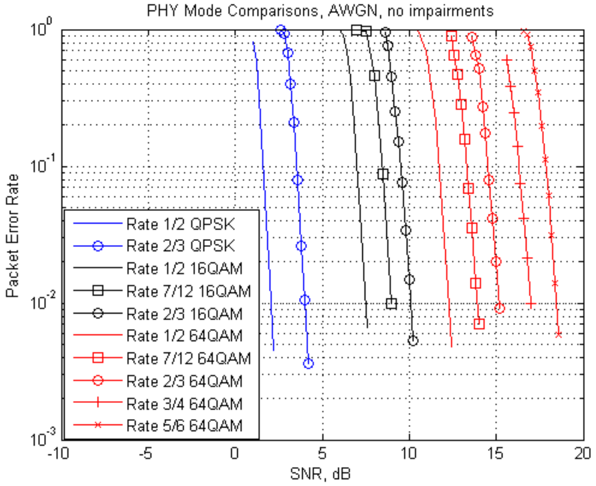


Figure 10 PER in AWGN channel

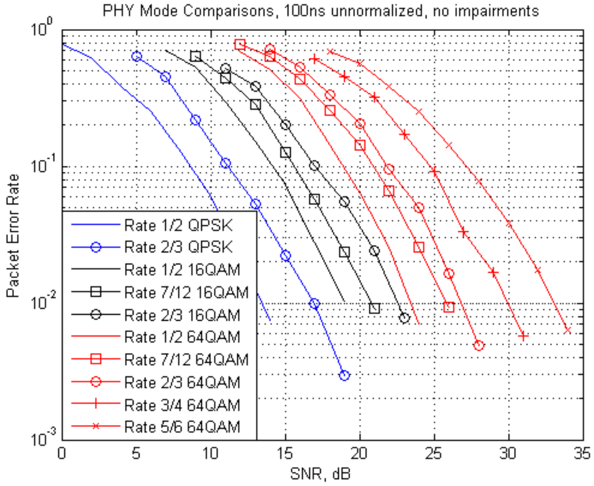


Figure 11 PER in 100ns Rayleigh fading multipath channel

The impact of packet size on PER is minor. Figure 12 shows the PER in 100ns Rayleigh fading multipath channel for different packet lengths. Similar performance is observed in AWGN channel as well. These results support the use of packet aggregation.

The performance of retransmission strategy (discussed in IV.C) is presented here. Retransmission I in Figure 13 refers to using a different interleaver for retransmission, whereas Retransmission II in the same figure refers to the case when a retransmitted packet is sent with the same interleaver as the original packet, but with a different scrambler seed.

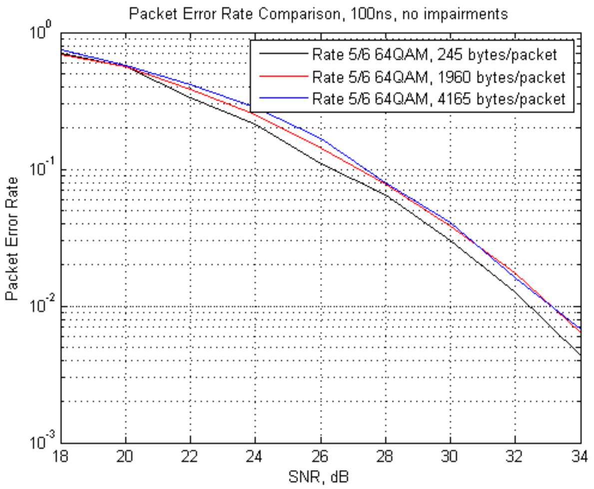


Figure 12 PER at various packet length

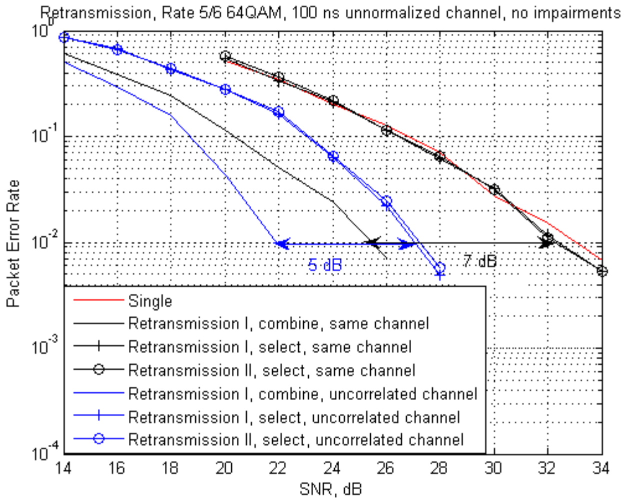


Figure 13 Retransmission strategy

B. *MAC Layer performance*

The effective throughput measured at MAC SAP is shown in Figure 14 and demonstrates the protocol efficiency of the standard. The system parameters used in the simulation are shown in TABLE 7. The effective throughput can reach 20 Mbps with the help of packet aggregation and burst transmission in reservation access mode.

TABLE 7 SYSTEM PARAMETERS FOR THROUGHPUT SIMULATION

Parameter	**Value**
Superframe Length	128 ms
MAS Length	500 µs
BP length	3 ms
Beacon Slot Length	1 ms
CSW size	1 ms
QP frequency	4 or 8 superframes
QP Duration	5ms
Aggregation header size	1 + 2xN (bytes), N is the number of aggregated MSDUs
Standard Preamble	63 µs
Burst Preamble	21 µs
MIFS	2 µs
SIFS	10 µs
PLCP header	196 bits
MCS for PLCP header	QPSK ½
MCS for data	64-QAM - 5/6
Transmission distance	30 meters
Channel model	100ns Rayleigh fading multipath channel
Link Budget	Shown in TABLE 1

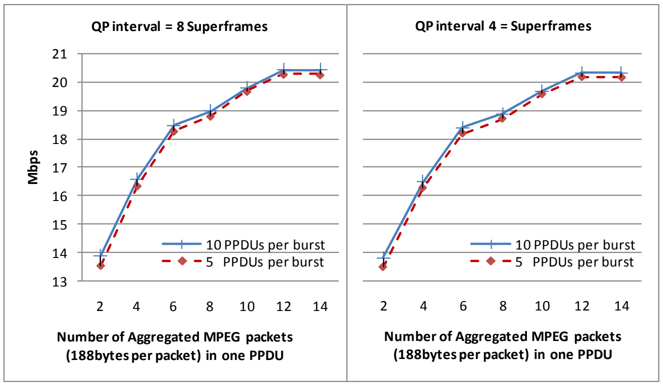


Figure 14 Effective MAC throughput

Figure 15 shows the reliability and speed of recovery from incumbent detection. From detecting incumbents in an old frequency channel to full recovery of HDTV streaming in a new frequency channel, it takes less than half second. With half- second or more video buffer at receiver, user will not experience image disruption or glitch in the channel switch transition.

VII. CONCLUSION

In this paper, we have described the significant features of the PHY and MAC layers for the first standard for cognitive networks for personal/portable devices in the white spaces being developed in Ecma TC48-TG1. The standard is flexible and can accommodate different bandwidths, network topologies as well as different incumbent protection strategies. Future enhancements such as multiple antenna options have been included in a manner that does not increase overhead. Simulation results demonstrate that the PHY/MAC choices result in a system that has very low overhead and has sufficient throughput to sustain HD transmission over a single 6 MHz channel. Thus, this standard will lead to a wide set of applications in the TV white spaces.

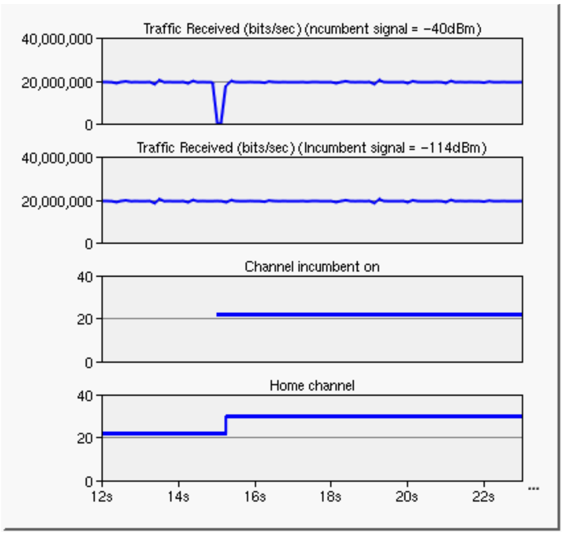


Figure 15 Impact of channel evacuation on throughput

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