

Research Article

Enabling Technologies for a Practical Wireless Communication System Operating in TV White Space

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This paper proposes the design of enabling technologies for practical wireless communication systems operating in the TV white space (TVWS). The main objective of this paper is to cover a macro perspective on the system design blocks including: (a) targeted use case applications and governing regulations, (b) channelization, physical (PHY) layer and medium access control (MAC) layer designs, and (c) achievable throughput and range. It is the intention of this paper to serve as a general guideline for designing wireless communication systems operating in TVWS. The core system design addresses both PHY and MAC layer issues with realistic system considerations. In the PHY layer, a channelization design that fits into the area-specific TV channels and a transceiver that enables data exchange in the TV bands are designed. In the MAC layer, a cognitive engine that manages access to vacant TV channels and MAC functionalities that facilitate effective medium access are also proposed. As a result, the system is capable of supporting up to a typical throughput of 80 Mbps, and a maximum number of 40 users, assuming all users performing the most bandwidth-hungry application in the use case scenario. The corresponding operating range is found reach up to 400 m.

1. Introduction

The recent regulatory development [1–3] has opened up new opportunities for unlicensed wireless communication systems to utilize unoccupied TV channels (a.k.a TV White Space or TVWS) in the very high frequency (VHF) and ultra-high-frequency (UHF) bands. TVWS is defined as the TV bands that can be occupied by secondary (often unlicensed) wireless systems with the condition that the related regulatory and technical requirements are met. The opening of TVWS has catalyzed more innovative and diversified wireless applications, and has invited overwhelming responses from the industrial community. Among others is the mobilization in international standardization initiatives [4–7].

It is, therefore, a timely window to provide to the technical community the enabling wireless technology for operation in the TVWS. The two core factors that drive the direction of the technology are: (a) potential application use cases that define and verify the necessity, and (b) governing regulations that dictate the “do’s and do not’s.” The enabling

technology shall consist of a system design capable of delivering the characteristics and performance as required by the targeted application use cases, and at the same time, capable of complying to the rules set by the regulations. For the design of TVWS enabling technology, it is of no exception. In order to validate its existence, the system has to possess a “killer-application”. And in order to harvest and utilize the new spectrum resources, the system has to possess the appropriate enabling functionalities to operate in the vacant TV channels within the boundaries set by local primary-user protection regulations.

For this purpose, in this paper, we have proposed a full system design taking into consideration all three elements: the potential application use cases, the governing regulations, and the corresponding cross-layer system design. Firstly, the use cases highlight the prospective applications that outline several requirements in communication speed and range. Secondly, the governing regulations set conditions and boundaries that fractionally limits the liberty of the system to access the TVWS. Thirdly, our system design is

specified to meet the use case requirements and to be able to comply to the regulations. The proposed cross-layer design is further divided into channelization design, physical (PHY) layer design, and cognitive medium access control (MAC) layer design. It should be emphasized that before detailed investigations and optimizations are conducted in each of these elements, it is essentially important to have the overall assessment that proves the feasibility of the technology in delivering the mandated task and to provide a high-level guidance in respective lower-level system design. To the best knowledge of the authors, such works are nonexistent in the current literature.

The contribution of this paper is threefold: (a) it verified that wireless technology operating in the TVWS does offer encouraging opportunities, (b) providing an overall cross-layer MAC and PHY cognitive system design that considers practical applications and regulations, and (c) providing realistic performance evaluation (e.g., throughput, coverage, etc.) in response to related requirements. It is our strong belief that this paper is of interest to both the academic and industrial community. The detailed design philosophy and step-by-step design procedure are given in Section 2. The combined discussion on how the requirements, design considerations, and system performance are related to each other is given in Section 6.

2. General Design Philosophy

This section gives an overview on the design philosophy and design flow of the TVWS enabling technology, as illustrated by Figure 1. The starting point of the TVWS often lies in the regulations and the use cases. In the case of TVWS, the development of regulations creates opportunities and requirements for the corresponding wireless technology. The opportunities have motivated the extended use cases of the technology, while the requirements affect the design of the system. Together, the regulations and the use case become the input factors that influence the system design. Sections 3 and 4 address these arenas.

In this paper, the system design consists of the channelization, the PHY layer, and the MAC layer design. The channelization design takes into consideration the specific TV channels allowed by different regulatory domains. In other words, the channelization engine has to be capable of supporting all the operable TV channels. In this work, a dual phase-locked loop (PLL) design is employed to produce both center frequencies and channel spacing. Section 5.1 provides a generic design with specific numerical examples.

The PHY layer intakes the output of the channelization design as input design parameters. The PHY design considers the transceiver design, the TV channel model, and the operating range. Among others, the operating range has to support the practical scenarios in the use cases. The output parameters of the PHY design such as error performance and PHY layer data rate will be sent to the MAC layer. Section 5.2 presents the practical PHY layer design for the communication system operating in the TVWS.

The MAC layer consists of the cognitive management engine and other MAC enabling protocols. The cognitive

management engine deals with the occupancy of TVWS taking into consideration the required regulations. Section 5.3 describes the cognitive engine design. Besides the TVWS occupancy management engine, other MAC protocols are also essential to enable communication control and data communication. The output parameters of the MAC design such as the system throughput are crucial and will be the core reference to support the targeted use cases. Section 5.4 provides the MAC layer design with practical numerical values.

In a nutshell, this paper provides a practical cross-layer design for a practical communication system operating in the TVWS based on realistic numerical values in the real-world industrial design.

3. Use Cases

The typical use case of communication in TVWS is often associated with wireless coverage of wide areas (e.g., suburban and rural areas) where installation of facilities can be costly. In this perspective, the TVWS communication is especially a suitable candidate given its long reaching and high penetrating VHF/UHF signal characteristics. Figure 2 illustrates the typical scenario of a wide area high-speed backbone connectivity fed by respective local subnetworks. Sites A, B, and C are far-apart locations each with high-power devices (HPD) antenna towers linked via TVWS connection, while the low-power devices (LPD) may be portable/mobile devices linked to HPDs via TVWS connection. The clear definitions of HPD and LPD are outlined in accordance to regulations. This general illustration can be applied to, but not limited to the following.

- (i) *Campus.* HPD—rooftop antenna of buildings.
LPD—computers and mobile devices.
- (ii) *Industrial Site.* HPD—antenna in control center.
LPD—machineries and automation.
- (iii) *Municipality.* HPD—municipal building antenna.
LPD—employee workstations.
- (iv) *Enterprise.* HPD—enterprise building antenna.
LPD—employee workstations.
- (v) *Utility Network.* HPD—antenna of utility provider.
LPD—data collectors and wireless meters.

The above use case scenarios have been constantly addressed in various initiatives [8–11] calling for enablement of communication in the TVWS. It is, therefore, a practical “killer-application” based on popular demand.

In these typical scenarios, the parameter requirements are given in Table 1. For backbone connectivity between HPDs in different locations (e.g., building rooftops) several hundreds of meters apart, the required throughput is typically 50 to 80 Mbps. These HPD will then be connected to LPDs (e.g., access points) that distributes the bandwidth to respective end users. Depending on the applications, each end user may require throughput of 100 kbps to 2 Mbps. For the 100 kbps requirement, hundreds of end users can be supported. As for the 2 Mbps requirement, tens of end users can be supported.

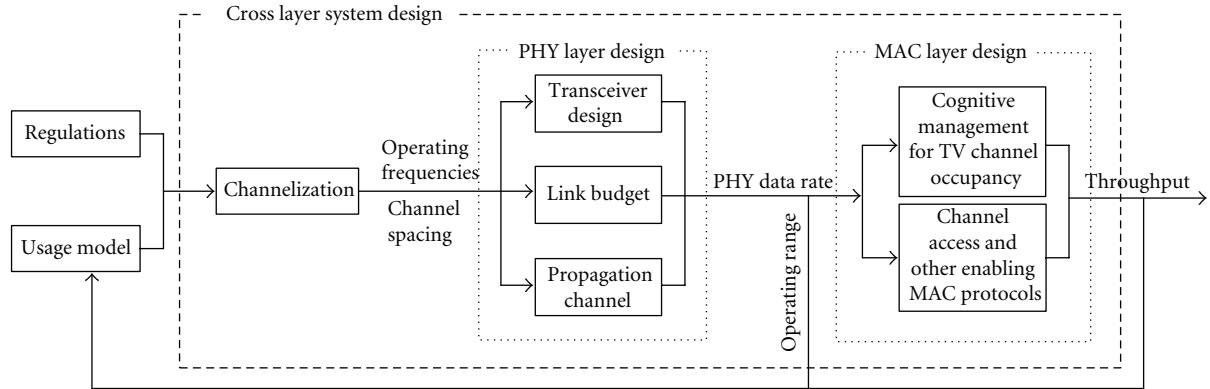


FIGURE 1: Cross-layer design philosophy and basic flow.

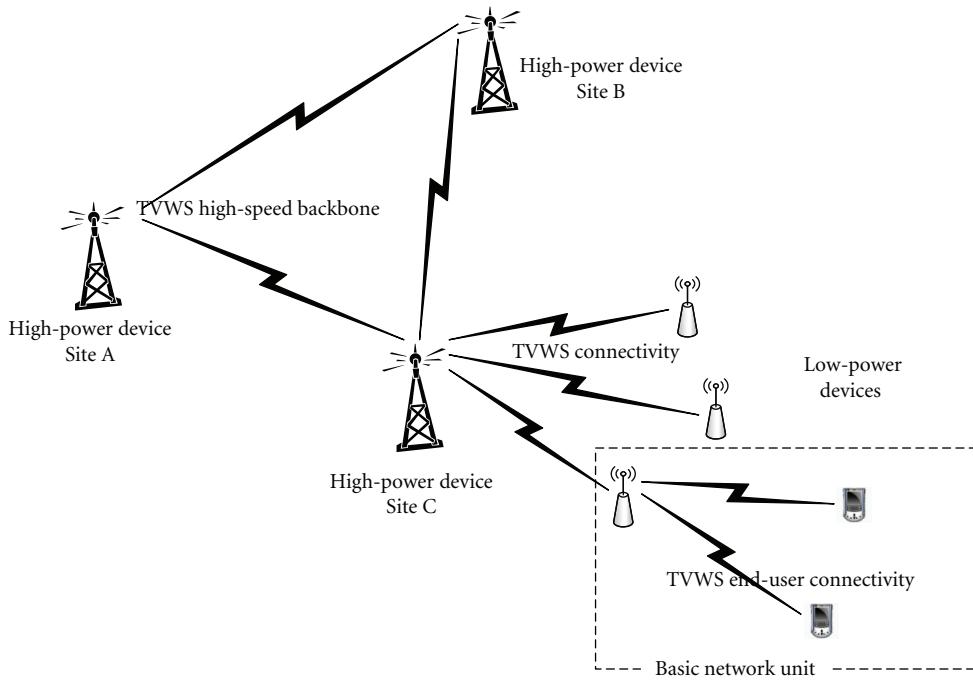


FIGURE 2: Typical use case example for TVWS communications.

TABLE 1: Parameters Requirement for TVWS Use Cases.

Parameter	Requirement		
Environment	LOS and NLOS		
Data rate class	Low rate	Medium rate	High rate
Data rate	Up to 100 kbps	Up to 2 Mbps	Minimum 60 Mbps
Average range	Several tens of meters	Several hundreds of meters	Several hundreds of meters
Connectivity type	End-user connectivity	Backbone connectivity	Backbone connectivity
Use case examples	Wireless meters, sensor networks	Video streaming, web browsing	Backbone
Required FER		0.08	
Number of end users	Several tens		Several

From the perspective of applications, the 100 kbps requirement mainly targets on sensor networks such as the smart utility networks [12], where low-power wireless meters are installed connected to wireless data collector. On the other hand, the 2 Mbps requirement mainly targets on broadband access including online video streaming, web browsing, and local file transferring. Among these applications, the online video streaming (e.g., MPEG4 format [13]) requires a typical throughput of 2 Mbps. The end users are connected to the backbone that supports a typical speed of several tens (e.g., 60 Mbps as given in Table 1) of Mbps.

4. TVWS Regulations

The occupancy of TVWS is closely tied to the policy and rule-making of the regulatory institutions. Up-to-date, the several regulators actively participating in TVWS regulations are the United States (US) Federal Communications Commission (FCC), the United Kingdom (UK) Office of Communications (OFCOM), the European Conference of Postal and Telecommunications Administrations (CEPT), and the Japanese Ministry of Internal Affairs and Communications (MIC). Some of these regulations have already reached a fairly matured specification sufficient for actual system deployment, while others are still in the stage of planning and brain-storming. This paper places weighted emphasis on the more complete and matured FCC regulations.

FCC has issued a report and order (R&O) [1] in Nov. 2008, and then later in Sept. 2010 [2], outlining the governing regulations for unlicensed usage in the TVWS. The TV band devices (TVBD) are categorized into two classes: fixed and personal/portable devices (hereon referred to as portable devices). The fixed device is a HPD operating at a fixed location with high-power outdoor antenna. The portable device is an LPD, and is further divided into Mode I and Mode II. A Mode I device is a client portable device controlled by a fixed device or a Mode II portable device. A Mode II device is an independent portable device with capability of accessing available TV channels.

Two cognitive radio capabilities are specified by the FCC for the TVBDs: the mandatory channel availability/geolocation awareness and the optional spectrum sensing. All devices, except Mode I portable devices, must include a location awareness capability by means of accessing the internet to obtain from a Geolocation Database (DB) information consisting of colocating incumbent TV broadcasting. Prior to operating, the unlicensed devices must access the geolocation DB to get the list of permitted channels currently not occupied by the incumbent services. Additionally, all devices may sense the spectrum for the presence of TV signals and wireless microphone signals. The sensitivity of the sensing is all the way down to a received power level of -114 dBm .

In the US, the TV channels usable by unlicensed users range from the VHF channels 2–13 to the UHF channels 14–51, while several limitations and exceptions apply [1]. Each TV channel is 6 MHz wide. Table 2 shows a fraction of the UHF TV channels in the US.

TABLE 2: TV channels in the United Stated: an example of available TVWS. f_L : lower frequency. f_H : upper frequency.

TV channel no.	Frequency band f_L-f_H (MHz)	TV channel no.	Frequency band f_L-f_H (MHz)
38	614–620	45	656–662
39	620–626	46	662–668
40	626–632	47	668–674
41	632–638	48	674–680
42	638–644	49	680–686
43	644–650	50	686–692
44	650–656	51	692–698

It should be noted that FCC is only one among the many regulatory organizations that outlined governing rules for operation in the TVWS. There are many other regulators actively working on similar rules and regulations. In this paper, although uses the examples and specific parameters of FCC, the same analysis can be repeated for other regulations.

5. System Design for Enabling TVWS Operation

In this section, system requirements inherent to the use cases as described in Section 3, and regulatory demands as described in Section 4, are taken into consideration for the overall system design. The cross-layer system design is divided into channelization, PHY layer design, cognitive management, and MAC layer design.

5.1. Channelization. The first essential parameter in enabling communication in TVWS is the channelization strategy. The communication system has to be equipped with the capability to operate at center frequencies and channel spacing of unused TV channels. For this purpose, a clock generator consisting of crystal oscillator and phase-locked loop (PLL) is designed. The clock generator employs a dual-PLL structure to produce both the center frequencies and symbol rate (i.e., Nyquist frequency) f_{nr} .

Figure 3 shows the architecture of the clock generator. In Figure 3—center frequency generation, the phase detector compares the two input signals f_{ic} and f_{bc} to obtain the error signal that is proportional to their phase difference. The error signal is then low-pass filtered (LPF) and used to drive a voltage-controlled oscillator (VCO) which creates an output frequency, f_{cen} . The output frequency is fed through a frequency divider back to the input system as f_{bc} , thus producing a feedback loop. If f_{cen} drifts, the error signal will increase, driving the VCO frequency in the opposite direction so as to reduce the error. Therefore, the output is locked to the input frequency f_{ic} , which is the product of a stable frequency f_{XTAL} derived from a crystal oscillator. This is the basic design to produce the center frequency of the TV channels. In Figure 3—symbol rate generation, the symbol rate f_{nr} can also be obtained by using the same procedure, with a different set of parameters.

By employing the designed dual-PLL clock, the specific center frequencies f_{cen} of the US TV channels given in Table 2

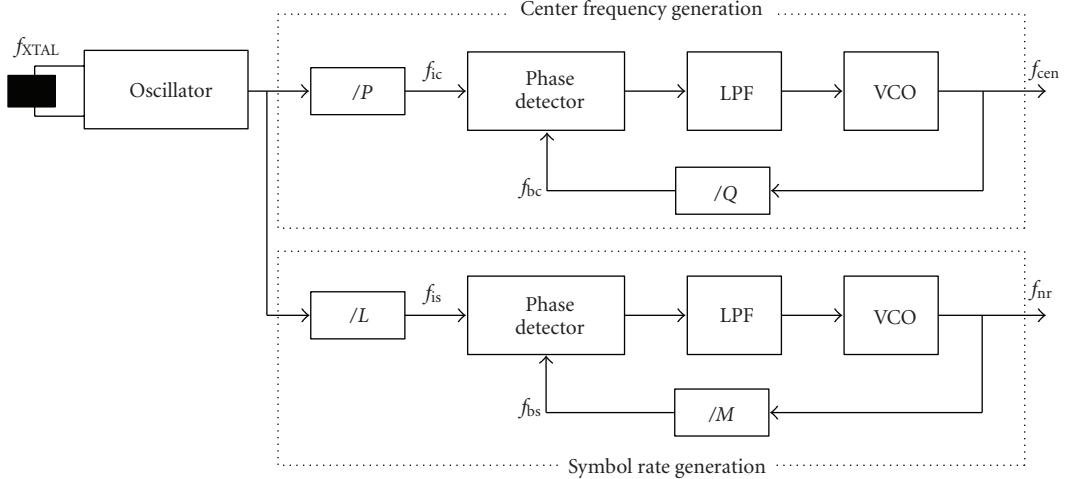


FIGURE 3: Dual-PLL reference diagram for clock generator.

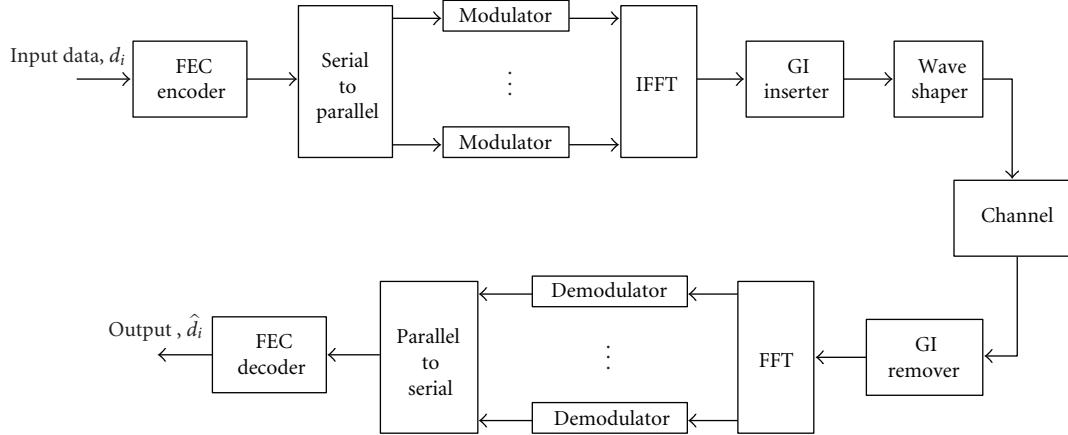


FIGURE 4: Block diagram for OFDM transceiver.

can be generated. In this numerical example, the 40 MHz crystal oscillator (i.e., $f_{\text{XTAL}} = 40 \text{ MHz}$), a popular choice for most 802.11 wireless local area network (WLAN) systems [14] is assumed. In Figure 3, by substituting $P = f_{\text{XTAL}}$, f_{ic} of 1 MHz can be obtained. Then, by employing $Q = f_L + (f_H - f_L)/2$ where f_H and f_L are upper and lower frequencies of the TV channels as shown in Table 2, f_{cen} for each TV channel can be generated. Similarly, by substituting $L = 1$, $f_{\text{is}} = f_{\text{XTAL}}$ can be produced. Next, by using $M = 8, 4$, and 2 , symbol rate f_{nr} of 5, 10, and 20 MHz can be generated. Note that the reason to select symbol rates of 5, 10 and 20 MHz is also motivated by the attempt to align the TVWS communication system to the popular WLAN.

While the specific numerical results are derived assuming particular regulations and existing wireless systems, the generic clock architecture is capable of supporting frequency generation in any band and channel spacing.

5.2. PHY Layer Design. The channel plan provided by the generator in Section 5.1 gives the starting point of designing the PHY layer. In the following sections, the PHY layer design

will be described, with the achievable PHY data rate and operating range as the output parameter.

5.2.1. Signal Model. Figure 4 shows an illustration of the orthogonal frequency division multiplexing (OFDM) transmission system for the TVWS operation. In the transmitter, the high-speed data is first encoded with a forward error correction (FEC) scheme with coding rate r_c , and then converted into parallel data of subchannels. The transmitted data can be expressed as [15]

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{i=0}^{L_{\text{FFT}}-1} d_i(k) \exp(j2\pi f_i(t - kT_{\text{sym}})) \times f_{\text{cen}}(t - kT_{\text{sym}}), \quad (1)$$

where L_{FFT} is the total number of OFDM subcarrier, T_{sym} is the OFDM symbol duration, f_i is the frequency of the i th subcarrier, and $f_i = f_{\text{cen}} + i/T_{\text{sym}}$. f_{cen} is the operating frequency. Note that each data d_i is a complex number, $d_i = d_{I_i} + jd_{Q_i}$, where d_{I_i} and d_{Q_i} are in the range of

$\{\pm 1, 0\}$, $\{\pm 1, \pm 1\}$, $\{\pm 3, \pm 3\}$ and $\{\pm 7, \pm 7\}$ for binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (16QAM), and 64 quadrature amplitude modulation (64QAM), respectively. The modulation level m_l for these schemes are 1, 2, 4, and 6, respectively. The chosen FEC scheme is the Reed-Solomon block codes.

Here, the subcarrier spacing ζ_{FFT} of the OFDM signal and its equivalent time domain representation T_{FFT} are given as

$$\zeta_{\text{FFT}} = \frac{f_{\text{nr}}}{L_{\text{FFT}}}, \quad T_{\text{FFT}} = \frac{1}{\zeta_{\text{FFT}}}, \quad (2)$$

where f_{nr} is the Nyquist frequency produced by the clock generator.

After the insertion of guard interval (GI), the OFDM signal is described as

$$s(t)' = \sum_{k=-\infty}^{\infty} \sum_{i=0}^{L_{\text{FFT}}-1} d_i(k) \exp(j2\pi f_i(t - kT_{\text{total}})) f'(t - kT_{\text{total}}), \quad (3)$$

where $T_{\text{total}} = T_{\text{sym}} + T_{\text{GI}}$, T_{GI} is the GI interval, $f'(t)$ is the modified pulse waveform of each symbol defined as $f'(t) = 1$ if $-T_{\text{GI}} \leq t \leq T_{\text{sym}}$, and $f'(t) = 0$ if $t < -T_{\text{GI}}$ and $t > T_{\text{sym}}$.

5.2.2. Receiver Model. At the receiver, the received signal is given by

$$r(t) = \int_0^\infty h(\tau, t)s(t - \tau)d\tau + \eta(t), \quad (4)$$

where $h(\tau, t)$ is the impulse response of the radio channel at time t , and $\eta(t)$ is the complex additive white Gaussian noise (AWGN). The receiver configuration is described in Figure 4. The output of the receiver is expressed as the i th OFDM subcarrier as

$$\hat{d}_i = \frac{1}{T_{\text{sym}}} \int_{kT_{\text{total}}}^{T_{\text{sym}}+kT_{\text{total}}} r(t) \exp(-j2\pi f_i)(t - kT_{\text{total}})dt. \quad (5)$$

Note that \hat{d}_i will be used to compare with the input data to obtain the error performance.

5.2.3. Design Parameter Considerations. This subsection presents the essential PHY parameters in designing the OFDM signaling. The output of the PHY layer design are the PHY data rate Ω_{PHY} and the operating range Y , that shall be sufficient to support the requirements in the targeted use cases, as given in Table 1. In order to achieve the sufficient Ω_{PHY} and Y , the critical parameters to be considered are modulation level m_l , FEC coding rate r_c , FFT size L_{FFT} , and GI size L_{GI} .

In the VHF/UHF band, existing channel propagation studies that are widely used are reported in [16, 17]. The important parameters extracted from these studies are the maximum delay spread ϵ_{max} that dictates the design of the OFDM signaling. In [16], ϵ_{max} is given as $10\text{--}20\ \mu\text{s}$ for the range of $10\text{--}20\text{ km}$. In [17], ϵ_{max} is $11\text{--}25\ \mu\text{s}$ for $17\text{--}33\text{ km}$

and $25\text{--}60\ \mu\text{s}$ for up to 100 km . As a result, it is concluded that within 10 km , ϵ_{max} can be set to $12\ \mu\text{s}$. Next, in order to effectively mitigate frequency selective fading in the OFDM signal, T_{GI} should be set larger than ϵ_{max} .

For backbone connectivity, L_{FFT} is chosen to be 1024 for the HPD, while for end-user connectivity, L_{FFT} is chosen to be 256 for the LPD for lower complexity. For both scenarios, T_{GI} is set to $T_{\text{FFT}}/4$. The Nyquist frequency f_{nr} for backbone connectivity and end-user connectivity are set to 5 and 20 MHz, respectively. These settings provide to both the backbone connectivity and end-user connectivity, $T_{\text{GI}} > \epsilon_{\text{max}} = 12.8\ \mu\text{s}$. In other words, the frequency selective fading can be mitigated with these settings.

5.2.4. Error Performance. The bit error rate (BER) can be quantified by comparing the transmitted bits d_i and the bits produced by the receiver \hat{d}_i in (5), as

$$\begin{aligned} \text{BER} = & P(d_i = +1)P(\hat{d}_i = -1 | d_i = +1) \\ & + P(d_i = -1)P(\hat{d}_i = +1 | d_i = -1), \end{aligned} \quad (6)$$

where $P(\cdot)$ denotes the probability and d_i and \hat{d}_i represent the i th transmitted and received data bit.

In similar way, the frame error rate (FER) can be described as

$$\begin{aligned} \text{FER} = & P(d_j = \varrho_j)P(\hat{d}_j \neq \varrho_j | d_j = \varrho_j), \\ & j = 1, 2, \dots, L_{\text{fr}}, \end{aligned} \quad (7)$$

where d_j and \hat{d}_j represent the j th transmitted and received data bit in a data frame, ϱ_j is the j th bit from the data bit sequence of length L_{fr} , sent as a transmitted frame. The relationship between FER and BER can be expressed by

$$\text{FER} = 1 - ((1 - \text{BER})^{L_{\text{fr}}}). \quad (8)$$

Specific numerical values are substituted into the PHY layer design to determine the error performance of the system. For this purpose, the FEC Reed-Solomon coding is designed to encode 239 to 255 block symbols. The chosen modulation schemes are QPSK, 16QAM, and 64QAM. The propagation channel is assumed to be a fading channel with Rayleigh distribution to consider the bottleneck of the channel condition. The signal to noise ratio (SNR) in the receiver is quantified as the ratio between energy per bit (E_b) to noise power spectral density (N_0). In this paper, we neglect the intercarrier-interference between OFDM subcarriers for simplicity.

Figure 5 shows the error performance of the OFDM system in a fading channel with Rayleigh distribution. The minimum performance requirement for the system is application-dependent, as given in Table 1. By using (8), the required BER can be approximated as 10^{-5} with typical $L_{\text{fr}} = 4096$ [14]. Figure 5 gives the equivalent required E_b/N_0 for QPSK, 16QAM, and 64QAM to be 23, 25.5, and 29 dB, respectively.

5.2.5. PHY Data Rates. This section calculates the achievable PHY data rate Ω_{PHY} based on the design parameters discussed in Section 5.2.3. The relationship between Ω_{PHY} and relevant design parameters can be expressed as

$$\Omega_{\text{PHY}} = f_{\text{nr}} m_l r_c \frac{L_{\text{FFT}} - L_{\text{GI}}}{L_{\text{FFT}}}. \quad (9)$$

Employing (9), the list of supported Ω_{PHY} are given in Table 3. In Table 3, Index 1 to 3 are designed for end-user connectivity which requires up to a total of 2 Mbps per user according as specified in Table 1. Index 4 to 6 are designed to fulfill the requirements of the backbone connectivity, suiting to various operating ranges Y . The analysis on Y will be conducted in Section 5.2.6. The combined analysis incorporating Ω_{PHY} , Y and the use case requirements will be conducted in Section 6.

5.2.6. Link Budget. Employing the PHY parameter settings in Section 5.2.5, the operating range Y of data communication can be determined as

$$\log_{10}(Y) = \frac{(P_{\text{TX}} + G_{\text{TX}} + G_{\text{RX}} - S_m - L_{\text{PLn}})}{10\phi}, \quad (10)$$

where P_{TX} and G_{TX} are the transmitter power and antenna gain, G_{RX} is the receiver antenna gain, and ϕ is the propagation loss index. Here, L_{PLn} is the well-known urban path loss model [18] and is not repeated in this paper. Note that L_{PLn} is a normalized parameter with center frequency $f_{\text{cen}} = 600$ MHz (a typical value assumed in this example), HPD and LPD antenna height of 30 m and 1 m, respectively. All parameters are in dB scale. The minimum receiver sensitivity S_m is calculated as

$$S_m (\text{dB}) = -174 + 10 \log_{10}(\Omega_{\text{PHY}}) + \text{NF} + \frac{E_b}{N_0}, \quad (11)$$

where NF is the receiver noise figure, and E_b/N_0 is the required SNR to reach the targeted BER.

By substituting the relevant PHY parameters into (10), the effective operating range Y can be determined. In this analysis, P_{TX} is set to 100 mW for LPD and 4 W for HPD as specified by [1], G_{TX} and G_{RX} are set to 0 dBi to indicate omnidirectional transmission, NF is set to 8 dB, and ϕ is set to 3. Other relevant parameters are set similar to the previous sections.

The achievable Y is given in Table 3. In Table 3, Index 1 to 3 are targeted for end-user connectivity and is thus confined within a shorter range between end users to the access point. On the other hand, Index 4 to 6 are intended for backbone connectivity which requires higher effective operating range to bridge across fixed stations. The combined analysis incorporating Ω_{PHY} , Y and the use case requirements will be conducted in Section 6.

5.3. Cognitive Management Plane. The cognitive management plane of the TVWS communication system consists of a master protocol, namely, the Dynamic Enabling Protocol (DEP) that controls the access to the targeted TV

channel. The cognitive management engine includes into the DEP mechanism the features of the channel availability/geolocation awareness and spectrum sensing. Figure 6 shows the typical state machine implementation of the DEP.

For fixed and portable Mode II devices, the channel availability/geolocation awareness through accessing the DB is a mandatory requirement while the spectrum sensing is an optional feature.

- (i) Upon power on, a device is in the “unenabled” state. In the “unenabled” state, the device is not allowed to transmit any energy into the air. Next, the “unenabled” device accesses the DB containing information of incumbent users through the internet to inquire the vacancy of the targeted channel to be used. If the DB indicates that the targeted channel is not occupied by an incumbent user, the state transits to the “becoming enabled” state.
- (ii) In the “becoming enabled” state, if spectrum sensing is activated, the device may still not transmit energy into the air. The device shall perform spectrum sensing to check the availability of the targeted channel. Upon determining the targeted channel to be vacant through spectrum sensing, the state of the device can then transit to the “enabled” state. This step is not necessary if spectrum sensing is activated. Additionally, at any time in the “becoming enabled” state, if a de-enablement signal is received from the DB, indicating that an incumbent user has occupied the same channel, the device shall transit back to the “unenabled” state.
- (iii) In the “enabled” state, the device may start to set up networks and perform data communication by transmitting signals into the air. At any time in the “enabled” state, the device transits to the “becoming enabled” state if a de-enablement signal is received from any other “enabled” device within the same channel OR if the spectrum sensing reports new activities of incumbent systems in the channel.

For portable Mode I devices, the state machine starts from the “becoming enabled” state. The rest of the state transition processes are the same.

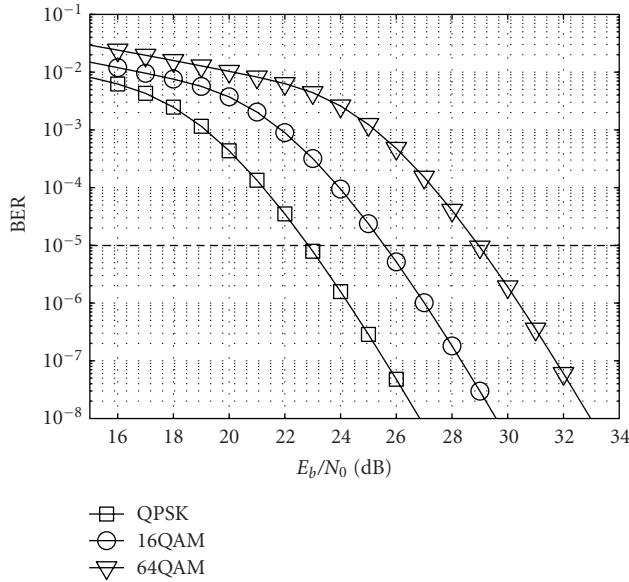
5.4. MAC Layer Design. Following the DEP described in Section 5.3, a device in the “enabled” state is allowed to transmit signal into the air. This section further specifies the basic MAC layer design necessary for enabling communication in the TVWS.

5.4.1. Network Topology and Resource. A typical network consists of N devices, one of which is selected as the network coordinator (NC). The remaining $N - 1$ will be dependent devices associated with the NC. The NC provides the network reference timing and manages the resource sharing among the devices. A basic network unit is illustrated in the dotted box in Figure 2.

Figure 7 shows the reference timing for the network controlled by the NC. A full cycle of the network timing is

TABLE 3: Achievable PHY data rate Ω_{PHY} and achievable operating range Υ .

Index	f_{nr} (MHz)	Mod.	m_l	r_c	L_{GI}	L_{FFT}	Ω_{PHY} (Mbps)	Dev. type	P_{TX} (mW)	Υ (m)
1	5	QPSK	2	0.9373	16	256	7	LPD	100	300
2	5	16QAM	4	0.9373	16	256	14	LPD	100	250
3	5	64QAM	6	0.9373	16	256	21	LPD	100	210
4	20	QPSK	2	0.9373	256	1024	28	HPD	4000	650
5	20	16QAM	4	0.9373	256	1024	56	HPD	4000	540
6	20	64QAM	6	0.9373	256	1024	84	HPD	4000	440

FIGURE 5: BER versus E_b/N_0 for fading channel with Rayleigh distribution. FEC: Reed-Solomon (255, 239).

known as the beacon interval (BI), which is the duration between two consecutive beacons. Following the beacon is a duration known as the contention access period (CAP). CAP is a duration that allows devices to access the wireless channel employing the carrier sense multiple access/collision avoidance (CSMA/CA) scheme. Following CAP is the contention free period (CFP). CFP allows the devices to access the wireless channel by using the time division multiple access (TDMA) scheme. In CFP, guaranteed time slots (GTSs) are allocated for each device to perform respective noncontentious communication.

The major reason of having both CAP and CFP for the MAC layer design is to support transmissions with and without stringent latency demands. As described in Section 3, the targeted use cases include local file transfer, web browsing, and video streaming. Particularly in video streaming, latency can be a delicate issue. Therefore, it is essential to have the hybrid CAP/CFP design to fulfill all needs.

5.4.2. MAC Functionalities. In order to enable communication in the TVWS, the MAC functionalities have to be specified. The basic set of functionalities to facilitate operation in

the TVWS are starting a network, association/disassociation, GTS allocation, and data streaming, as shown in the message sequence charts (MSC) in Figure 8.

Starting a network involves the scanning process followed by the transmission of a beacon signal. In Figure 8(a), the MAC of a device receives request from the MAC Layer Management Entity (MLME) to scan all channels 1 to M . After the scan is completed, the MAC will report the results to the MLME. Next, a beacon frame will be sent by the device (now known as the NC) to seek other devices in the same location to form a network.

As shown in Figure 8(b), if a device receives a beacon frame and intends to join the network, the MLME will send an association request to the MAC. The MAC will then send an association request frame over the air to the NC. Upon receiving the request frame, the NC acknowledges with an acknowledgment (ACK) frame. The NC will then process the request and respond accordingly by sending the associate response frame. Similarly, the device acknowledges after receiving the associate response frame and reports to the MLME.

Figure 8(c) shows the GTS allocation for occupying the CFP. The device intending to occupy a GTS sends a GTS request frame to the NC. The NC acknowledges with an ACK frame, then sends to the MLME the request. In the next beacon transmission, the NC will insert into the beacon frame, the timing information of the GTS allocated for the device. The device upon receiving the beacon will wait until the CFP period and its turn to perform data streaming.

In Figure 8(d), data streaming is described. Assuming that the GTS notification is received by the preceding beacon, the device will send data frame to the destination (e.g., the NC) in the allocated GTS. The destination device will reply with an ACK frame if the data frame arrives.

5.4.3. Channel Access. As mentioned in Section 5.4.1, the two channel access methods to support data transmission in the TVWS are CSMA/CA in CAP and TDMA in CFP. This hybrid access method is a popular choice of major industrial standards specifications [14, 19, 20]. The following sections evaluates the achievable throughput for both schemes based on the data rate and other parameters provided by the PHY layer.

In the CSMA/CA scheme, a device attempting to transmit a frame first scan the TV channel. If the channel is idle for a period larger than α , the device will transmit. If the device

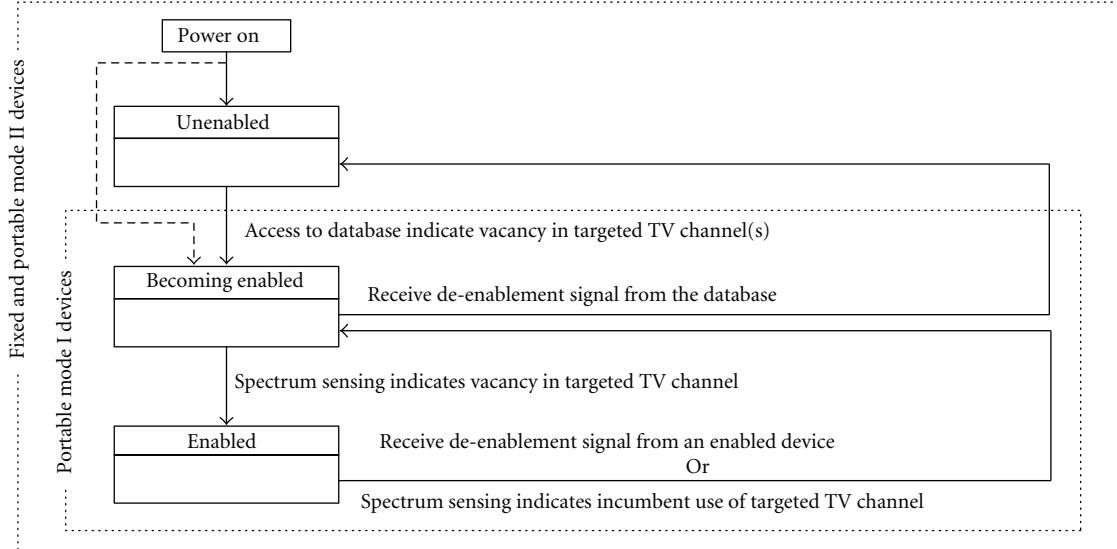


FIGURE 6: Cognitive management engine: Dynamic Enablement Protocol.

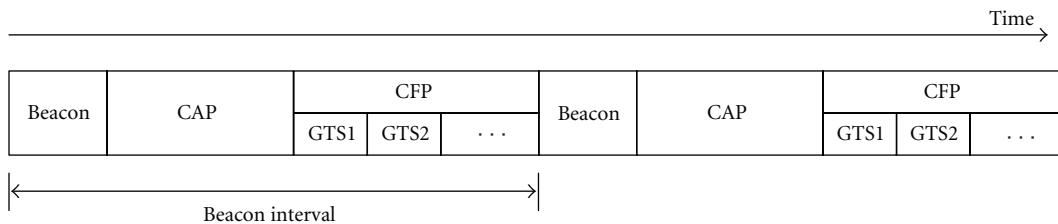


FIGURE 7: Basic network reference timing of the NC.

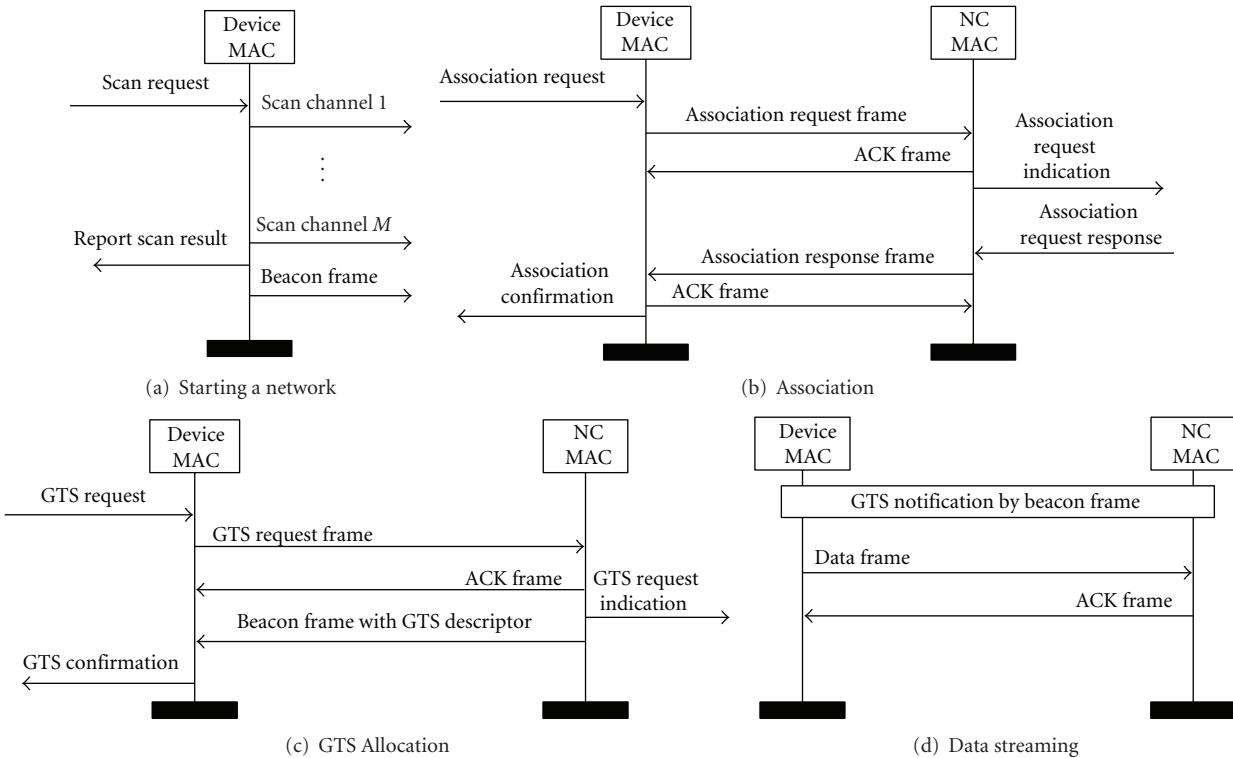


FIGURE 8: MSC for basic MAC functions in TVWS communication system.

detects that the channel is busy, it will persist to monitor the channel until it is idle. At this point, the device generates a random back-off interval to minimize collisions with frames from other devices. The back-off scale is discrete in time. The time following α is slotted, and a device is allowed to transmit only at the beginning of each slot time σ . Slot time σ is a value dependent on the PHY layer design, taking into consideration the radio design such as propagation delay, transmitter-receiver-turn-around time, and so on.

The CSMA/CA uses an exponential back-off scheme. At each frame transmission, the back-off time is uniformly chosen in the range $(0, w - 1)$, where w is the contention window dependent of number of failed transmissions. At the first transmission attempt, w is set to the minimum value CW_{\min} . Each unsuccessful transmission increases w until the maximum value CW_{\max} .

The transmitting device has no means of detecting a potential collision of the frames sent out, it is essential to also specify a feedback loop for the receiving device to acknowledge the successful receipt of frames. The ACK frame is transmitted by the destination device to the source device after receiving the whole frame. The interval between the end of the frame and the beginning of the ACK frame is noted as β . The system designed should be tailored to have $\beta < \alpha$, so that no other devices is able to detect the channel as idle during the ACK frame feedback.

In order to calculate the effective system throughput, we firstly express Λ as the probability of a device transmitting in a randomly chosen slot time. Probability Λ can be expressed as [21, 22]

$$\Lambda = \frac{2(1 - 2p)}{(1 - 2p)(CW_{\min} + 1) + p \cdot CW_{\min}(1 - (2p)^m)}, \quad (12)$$

where p is the probability that a transmitted frame encounters a collision and m is the maximum back-off stage such that $CW_{\max} = 2^m CW_{\min}$. In the simplified case of $m = 0$ (i.e., no exponential backoff is considered), (12) can be rewritten as

$$\Lambda^{(m=0)} = \frac{2}{CW_{\min} + 1}. \quad (13)$$

Let T_I be the idle duration. When all devices are counting down, no frame transmissions take place; thus,

$$T_I = \sigma. \quad (14)$$

Let T_{SE} be the success/error duration. When a frame is successfully transmitted or it is corrupted due to channel noise, the slot duration is given by

$$T_{SE} = T_{pre} + T_H + T_{fr} + \beta + \delta + ACK + \alpha + \delta, \quad (15)$$

where T_H is the total header duration including the PHY and MAC headers, T_{pre} is the duration of the preamble, T_{fr} is the payload duration, and δ is the propagation delay.

Let T_C be the collision duration. When two or more devices transmit at the same time and collision occurs, the sender will wait for the next transmission. So,

$$T_C = T_{pre} + T_H + T_{fr} + \alpha + \delta. \quad (16)$$

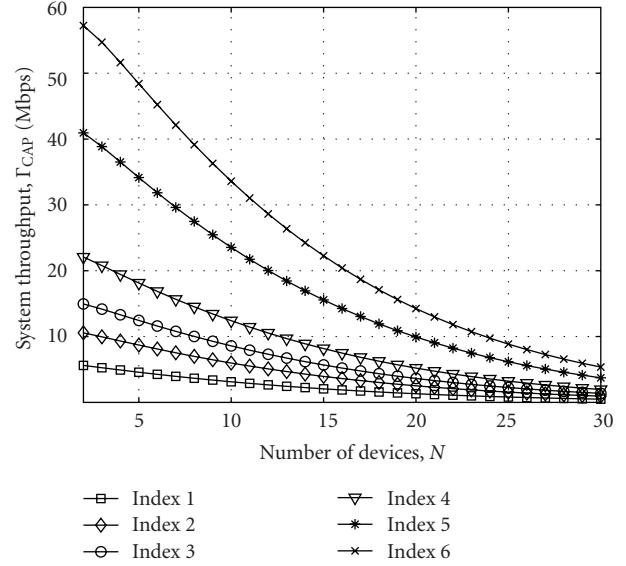


FIGURE 9: Number of devices versus system throughput in CAP. For Index numbers refer Table 3.

Let P_I , P_{SE} , P_C represents the probabilities of *idle*, *success/error*, and *collision* events. In a channel with a total of N devices,

$$P_I = (1 - \Lambda)^N,$$

$$P_{SE} = \binom{N}{1} \Lambda (1 - \Lambda)^{(N-1)}, \quad (17)$$

$$P_C = 1 - P_I - P_{SE}.$$

The normalized system throughput $\Gamma_{CAP}^{(nor)}$ (bps/Hz) can be given as

$$\Gamma_{CAP}^{(nor)} = \frac{P_{SE} L_{fr} (1 - FER)}{P_I T_I + P_{SE} T_{SE} + P_C T_C}, \quad (18)$$

where $L_{fr} = \Omega_{PHY} T_{fr}$ denotes the frame payload size in octets.

Finally, the effective system throughput (bps) can be expressed by

$$\Gamma_{CAP} = \Omega_{PHY} \Gamma_{CAP}^{(nor)}, \quad (19)$$

where Ω_{PHY} is the data rate provided by the PHY layer design.

The specific MAC parameter settings for this analysis is given as follows [14]: for Index 1 to 3 where $f_{nr} = 5$ MHz, σ is set as $21 \mu s$, β is set as $64 \mu s$, and T_{pre} and T_H are 16 and $64 \mu s$, respectively. As for Index 4 to 6 where $f_{nr} = 20$ MHz, σ is set as $9 \mu s$, β is set as $16 \mu s$, and T_{pre} and T_H are 4 and $16 \mu s$, respectively. Other parameters such as α is equivalent to $\beta + 2\sigma$, δ is set as $1 \mu s$, and CW_{\min} and CW_{\max} are set as 16 and 1023. Also note that the ACK frame is 14 octets while the average data frame L_{fr} is 4096 octets.

Figure 9 presents the relationship between number of devices and achievable system throughput Γ_{CAP} . In Figure 9, Index 1 to 3 shows Γ_{CAP} for end-user connectivity, while Index 4 to 6 are particularly designed for backbone connectivity. With low number of devices sharing the channel

(e.g., $N = 2$), the efficiency of CAP is at least 75% for all cases. As N increases, more collision among the users take place and Γ_{CAP} decreases.

In the TDMA scheme, a device conducts communication only in the dedicated time slot allocated by the NC. The TDMA is employed to perform time-sensitive data streaming for better quality of service. Applications that may benefit from this scheme are the online video streaming and peer-to-peer video transmission.

Referring to Figure 7, the time slots are scheduled in the CFP, which is the period following the CAP. Devices intending to reserve the GTS in the CFP shall first request for time slot allocation from the NC in the CAP. Figure 8(c) shows the handshakes between the device and the NC for GTS allocation. The device first sends a GTS request frame to the NC, then awaits the ACK frame. If it receives the ACK frame, it will expect the next incoming beacon frame to carry the timing descriptor of the allocated GTS. The device will, therefore, conduct its collision-free streaming in the allocated GTS. The data streaming in GTS takes place as the time of the allocated GTS arrives. As shown in Figure 8(d), the source device will send data to the destination device and receives an ACK frame if successful.

The normalized system throughput $\Gamma_{\text{CFP}}^{(\text{nor})}$ (bps/Hz) can be given as the ratio between average payload information and the total frame length plus the frame-to-frame interval

$$\Gamma_{\text{CFP}}^{(\text{nor})} = \frac{E[L_{\text{fr}}]}{E[L_{\text{fr}}] + L_H + L_{\text{pre}} + \beta}. \quad (20)$$

Finally, the effective system throughput (bps) can be expressed by:

$$\Gamma_{\text{CFP}} = \Omega_{\text{PHY}} \Gamma_{\text{CFP}}^{(\text{nor})}. \quad (21)$$

The calculation of Γ_{CFP} is more straightforward due to the collision-free transmission. The specific MAC parameter settings for this analysis is given as follows [14]: for Index 1 to 3 where $f_{\text{nr}} = 5 \text{ MHz}$, β is $64 \mu\text{s}$, and T_{pre} and T_H are 16 and $64 \mu\text{s}$, respectively. As for Index 4 to 6 where $f_{\text{nr}} = 20 \text{ MHz}$, β is $16 \mu\text{s}$, T_{pre} and T_H are 4 and $16 \mu\text{s}$, respectively. The average data frame L_{fr} is 4096 octets.

Employing (21) and the relevant parameters, Γ_{CFP} calculated for Index 1 through 6 are given as 6.5, 13, 19.6, 27.5, 55, and 82.5 Mbps, respectively. Note that Γ_{CFP} is the average system throughput for the system, where each user may occupy only a certain time slot for respective transmission.

6. A Combined Analysis

This section combines all the analysis from the previous sections to outline the entire design flow of the enabling technology for TVWS operation, as described in Section 2 and Figure 1. In Section 3, the use case scenarios are described highlighting both TVWS backbone connectivity and end-user connectivity with applications requiring throughput from 100 kbps up to 2 Mbps. The use case scenarios also specify other required parameters such as FER and supported number of users to be 0.08 and 30. In Section 4, the requirements in the regulation such as cognitive radio capability and

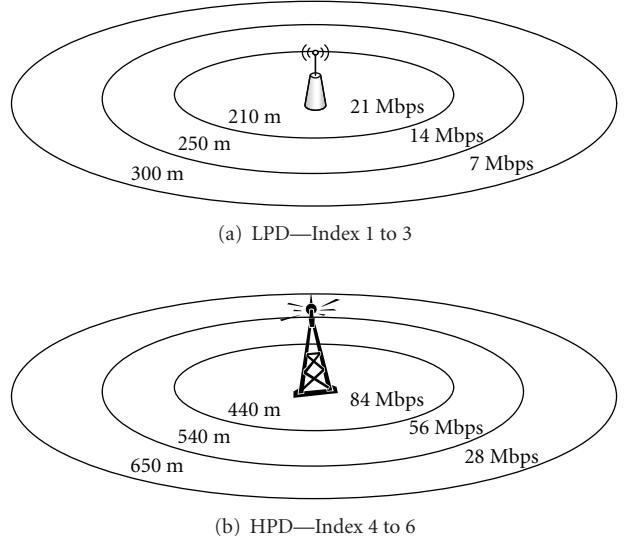


FIGURE 10: Achievable PHY data rate and operating range for HPD and LPD.

TV channel plan are given. Together, the use case and the regulations define the “perimeter” of requirements for the system design.

The system design consists of the channelization design, the PHY and MAC layer designs. In Section 5.2, the PHY layer design employing OFDM signal is proposed with the output data rates of at least 7 Mbps. The minimum achievable operating range is 300 m. A total of six data rate modes (Index 1 to 6) are proposed to support different application demands, as illustrated in Figure 10.

Next, in Section 5.4, the cognitive management engine and other enabling MAC protocols are specified. The cognitive management engine specifies a state transition diagram based on the regulation requirements (i.e., geolocation awareness and spectrum sensing) to control the occupancy of TV channels. Other enabling MAC protocols such as channel access procedures specify the channel access mechanism that facilitates the sharing of the same channel by multiple users. A hybrid CSMA/CA and TDMA channel access method is proposed to support both effective multiple access and quality of service transmissions. In the CSMA/CA method, the minimum and maximum system throughput are 5.6 and 57.2 Mbps, respectively, whereas in the TDMA method, 6.5 and 82.5 Mbps, respectively.

Finally, according to Figure 1, the system throughput and operating range are fed back to the use case requirements. With the achievable system throughput, the communication system in TVWS is capable of supporting up to a typical number of 40 users (e.g., assuming simultaneous video streaming) in some 400 m radius. The supportable number of users that conduct web browsing or other less bandwidth hungry applications may even be higher. Additionally, for applications in need of higher power efficiency, devices with lower complexity and lower power may be employed at the expense of lower number of supported users and shorter range.

7. Conclusion

This paper proposes a cross-layer MAC/PHY layer design for wireless communication system operating in the TVWS, taking into consideration practical issues such as application use cases and governing regulations. The advantages offered by the proposed communication system in supporting the targeted use cases and complying to the regulations are verified. Future works include the specific optimization in each of the design block shown in this paper.

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