# DYNAMIC INTERFERENCE SUPPRESSION FOR TV WHITE SPACE: THE CASE OF THAILAND

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***ABSTRACT***

*In this work, we study the problem of co-existence between the LTE (Long Term Evolution) and the Digital Terrestrial Television Broadcasting (DTTB) channel. There are three scenarios: co-channel, upper and lower adjacent channels. We use the broadcasted signal from channel 3 called ThaiPBS, the actual case of Thailand for our study where the standard of digital terrestrial television broadcasting is DVB-T2 adopting 8 MHz bandwidth, while the 5 MHz bandwidth of LTE is considered as the interference. We propose a dynamic interference suppression method for increasing spectrum usage by optimizing TV white space utilization and minimizing interference. This method adopts the protection ratio concept to suppress the LTE interference on TV receiver. We implement our proposed algorithm as an adaptive interference controller using a Radio Frequency (RF) attenuator and a Raspberry Pi board for our testbed hardware. We illustrate the effectiveness of our proposed algorithm by doing experiment using our testbed and assessing the quality of the received TV signal by adopting the Quality of Experience (QoE) assessment. In our testbed hardware, a Log Periodic antenna is used for receiving the DTTB signal, while an RF digital transmitter is used for generating a 5MHz bandwidth of LTE signal, an ultra-high frequency (UHF) mixer is used to combine both signals, then a field strength meter is used to monitor video picture quality and to analyze the spectrum. According to the experiment, our proposed method can reduce the perceived video distortion by at least 62.5% for co-channel and 87.5% for adjacent channel, while the spectrum usage is increased by 100%.*

***KEYWORDS***

*Adjacent Channel, Co-channel, Protection Ratio, Quality of Experience, Radio Frequency Attenuator, Raspberry Pi, TV White Space, Visibility Threshold*

## 1. INTRODUCTION

In digital terrestrial television broadcasting system, the VHF (Very High Frequency) and UHF (Ultra High Frequency) frequency bands are assigned by regulators for television broadcasting service of licensed users. However, there are many in-band frequencies that are unused in each area. That is, there are frequencies available for secondary or unlicensed users. In addition, the need of frequency spectrum for wireless and mobile communication services, i.e., wireless broadband Internet access, IoT network, etc,. has been significantly increasing in recent years [24]. One good example is the reassignment of 700MHz frequency band for mobile communications [19].

Since not all the designed channels have been deployed in terrestrial television broadcasting in any given region, therefore, the channel called TV White Spaces (TVWS) in which the channels that are not used for broadcasting may be available for the other purposes. In general, the TV White Space spectrum ranges from 470 MHz to 790 MHz, but it may be different on any region [18]. For instance, in Thailand and some countries, the frequency spectrum of 510 MHz to 790 MHz has been assigned for Digital Terrestrial Television Broadcasting [15].

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Actually, there were several TVWS trials conducted by various countries [9][11][13]~[15] [18]. In 2011, the largest TVWS trials occurred in Cambridge, and there was an implementation of the TVWS to connect the city's infrastructure in Wilmington, North Carolina. In 2013, the TVWS was used to power a "super Wi-Fi network" in West Virginia University. In 2014, NICT Japan and partner confirmed a successful implementation of long-range wireless communication by using IEEE 802.22 and IEEE 802.11af based systems in Tono city, Japan [18]. In Thailand, NBTC also conducted a first TVWS trial to provide the wireless broadband access in a rural area [15].

Regarding the spectrum usage in Thailand nowadays, although the demand is rapidly increasing, it is not enough. During the last year, there was the reallocation of the 700 MHz band of frequency channel used for DTTB to the mobile broadband system [19]. Presently, only the bandwidth of 184 MHz is left for the DTTB. Since the digital terrestrial television broadcasting system in Thailand has been operating in both Single Frequency Network (SFN) and Multi-Frequency Network (MFN), this can save the frequency spectrum on UHF (Ultra-High Frequency) band and can avoid the interference as well. However, only five frequency channels are adopted in some areas. This results in many unused frequency spectrums and inefficient usage. In case of coexistence between TV broadcasting signal and wireless broadband signal such as LTE, the LTE causes interference in DTTB system. In [17], they found that this situation happens when the traffic load of LTE base station exceeds 80% of its capacity in rural and suburban scenarios. In ITU recommendation [7], the protection ratios for DVB- T2 being interfered by LTE base station and user equipment were analyzed. This shows that different traffic load can cause different protection ratio. A dynamic interference management has been proposed before in the literature [17]. However, it investigated only rural and suburban scenarios in Havana, Cuba, and Ghent, Belgium. Certainly, these scenarios are different from the scenario in Thailand due to different terrain, frequency band allocation and network topology. Additionally, the specifications of the broadcasting transmitter, the propagation environment and the modulation and coding schemes are different as well.

Based on the rationale described above, we are interested in the flexible approach that can analyze the interference case-by-case and the appropriate analysis will lead to the high efficiency of the system. Furthermore, for future development of wireless communications operated on TVWSs, it also needs the optimization of spectrum usage efficiency without affecting the users' Quality of Service (QoS) and Quality of Experience (QoE).

In this work, the advantages of TVWS are thoroughly studied. The solution to the problem of operating TVWS in Thailand effectively is investigated. We propose a dynamic interference management for TVWS, especially in Thailand. In our system, we consider the scenario of DTTB signal being interfered by LTE signal. Then, we implement our proposed system using Raspberry Pi as a testbed. One of the inputs to our hardware testbed is the DTTB signal which is actually received from the Thai Public Broadcasting Service (ThaiPBS) network, which is the major public broadcasting network in Thailand, while the LTE signal is generated from the signal generator. We consider the interference of frequency spectrum of 3 scenarios: co-channel, upper and lower adjacent channels. The effectiveness of our proposed method is evaluated by QoE assessment method. The contribution of this work is the hardware devices which could be used to suppress the interference of LTE on DTTB signals.

The rest of this paper is structured as follows: In section 2, we describe the relevant literature review. Section 3 presents the proposed method including the detailed parameters, algorithms, all of details of testbed and assessment method, while Section 4 describes the experimental results including program and testbed validations and assessment results. Finally, we conclude our work and future work in section 5.

## 2. Related Works

In this section, we review the relevant literatures to our work.

Up until now, there are many research works proposing the methods to solve the interference problem in TVWS (TV White Space), such as interference occurring with the primary users; TV broadcasting users. The cognitive radio and dynamic spectrum access are the potential solutions, along with the geo-location database method [14]. Cognitive radio paradigms over different regulatory constraints have been proposed as a future solution for the increased radio spectrum demands. ESTI technical report analyzes the feasibility of Long-Term Evolution (LTE) Cognitive radio systems operating on TVWS, and it also evaluates the coexistence between LTE on TVWS and television broadcasting services [3].

In terms of the frequency allocation, the cognitive radio system has been used to identify the white spaces adopted in other networks using three methods, namely beacon signal (pilot channel), geo-location database, and spectrum sensing method [23]. There are two standards that provide rural connectivity such as IEEE 802.11af and IEEE 802.22, where both standards use a geo-location database to acquire the TV band [12]. The geolocation database is the preferred method for detecting available channels and for tackling the interference problems for TVWS. In Japan, NICT has successfully developed a white space database to be included in the OFCOM's databases list [20]. In Thailand, a similar system was carried out [15], and it is a challenging topic nowadays.

Although geolocation base method might lead to lower interference and it also works as a common spectrum distribution mechanism for different networks, it causes a lower usage efficiency [16]. The case-by-case analysis is not carried out, and the database is not updated in real time. In [17], it found that cognitive radio networks on TVWS in real scenarios might cause severe interference to the broadcasting services, even though ETSI determined specifications of the device in TVWS to ensure that they will not interfere to the licensed users [20]. In [14][19], they proposed technical point of view by using the geolocation database. Although the geo-location database is a solution for TVWS usage without interference, the database updating in non-real time is still the main disadvantage.

In [17], a dynamic interference management algorithm operating in a centralized spectrum management architecture along with assessment from the users was proposed. The Quality of Experience (QoE) with Threshold of Visibility (TOV) and Subjective Failure Point (SFP) are the proposed assessment for evaluating the DTTB system in [6][8]. This technique can reduce at least 50% and 27.5% of the interference in rural and suburban areas, respectively, with only 8% increment of spectrum usage compared to traditional cognitive network.

To protect the mutual interference from primary to secondary services, that are operated in the same or adjacent frequency and vice versa, the protection techniques such as cooperative sensing and advanced geo-location database were proposed [3]. These techniques use the combined interference monitoring and geo-location database to protect the incumbent system from harmful interference while expanding white space opportunities. The interference monitoring aims to enhance accuracy of carrier-to-interference ratio (C/I) of the incumbent receiver [4].

There are white space and gray space concepts in [3]. This concept concerns TV coverage areas where the broadcasting stations use the same frequency (SFN; Single Frequency Network). Based on only the location of TV broadcasting stations, this frequency can only be used by a Cognitive Radio (CR) device outside the area of the coverage areas. This means that the white space spectrum concentrates on protection of TV broadcasting stations. At TV receivers, a CR device can utilize the same frequency as the signal frequency transmitted by TV broadcasting station inside the coverage area. This means that the gray space spectrum focuses on protecting TV receivers.

In practice, the technical standards of DTTB of each country are different, so it can cause different protection requirements such as the minimum protected field strength, the minimum required separation distance, and the percentage of location probability degradation [2]. In [22], the coexistence scenario of a DTTB transmitter and an 802.22 base station was performed using indoor and outdoor Customer Premise Equipment (CPEs) in rural environment. The initial transmission power level of the IEEE 802.22 signal was set with the protection ratio to achieve the bit error rate (BER) of $2x10^{-4}$. In [11], protection of incumbent service in TVWS was considered. In [5], the significant impact of terrain and frequency on the protection distance was shown. The separation distance values depending on type of Cognitive Radio (CR) device, antenna height and co-channel or adjacent channel adoption. In the interference protection requirements of the FCC, portable CR devices should comply with the minimum co-channel separation distance of 4 km. For instance, in [21], they investigated the coexistence of the DVB-T/T2 and LTE downlink services in co-channel, considered interfering LTE signals with different bandwidths. Moreover, the modulation error ratio (MER) is used to evaluate performances of DVB-T/T2 systems. From the study, in co-channel coexistence scenarios, unwanted narrowband interfering LTE signals have less impact on DVB-T/T2 performance than the broadband. In [10], the LTE radio planning pertaining to the maximum acceptable LTE radio interface load, up to which a targeted user data rate can be maintained, was studied. The model of LTE radio scheduler was given. It provides the optimum traffic balancing for two cells. The work of [11] was studied under pure LTE radio spectrum and was analyzed using the actual data from commercial LTE networks. Some works in the literature studied the impact of interference in the co-channel scenario [10],[25]. In [25], the transmitter power on co-channel interference was studied. However, the signal under consideration is WiFi.

In [1], the study of the SFN which compares field measurement results with simulation results of propagation models using the PROGIRA software was carried out. It was found that the Okumura-Hata model provides the smallest average error for a suburban area and for a path with obstruction. In [17], the experiment was performed to find how frequent the protection ratio limits are exceeded. Both TOV (Threshold of Visibility; defined in Report ITU-R BT.2035-2/2008) and SFP (Subjective Failure Point; defined in Recommendation ITU-R BT.1368-13/2017) have been defined as a criterion to find a limit for a just error-free picture at a TV screen for protection ratio measurements.

# 3. PROPOSED MODEL

## 3.1. System Model and Parameters

The block diagram of the proposed dynamic interference analysis system is shown in figure 1. In our work, we consider the scenario where DVB-T2, the digital terrestrial television broadcasting (DTTB) standard adopted in Thailand, is a primary service coexisting with mobile wireless communication (LTE) which is a secondary service. Both signals are the inputs of the dynamic interference suppression algorithm, which is implemented on Raspberry Pi, our programmable testbed. Then, we assess the effectiveness of our implemented algorithm in reducing the LTE interference on DTTB signal by the QoE assessment method. The detail of all these procedures is described in the following subsections.

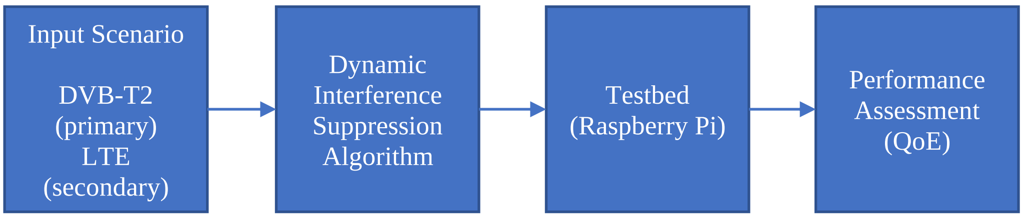



Figure 1. The Block Diagram of Dynamic Interference Analysis System

As mentioned previously, the standard of digital terrestrial television broadcasting (DTTB) in Thailand is DVB-T2. The coverage is approximately 95% of households in Thailand. The network is operated in both Single Frequency Network (SFN) and Multiple Frequency Network (MFN) using the limited frequency bandwidth of 184 MHz. The specifications of DVB-T2 adopted in DTTB Thailand is shown in Table 1 [24] as follows:

Table 1. DVB-T2 Digital Terrestrial Television Broadcasting Parameters in Thailand

| Parameters | Values |
|---|---|
| Frequency Band/Bandwidth | 510-694 MHz/ 8 MHz |
| FFT Size | 16K Extended |
| Guard Interval | 19/228 or 266 $\mu s$. |
| Pilot Pattern | PP2 |
| L1 Modulation | BPSK |
| PLP Type | Single |
| Modulation | 64-QAM |
| Rotated Constellation | No |
| Code Rate | 3/5 |
| Max FEC Block per Interleaving Frame | 99 |
| Maximum Distance from Tower for SFN | 79.8 Km |
| Maximum Bit Rate | 21.86 Mbps |
| C/N Fixed Rooftop (Rice) | 15.17 dB |
| C/N Portable Indoor (Rayleigh) | 16.91 dB |

The model for analyzing the actual interference between the DTTB and LTE signal at TV receiver in this work is illustrated in figure 2. In this study, the system parameters under consideration are shown in Table 2.

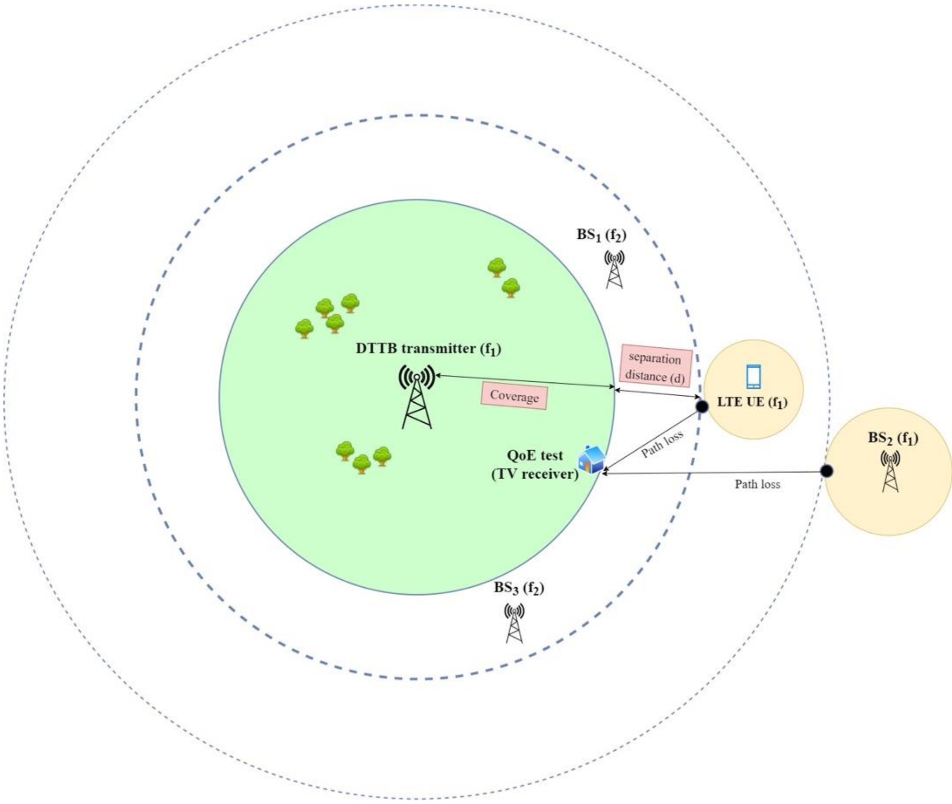



Figure 2. The Interference Analysis Model

Table 2. System Parameters under consideration

| Parameters | Value |
|---|---|
| Rooftop Antenna height of TV receiver | 10 m |
| Center Frequency of DTTB | 658 MHz (channel 44) |
| DTTB Bandwidth | 8 MHz |
| LTE Bandwidth | 5 MHz |

In our model, assume that the TV receiver is under the coverage BS1 and can receive both signals from BS1 and LTE UE1.The 8 MHz bandwidth of DTTB signal is transmitted using the center frequency of 658 MHz (channel 44), while the 5 MHz bandwidth of LTE signal is operated on co-channel and adjacent channel of the DTTB signal. That is, the LTE signal has the center frequency of 658 MHz, 663 MHz and 653 MHz for the co-channel, upper and lower adjacent channels, respectively as shown in Figure 3. The actual coexistence scenarios of frequency spectrum between DTTB and LTE are measured by using device called PROMAX field strength meter, as shown in Figure 4 (a), (b), (c). This illustrates the case of video without degradation due to the large enough different level of channel power between DTTB and LTE signals.

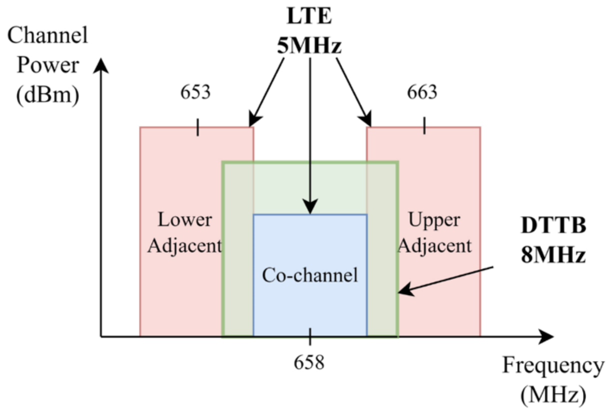



Figure 3. The Coexistence Scenario between DTTB and LTE Signal

(a) Co-channel (b) Upper adjacent channel (c) Lower adjacent channel

Figure 4. The Coexistence Scenario between DTTB and LTE Signal without Video Degradation

## 3.2. Proposed Algorithm

In this work, the dynamic interference suppression algorithm in [17] is implemented on our testbed hardware. This algorithm is based on the cognitive radio system which needs various inputs namely, user density, traffic demand, WSD (White Space Device) and DTTB specifications. Here, we consider LTE as the representative of WSD.

The diagram of the algorithm implemented on our hardware is shown in figure 5.

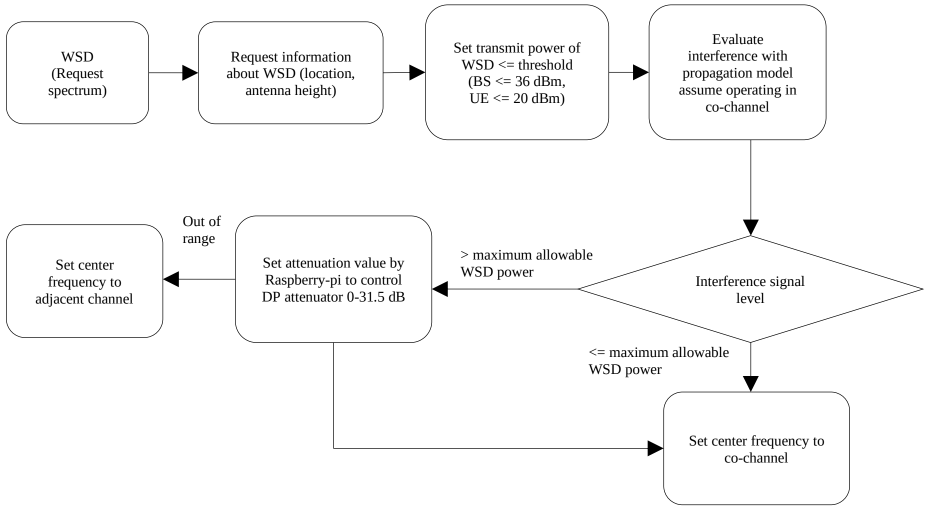



Figure 5. Block Diagram of the Proposed Algorithm implemented in our Hardware

The procedure of our implemented algorithm can be explained step-by-step as follows:

(1) Request for Spectrum: in this step, WSD information including location and antenna height are required for processing.

(2) Set Transmission Power of WSD: the maximum power of 36 dBm and 20 dBm are set for base station and user equipment, respectively.

(3) Then, the Raspberry Pi testbed is programmed using Python to calculate the Interference Signal Level (ISL) putting into account the path loss based on the Okumura-Hata propagation model assuming that they are operated in co-channel mode.

(4) Calculate the maximum allowable WSD power at TV receiver based on the suitable D/U ratio achieved from our prior investigation.

Then, regarding the interference evaluation step and attenuation adjustment, there are three scenarios:

(1) If ISL is less than the maximum allowable WSD power, the WSD will be set to operate in co-channel. No attenuation is needed.

(2) If ISL is greater than the maximum allowable WSD power, the LTE power attenuator is adjusted within the range of 0-31.5 dB and WSD will be set to operate in co-channel as well.

(3) If the difference between ISL and maximum allowable WSD power is greater than 31.5dB, then WSD will be set to operate in adjacent channel instead of co-channel since this case is out of range of the attenuator.

### 3.3. Testbed

The block diagram of our testbed hardware is shown in figure 6. The LTE signal is generated from an RF transmitter. The interference suppression algorithm is implemented on Raspberry Pi to control the RF attenuator to automatically adjust the level of interference based on the calculation of algorithm. The LTE signal is combined with the DTTB signal by a UHF mixer.

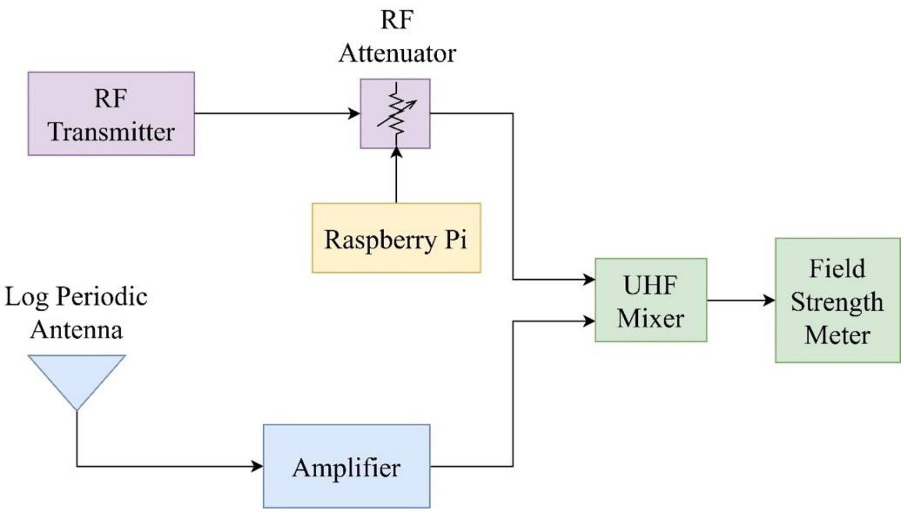



Figure 6. Block Diagram of the Testbed

In our experiment, the Log Periodic antenna with the gain of 11dB, as shown in figure 7(a), is used to receive the DTTB signal at rooftop and the amplifier with the gain of 30dB, as shown in figure 7(b), is used to adjust the signal level of DTTB. While the PROMAX field strength meter is used to analyze the spectrum of the received DTTB signal, as shown in figure 8. The picture on the right-handed side of Figure 8 is the video demodulated from the received carrier frequency shown on the left-handed side. It implies the adequacy of the signal power for a TV receiver.


(a) Log Periodic Antenna (b) Amplifier (Gain30 dB)

(c) RF Digital Transmitter

Figure 7. Key Components used in our Testbed

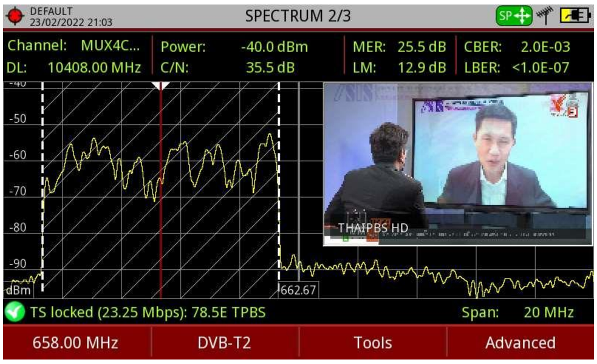



Figure 8. The received DTTB Signal of 8MHz Bandwidth at Frequency of 658MHz measured by a PROMAX Field Strength Meter.

The RF digital transmitter, as shown in figure 7 (c), is used to generate the 5MHz bandwidth of LTE signal based on OFDM (Orthogonal Frequency Division Multiplexing) technique. Then, the output level is adjusted within the range of -10 dBm to 10 dBm depending on the request of the interference suppression algorithm. Figure 9 shows an example of a 5MHz LTE signal generated, including a channel power of -54.16 dBm consisting of cable loss, connection loss and added external attenuators.

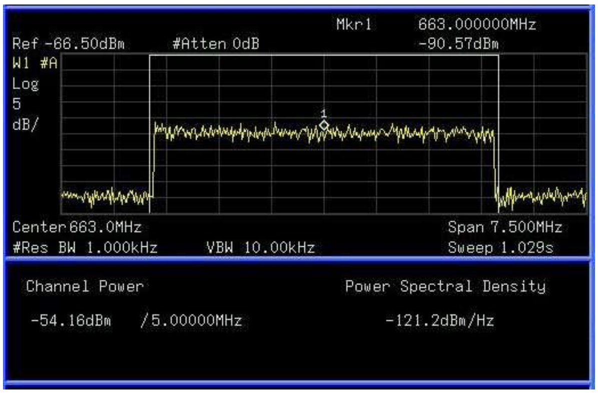



Figure 9. The LTE Signal with 5MHz Bandwidth measured by KEYSIGHT N9320B Spectrum Analyzer.

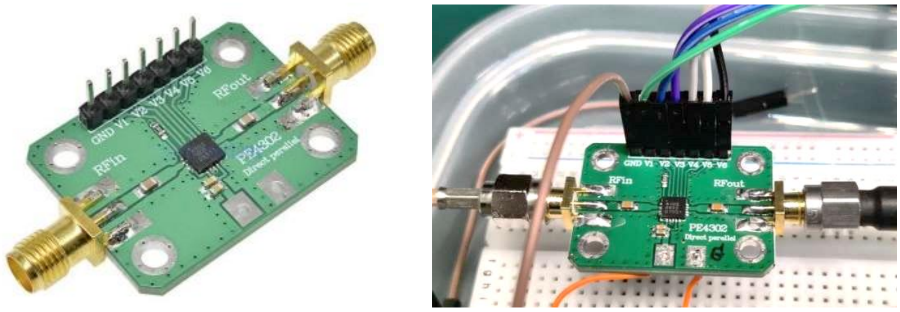


Figure 10. The RF Attenuator

Table 3. The Specifications of RF Attenuator

| Parameters | Values |
|---|---|
| Attenuation | 0.5 - 31.5 dB |
| Operation Frequency | DC to 4,000 MHz |
| Impedance | 50 Ω |

| | |
|---|---|
| $V_{DD}$ Power Supply Voltage | Min 2.7 V, Typical 3.0 V, Max. 3.3 V |
| $I_{DD}$ Power Supply Current | 100 $\mu A$ |
| Digital Input High | Minimum 0.7x$V_{DD}$ V |
| Digital Input Low | Maximum 0.3x$V_{DD}$ V |
| Input Power | +24 dBm |

The 6-bit Digital Step Attenuator (PE4302 model) as shown in figure 10, is used as a programmable attenuator whose specification is shown in Table 3, while the attenuation state is shown in Table 4. The physical board consists of six pinouts for connecting each bit, namely V1~V6. In this experiment, this device is set to operate in direct parallel mode, the Latch Enable (LE) line should be pulled HIGH. The parallel interface consists of six CMOS-compatible control lines that select the desired attenuation state, as shown in Table 4. The attenuation value can be changed by changing attenuation state control values C0.5-C16, where there are totally 64 possible combinations.

Table 4. The Attenuation State

| P/S | C16 | C8 | C4 | C2 | C1 | C0.5 | Attenuation Value |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | Reference Loss |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0.5 dB |
| 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 dB |
| 0 | 0 | 0 | 0 | 1 | 0 | 0 | 2 dB |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 4 dB |
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 8 dB |
| 0 | 1 | 0 | 0 | 0 | 0 | 0 | 16 dB |
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 31.5 dB |

For a Raspberry Pi board, we use six pinouts for sending data to the RF attenuator. These are General Purpose Input/Output (GPIO) pins on BCM mode, as shown in Figure 11. All GPIO pins are set to the output GPIO to send a binary bit to pinouts of a RF attenuator. The Raspberry Pi is directly connected for each pin to the RF attenuator, as shown in Table 5.

Table 5. The connection between a Raspberry Pi and a RF attenuator

| Raspberry Pi GPIO pinout | RF Attenuation pinout | CMOS |
|---|---|---|
| GPIO pin 22 | V1 | C0.5 |
| GPIO pin 27 | V2 | C1 |
| GPIO pin 17 | V3 | C2 |
| GPIO pin 25 | V4 | C4 |
| GPIO pin 24 | V5 | C8 |
| GPIO pin 23 | V6 | C16 |

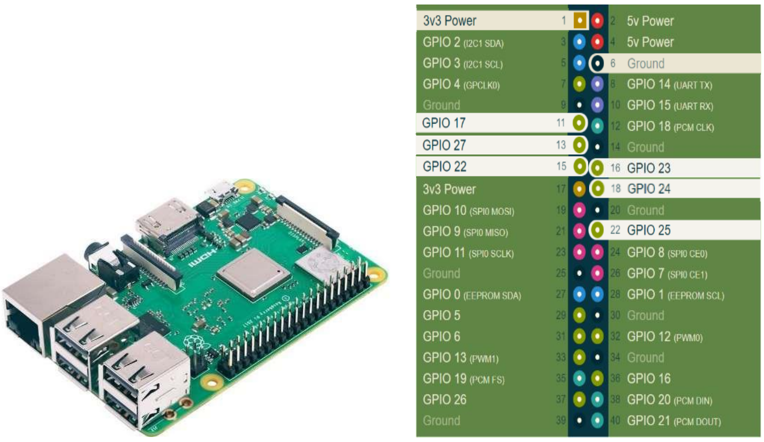



Figure 11. The Raspberry Pi Board and used Pinouts

Here, we program the Raspberry Pi using to execute our proposed algorithm. The output of the algorithm is an attenuation state that is sent to the RF attenuator for adjusting the interference signal level.

The steps to implement this are as follows:

Firstly, the GUI is created with Tkinter in Python. This GUI allows users to fill in the information that is needed for algorithm processing, as shown in figure 12. The 1st and 2nd boxes (from the top) are for inputting the location of a WSD in terms of Latitude and Longitude in degree, respectively. The 3rd and 4th boxes are for inputting the location of a TV receiver in terms of Latitude and Longitude in degree, respectively. The 5th and 6th boxes are for inputting the antenna height of a WSD in meters and the transmitted power of a WSD in dBm, respectively. The 7th, 8th and 9th boxes are the antenna height of a TV receiver in meters, the frequency of a TV receiver in MHz and the received power of a TV receiver in dBm, respectively.

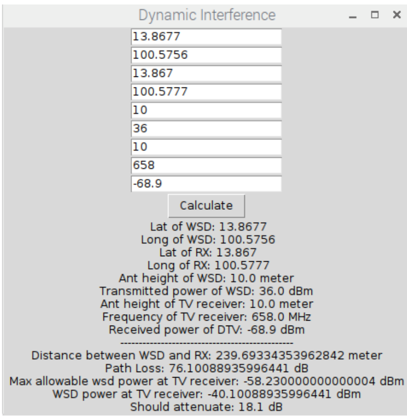



Figure 12. The GUI of the Dynamic Interference Suppression System

Secondly, when the user starts the calculation, the input information and results will be displayed on screen as shown in the lower half of figure 12. There are five results such as the distance between WSD and TV receiver, the path loss, the maximum allowable WSD power at TV receiver, the WSD power at TV receiver and the result of interference evaluation. At the bottom line, the result of interference evaluation is shown, namely the co-channel can be used, the interference signal should be attenuated, or the adjacent channel should be used.

In case the co-channel can be used, the attenuation state is 0 dB. Similarly, in case the adjacent channel should be used, the attenuation state is 0 dB as well. However, in case the interference signal should be attenuated, the attenuation value derived from our proposed algorithm is converted into the attenuation state. If the attenuation value is lower than 0.5dB, it is rounded up to 0.5dB. However, if the attenuation value is greater than 0.5dB, this state is rounded up to 1dB.

After the algorithm runs, the output power of the WSD signal is reduced by an RF attenuator. In figure 13, the algorithm processing with the testbed hardware is illustrated. As an example, when the output calculated from the algorithm is 19dB, the Raspberry Pi transforms this value to a 6-bit binary digit. Then, all these binary digits are sent to the RF attenuator, which is '1 0 0 1 1 0' in this case. Finally, at RF output of the attenuator, the channel power of this signal is decreased by 19dB.

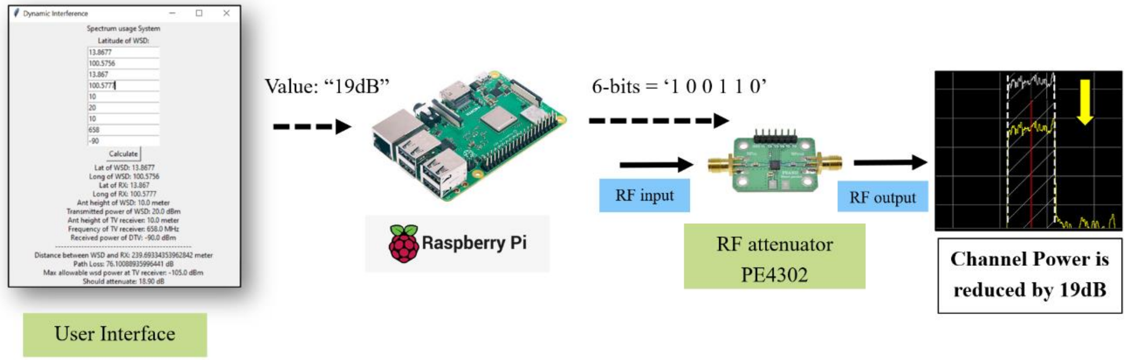



Figure 13. Algorithm Processing with Testbed Hardware.

### 3.4. Performance Evaluation Metrics

Here, the performance of our proposed method is evaluated technically and subjectively.

#### 3.4.1 Technical Evaluation Metrics

The technical evaluation metrics consists of two metrics as follows:

(1) Protection ratio or D/U (Desired-to-Undesired) ratio. The definition of D/U ratio can be given as follows:

$$D/U\ ratio = \frac{Received\ signal\ power\ of\ signal\ under\ consideration}{\sum Receieved\ signal\ power\ of\ the\ other\ signals}$$

The value of protection ratio or D/U ratio are identified by several organizations, namely FCC and OFCOM. In this work, we need to investigate the appropriate D/U ratio for our study since the value identified by those organizations are different. In doing this, the Testbed hardware in section 3.3 is used for testing.

(2) Modulation Error ratio (MER)

The modulation scheme is one factor that needs to be tested, since different modulation scheme provides different data rates. For instance, 64QAM and 256QAM provide data rates of 13Mbps and 18Mbps, respectively. Therefore, MER (Modulation Error Ratio) which is an indicator by measurement, can be used to quantify the interference effect.

Firstly, we investigate the relevance between D/U ratio and modulation techniques. In addition, we need to investigate the appropriate value of D/U ratio for use as a benchmark for our QoE (Quality of Experience) test. The result of our experiment is shown in figure 14. In figure 14, the D/U ratios of various modulation schemes are illustrated with the 95% confidence interval. It is obvious that the modulation schemes are irrelevant to the D/U ratio. From our tests, we achieve the average D/U ratio of 13.93 dB and -10.67 dB for co-channel and adjacent channel, respectively. These values will be used as the benchmark of our algorithm in QoE test.

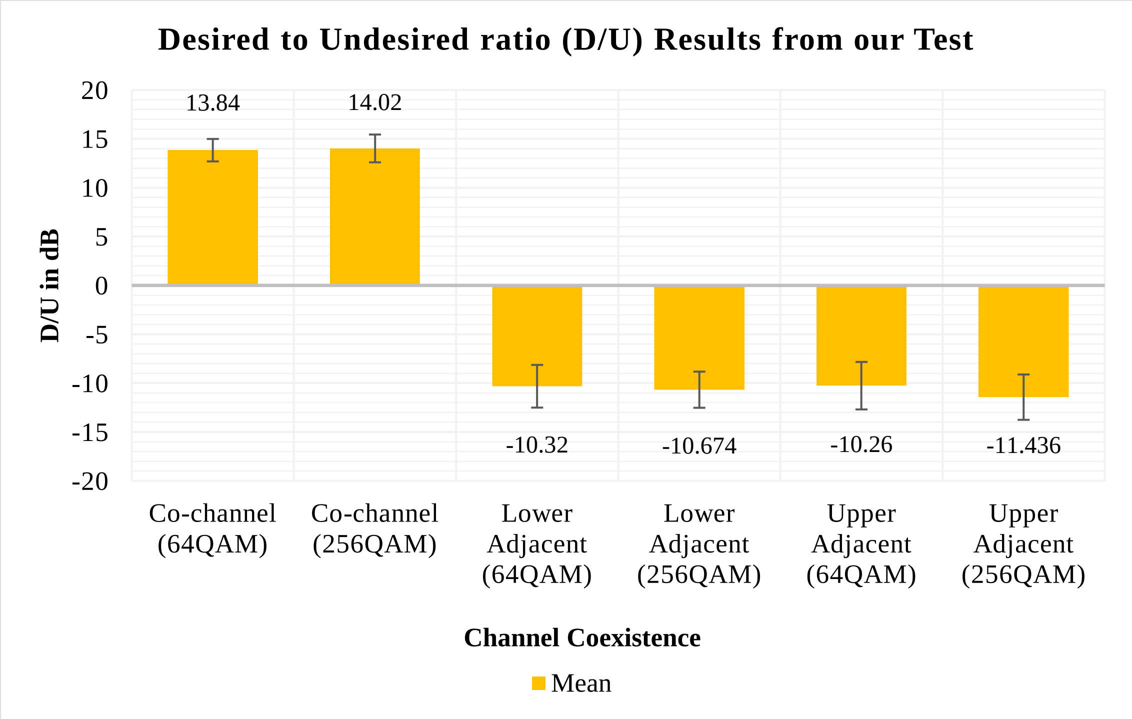



Figure 14. D/U Ratio Results from our Test

### 3.4.2. Subjective Evaluation Metric

To evaluate the performance of our proposed method subjectively, the Quality of Experience (QoE) method is adopted to assess the impact of LTE interference on the DTTB. In figure 15, the QoE implementation in this work is illustrated. This method of assessment for observing the screen irregularity is called TOV (Threshold of Visibility) technique. This TOV technique can be carried out step-by-step as follows:

- The observer is located at a recommended distance of 1.2 to 1.8 meters from the TV receiver. In this work, we use a PROMAX field strength meter as a TV receiver.
- This overall assessment takes totally 40 minutes divided into 4 sets of 10 minutes each [17].
- During observation, the observer will assert 1, if at least one pixilation or distortion appearance in any timestamp of 1 minute [17]. The screen irregularity, such as black or freezing screens sometimes occurs, as shown in figure 16.
- This result is recorded and the percentage of the video degradation is calculated, given that the level of LTE signal is recorded without adjusting the interference.

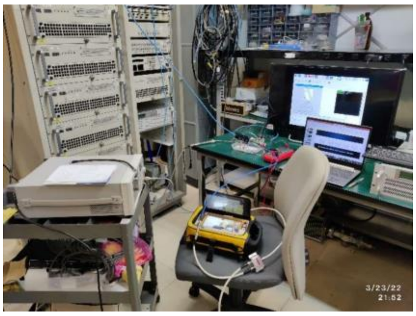


Figure 15. QoE Assessment Equipment and Facility


Figure 16. Examples of Video Distortion on TV screen (black and keep freezing)

Here, the parameters used for QoE assessment are illustrated in Table 6. The scenarios under consideration are the co-channel, the upper and lower adjacent channels.

Table 6. The Parameters for QoE Assessment

| **Parameters** | **Co-channel** | **Upper adjacent channel** | **Lower adjacent channel** |
|---|---|---|---|
| Location of WSD (Latitude & Longitude) | (13.8677, 100.5756) | | |
| Location of TV Receiver (Latitude & Longitude) | (13.8670, 100.5777) | | |
| Antenna Height of WSD (m) | 10 | | |
| Transmitted Power of WSD (dBm) | 20 | 36 | 36 |
| Antenna Height of TV Receiver (m) | 10 | | |
| Frequency of TV Receiver (MHz) | 658 | 663 | 653 |
| DTTB Power (dBm) at TV receiver | -49.4 | -68.9 | -68.9 |
| LTE Power at TV Receiver (dBm) (calculated from algorithm) | -56.1 | -40.1 | -40.1 |
| Minimum required D/U Ratio (dB) | 13.93 | -10.67 | -10.67 |

## 4. EXPERIMENTAL RESULTS

This section presents the results of our experiment described in section 3. Firstly, we validate our program and testbed by 2 experiments. The attenuation error can be achieved. Secondly, we test the D/U ratio vs MER (Modulation Error ratio) and illustrate the results. Finally, we perform the QoE testing and illustrate the video degradation with and without our proposed algorithm.

### 4.1. Validation of Program and Testbed

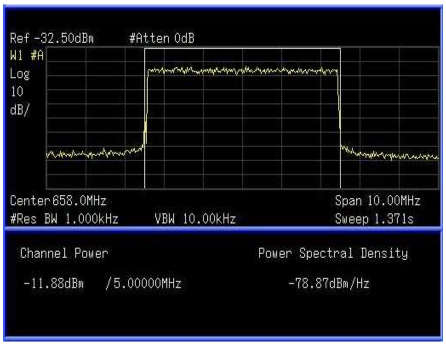
Firstly, the validation of our program as well as our testbed is carried out only on the co-channel in 2 cases by varying the power of signal received at TV receiver. The parameters as well as their values are shown in Table 7.

Table 7. The Parameters for Validation of Program and Testbed

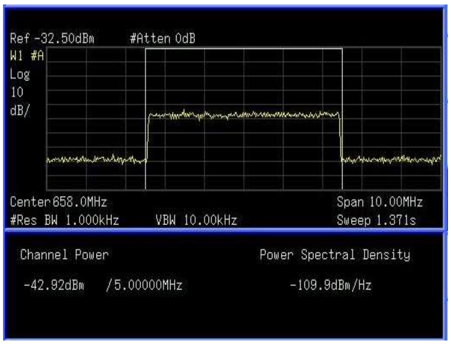
| **Parameters** | **Case 1** | **Case 2** |
|---|---|---|
| Location of LTE Device (Latitude & Longitude) | (13.8677, 100.5756) | |
| Location of TV Receiver (Latitude & Longitude) | (13.8670, 100.5777) | |
| Antenna Height of WSD (m) | 10 | |
| Transmitted Power of WSD (dBm) | 20 | |
| Antenna Height of TV Receiver (m) | 10 | |
| Frequency of TV Receiver (MHz) | 658 | |
| DTTB Power (dBm) at TV receiver | -70.0 | -102.5 |
| Distance between LTE Device and TV Receiver | 239.6933 | |
| Path Loss (dB) | 76.1009 | |
| Max Allowable LTE Power at TV Receiver (dBm) | -85.0 | -117.5 |
| Required Attenuation Level (dB) | 0 | 31.4 |

The frequency spectrums of our validation are shown in figures 17(a) and (b). In case 1, as shown in figure 17(a), the attenuator is not necessary, since the D/U ratio already satisfies the minimum requirement. That is, the co-channel frequency can be used by both DTTB and LTE. While case 2, as illustrated in figure 17(b), represents a 5 MHz bandwidth of LTE signal which has power of -11.88 dBm. However, the LTE signal whose power is -42.92 dBm needs to be attenuated by 31.4 dB to satisfy the minimum requirement of D/U ratio.

According to these results, it can be ensured that our testbed works properly. However, it is found that the attenuator error occurs. Based on the specifications of the RF attenuator, the error may occur due to the frequency, the attenuation setting, and the temperature. Therefore, we need to investigate the attenuation error in our work. Then, we plot the graph of the attenuation error versus the attenuation state setting on the same frequency of 658 MHz and the same temperature of 25C. The result of the attenuation error is shown in figure 18. Overall, the attenuation error is less than 0.2dB at all attenuations except at the attenuation of 31.5 dB, where the attenuation error is approximately 0.46 dB. It can be concluded that the error of RF output may occur, and it needs to be noticed when the attenuation result is observed.




(a) Case 1 (No attenuation).




(b) Case 2 (attenuated by 31.4 dB)

Figure 17. The Frequency Spectrum of LTE signal

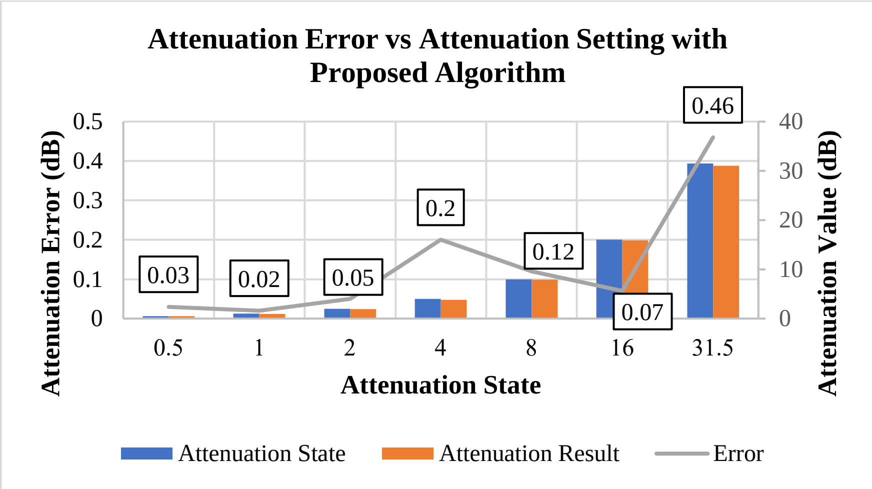
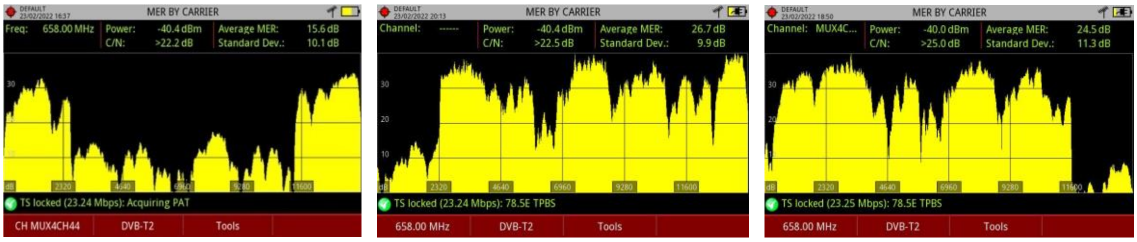



Figure 18. The graph of Attenuation Error vs Attenuation Setting

## 4.2. D/U Ratio vs MER (Modulation Error Ratio) Results

It is well-known that the Modulation Error Ratio (MER) is one of the important metrics used to evaluate the performance of DTTB. The higher the value of MER, the better the received DTTB signal is. In this work, the PROMAX field strength meter is used to analyze the MER for each carrier on the selected channel. It represents the frequency spectrum where the MER degrades. For example, if a 5MHz bandwidth LTE signal is operated on the same channel of an 8MHz DTTB, so the MER at the center of channel will be degraded. The MER measured by carrier measurement for the co-channel, lower and upper adjacent channels in this work are shown in figure 19(a)~(c), respectively.




(a) Co-channel (b) Lower adjacent channel (c) Upper adjacent channel

Figure 19. MER (Modulation Error Ratio) by Carrier Measurement

Furthermore, we investigate the relationship between the D/U ratio and MER. The result is shown in figure 20. According to the graph of D/U ratio versus MER, it is obvious that the high D/U ratio causes the high MER for all types of coexistence of DTTB and LTE. That is, the undesired signal or the interference is very low compared to the designed signal. Therefore, the quality of the received signal is excellent. In this work, we investigate only the D/U ratio that causes the average MER of at least 15.6 dB which is high enough for our receiver.

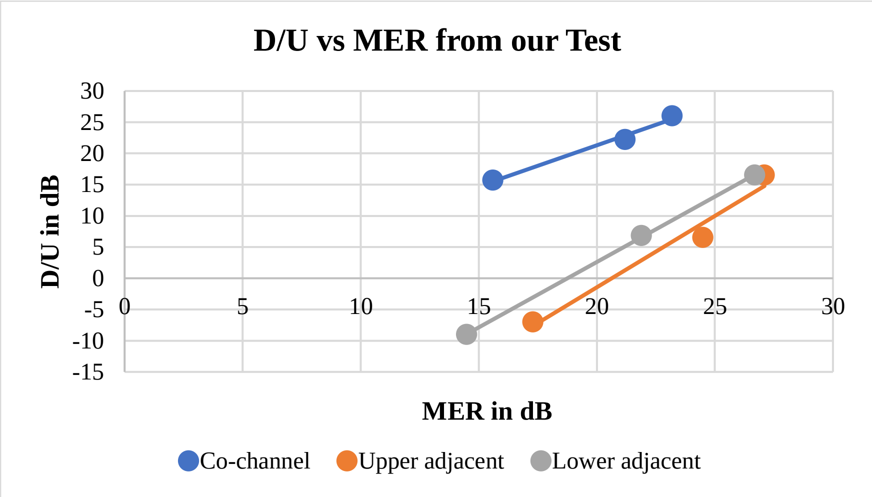



Figure 20. The Graph of D/U Ratio versus MER (Modulation Error Ratio)

### 4.3. QoE Results

In this section, the effectiveness of our proposed algorithm is shown in figure 21, where the percentages of video degradation with and without our proposed algorithm are illustrated. It is obvious that in all frequency bands, the video degradation of the scenario adopting our proposed algorithm is drastically lower than the video degradation without adopting our proposed algorithm. The percentages of video degradation of co-channel and adjacent channel in case of adopting our proposed algorithm is less than without adopting our proposed algorithm at least 62.5% and 87.5%, respectively.

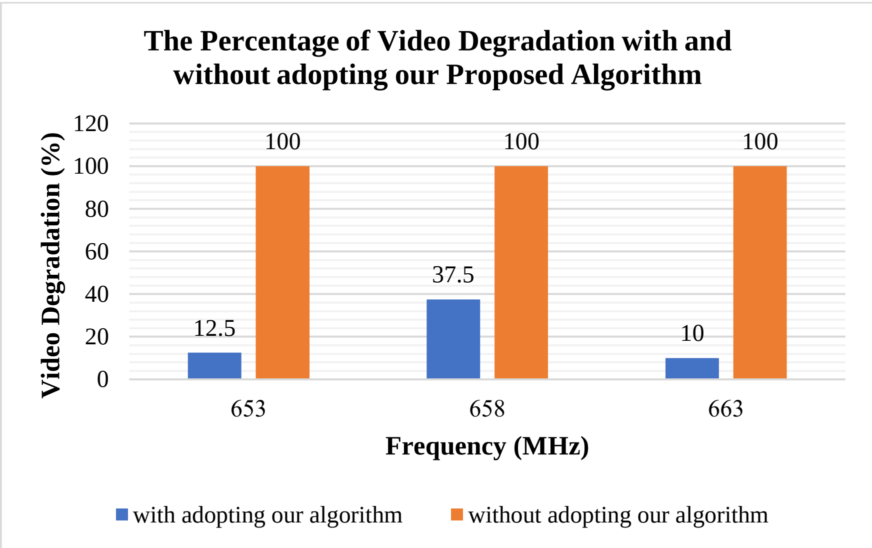



Figure 21. The Percentage of Video Degradation with and without adopting our Proposed Algorithm

## 5. Conclusions

In this work, the fundamental concept of TVWS (TV White Space) including the optimization of TVWS by using the dynamic interference method is studied. This method exploits a protection ratio concept that is used to protect a DTTB receiver from 5MHz LTE signals when the co-channel or adjacent channel is employed. We implement the algorithm using Raspberry Pi as our testbed.

According to our experiment, it is found that the appropriate D/U ratios achieved from our proposed algorithm for the co-channel and adjacent channel are 15.93 dB and 10.67 dB, respectively. As a result, this can reduce the perceived video distortion by at least 62.5% and 87.5% for co-channel and adjacent channels, respectively. Moreover, this method can increase the available frequency channel for any WSD by 100% for co-channel, upper and lower channels. This means that normally the WSD can only be operated on the White Space channel, but by adopting our proposed algorithm and hardware, the WSD can also be operated on the co-channel and adjacent channel. Even though this method can minimize interference and increase spectrum usage, the percentage of video degradation is still high in actual utilization.

Based on the achievement from this work, an automatic real-time interference management is highly recommended putting into account the QoE for digital television users. For example, TV receiver should be equipped with device to send the feedback regarding the interference to the system management. In this work, only a 5 MHz LTE signal generated from the signal generator is considered. However, the actual LTE parameters, such as traffic load as well as the geographical environment have not been put into account. Therefore, the scenario adopting the actual LTE signal should be studied further.

### Recommendation for Future Problems

For future development of wireless communications operated on TVWSs, it also needs the optimization of spectrum usage efficiency without affecting the users' Quality of Service (QoS) and Quality of Experience (QoE). In addition, the actual Wireless Broadband signal should be used in experiment.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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