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การศึกษาประสิทธิภาพของเครือข่ายนำร่องคลื่นความถี่ของกิจการโทรทัศน์ที่ไม่มีการใช้งานในประเทศไทย

PERFORMANCE STUDY OF TELEVISION WHITE SPACES (TVWS) PILOT NETWORK IN THAILAND

บิพุน แม้นพาที[1] อัฐพงษ์ เทพารักษ์ษณากร[2] อดิสรณ์ เลิศสินทรัพย์ทวี[3]
นิศารัตน์ ตันสกุล[4]

Bipun ManPati[1] Attaphongse Taparugssanagorn[2]
Adisorn Lertsinsrubtavee[3] Nisarat Tansakul[4]

สถาบันเทคโนโลยีแห่งเอเชีย (เอไอที) ปทุมธานี 12120 [1 ถึง 4]
Asian Institute of Technology, Pathum Thani 12120, Thailand [1 to 4]

Corresponding E-mail : st119320@ait.ac.th[1]

Received Date January 8, 2019
Revised Date February 11, 2019
Accepted Date February 11, 2019

บทคัดย่อ

การวิจัยในบทความนี้ มีวัตถุประสงค์เพื่อศึกษาประสิทธิภาพของเครือข่ายนำร่องคลื่นความถี่ของกิจการโทรทัศน์ที่ไม่มีการใช้งานในแต่ละพื้นที่หรือที่เรียกว่า ทีวีไวท์สเปซ โดยระเบียบวิธีวิจัยนั้น เครือข่ายนำร่องถูกติดตั้งขึ้นและทดสอบที่พื้นที่ทางไกลเข้าถึงยากทางภาคเหนือของประเทศไทย ทีวีไวท์สเปซนี้อ้างถึงช่องสัญญาณในย่านความถี่สูงยิ่ง (ยูเอชเอฟ) ครอบคลุมตั้งแต่ 510 ถึง 790 เมกะเฮิรตซ์ที่ได้ถูกจัดสรรสำหรับกิจการโทรทัศน์ดิจิทัล และสามารถถูกใช้งานโดยผู้ใช้รองเมื่อมีโอกาสนั่นหมายถึง เมื่อมีช่องสัญญาณว่าง เราศึกษาประสิทธิภาพของเครือข่ายโดยวัดระดับสัญญาณ ณ จุดติดตั้งอุปกรณ์ตัวรับสัญญาณ ค่าทรูพุต อัตราการล่าช้า การสูญเสียของแพ็กเก็ต และค่าผันแปรของความล่าช้า ผลการวิจัยศึกษาพบว่าค่าทรูพุตที่ได้นั้น มีค่า 4-13 เมกะบิตต่อวินาที ค่าอัตราการล่าช้าและค่าผันแปรของความล่าช้ามีค่าต่ำน้อยกว่า 16 มิลลิวินาที และ 2.5 มิลลิวินาทีตามลำดับ ทั้งกรณีเชื่อมโยงแบบจุดต่อจุดและแบบจุดต่อหลายจุด ส่วนการสูญเสียของแพ็กเก็ตขึ้นกับอัตราการส่งข้อมูล ซึ่งที่อัตราส่งข้อมูล 5 เมกะบิตต่อวินาที การสูญเสียของแพ็กเก็ตส่วนมากไม่สูงกว่า 10% ซึ่งบ่งบอกถึงประสิทธิภาพที่ดีของเครือข่าย เหมาะกับการสื่อสารข้อมูลทั้งเสียงภาพวิดีโอและข้อมูลเรียลไทม์ซึ่งถือเป็นระบบการสื่อสารทางเลือกที่ดี ต้นทุนต่ำ เหมาะกับทั้งในพื้นที่ทางไกลเข้าถึงยาก หรือจะเป็นการช่วยถ่ายโอนลดภาระโหลดหรือที่เรียกว่า ออฟโหลด จากเครือข่ายที่มีการใช้งานหนาแน่น เช่น เครือข่ายเซลลูล่าร์ในเมืองใหญ่ เช่น กรุงเทพฯ และสำหรับรองรับการประยุกต์ใช้ที่เกิดขึ้นใหม่ เช่น ไอโอทีหรืออินเทอร์เน็ตของสรรพสิ่ง

คำสำคัญ : ความล่าช้า อัตราส่วนกำลังสัญญาณที่ต้องการต่อกำลังของสัญญาณรบกวน ความเร็ว การครอบครองคลื่นความถี่ ค่าผันแปรของความล่าช้า

Abstract

In this paper, we study the performances of a Television White Space (TVWS) pilot network, which is deployed in a rural and remote region in Northern Thailand. TVWS referring to vacant channels in the Ultra-High Frequency (UHF) band between 510 MHz and 790 MHz assigned for Digital Television (DTV) broadcast and can be used opportunistically by Secondary Users (SUs). The TVWS pilot network provides a point-to-multi-point Internet connectivity to three rural locations. We investigate the basic network performance metrics including the powers of received signals, network throughputs, round-trip latencies, packet losses, and jitters. The performance results show good throughput for each link, which is in the magnitude of 4 to 13 Mbps. The latency and jitter in both point-to-point and point-to-multi-point modes are less than 16 ms for typical packet sizes ranging from 32 to 1500 bytes and less than 2.5 ms, respectively. In addition, the packet loss rate, which is proportional to bit rate, is less than 10% at the data rate of 5 Mbps indicating good performance of the network. The performance is excellent and suitable for voice, video and real-time data transmissions. A TVWS based wireless broadband system can be considered as a good alternative with low cost for both hard-to-access rural areas or for data offloading techniques in dense cellular networks in major cities such as Bangkok and for supporting emerging applications such as Internet of Things (IoT).

Keywords : Delay, SNR, Speed, Spectrum Occupancy, Jitter

Introduction and Problem Statement

Wireless communication networks are the most feasible broadband solution for rural and remote hard-to-access areas with low density and lack of more costly fixed line infrastructure. Nevertheless, wireless networks rely on the availability and affordability of Radio Frequency (RF) spectrum, which is scarce in nature. Several studies assert that the utilization of the licensed frequency bands varies from 10% to 85% depending on the geographical location and time of the day (Lysko et al., 2015). Dynamic spectrum sharing, especially on Television White Space (TVWS) referring to vacant channels in the Ultra-High Frequency (UHF) band between 510 and 790 MHz assigned for Digital Television (DTV) broadcast (in Thailand and some other countries) can be used opportunistically by Secondary Users (SUs) has become of great interest due to its potential in increasing the availability and ubiquity of broadband access (Masonta et al., 2013).

As a result, there have been a number of TVWS trials conducted around the world. The results of these trials contributed significantly towards the formulation of regulatory rules governing the use of TVWS in the United Stated of America (USA) (Federal Communications Commission , 2012) and United Kingdom (Ofcom, 2015). The Council for Scientific and Industrial Research (CSIR) with its partners have conducted two TVWS trials in South Africa, i.e. Cape Town TVWS trial (Lysko et al., 2014) and Limpopo TVWS trial (Masonta et al., 2015). The Cape Town TVWS trial started in 2012 and most of the technical results have been published and were used by the Federal Communication Commission, USA to motivate softening of the guard band requirements of the TV channels and TVWS (Federal Communications Commission, 2014). Many TVWS trial networks have been deployed, for instance, the Cambridge white spaces trial in UK including various scenarios, such as city center, rural, and Machine-to-Machine (M2M) connectivity (DSA, 2015). In Singapore, a commercial pilot study began in 2013 covering various commercial services, for example, monitoring applications and video surveillance (DSA, 2015). The National Institute of Information and Communications Technology (NICT) in Japan with support from the King's College London launched a trial network under the patronage of the Ofcom TVWS Pilots (Microsoft, 2013). A Long-Term Evolution (LTE) cellular system extended to operate using TVWS frequencies, aggregated 3 TV channels and achieved a downlink throughput of 45 Mbps in Frequency Division Duplex (FDD) mode and 19 Mbps in Time Division Duplex (TDD) mode (NICT, 2014). The IEEE 802.11af, a.k.a., Super WiFi or White-Fi system established a 3.7 km point-to-point link using one TV channel achieving a downlink throughput of over 2 Mbps. A TVWS network was set up and backhauled through Very Small Aperture Terminal (VSAT) for a disaster recovery application in Philippines. Besides South Africa, the TVWS trials have been deployed in several other countries in Africa including Tanzania, Malawi, Kenya, Namibia, and Ghana (Lysko et al., 2015, ETSI, 2014, Mikeka et al., 2014). While the Cape Town trial is the first large scale TVWS trial network in Africa providing alternative means of reliable high speed wireless connectivity (Lysko et al., 2014), the Namibian trial is currently the largest trial network in the world (Federal Communications Commission, 2014). In Thailand, under the TVWS project funded by the NBTC Research and Development Fund of Thailand, it is the first time of the research and of the pilot trial on TVWS.

While the expectations from using TVWS for wireless broadband service are high, the commercial and technical viability of TVWS operations is still largely unknown (Haji, 2013). Several researchers have studied the use of TVWS for other applications (Achtzehn et al., 2012, Gomez, 2013). The feasibility on the use of TVWS for broadband access is not only for rural areas but also for urban areas with the potential for traffic offload from congested mobile broadband networks. Most of the studies on TVWS have either focused on the availability of the TVWS or the development of TVWS regulatory framework and white space device specifications (Achtzehn et al., 2012, Gomez, 2013). On the other hand, there are very few studies focused on the performance of a deployed TVWS network. Therefore, this paper presents the performance study of our TVWS pilot network, which is deployed in a rural and remote region in Northern Thailand. The evaluation of the performance of well-defined secondary systems in realistic scenarios will eventually help to gauge the market prospects for TVWS-driven technologies and potentially guide subsequent regulatory rule-making.

Methodology

This section includes the research methodology outlining 1. the system setup, 2. received signal measurements, and 3. network performance monitoring.

1. System Setup

The TVWS broadband radio used the radio commercial TVWS cognitive radio system from Carlson called RuralConnect® Gen 3 utilizing white space spectrum within the UHF TV band from 470 to 698 MHz (up to 790 MHz in some countries) (Carlson Rural Connect). The Base Station (BS) is an Outdoor Unit (ODU) with three radios, each to be connected to a 120-degree sector antenna. The Customer Premise Equipment (CPE) ODU has a single TVWS radio with 75-Ohm F-connector. The CPE utilizes a directional log-periodic antenna to receive up to 24 Mbps (6 MHz) or 32 Mbps (8 MHz) over the air. The RuralConnect® uses the IEEE 802.11af standard, also called “Super WiFi or White-Fi.” Orthogonal Frequency Division Multiplexing (OFDM) is used to provide protection against signal fading caused by multipath interference (Phase-shifting) due to inevitable reflections from trees, buildings, and hills while offering a robust clean transmit spectrum. The robustness and high data rate are obtained with an adaptive modulation algorithm using BPSK, QPSK, 16QAM, 64QAM, and 256QAM modulation types.

Figure 1 shows the TVWS pilot network connects a school named "Ban Mae Kuang Luang Khanchai Mittaphap 182 School" in Tak, the province in the Northern Thailand located close to Myanmar, to three following villages in Maekasa district, namely, 1. Thai Samakkhi Village Moo 1, 2. Thai Samakkhi Village Moo 9, and 3. Baan Mai Rim Moei Moo 10 with the following distances, 0.45 km, 0.85 km, and 1.41 km, respectively.

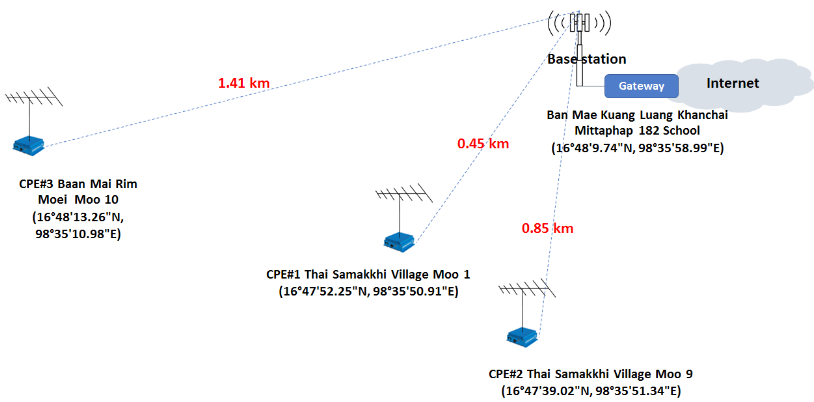


Figure 1 Topology of the TVWS pilot network showing all the participating CPE sites and the BS

Obviously, the pilot network has a star topology with a BS and its antenna located on the pole with a height of 24 m in the Ban Mae Kuang Luang Khanchai Mittaphap 182 School. This height is valid since per FCC regulations, antennas used with fixed TV Band devices may not be more than 30 m above ground level, or 250 m above average terrain. The height of the antenna at each CPE terminals is 10 m. At the BS in the Ban Mae Kuang Luang Khanchai Mittaphap 182 School. there has been also using a high-speed Internet using fiber optic with the speed of 100/50 Mbps. As depicted in Figure 1, the CPE at Point 1, Thai Samakkhi Village Moo 1 is the closest from the BS, but there are high trees and several houses along the link, while Point 3, Baan Mai Rim Moei is the farthest from the BS, but the link has both some obstructions and open fields.

The 120-degree sector antenna of the BS uses 658 MHz (Radio channel#44), 522 MHz (Radio channel#27), and 538 MHz (Radio channel#29) for Sectors 1, 2, and 3, respectively. The first link (Link#1) and the second link (Link#2) to Thai Samakkhi Village Moo 1 and Thai Samakkhi Village Moo 9 use the same frequency band, i.e., 658 MHz (Radio channel#44) since these two villages located in the same coverage of Sector 1, while the third link (Link#3) to Baan Mai Rim Moei uses Sector 2, i.e., 522 MHz (Radio channel#27).

2. Received Signal Measurements

After installing and commissioning our TVWS system, the preliminary testing is to measure the powers of received signals P_R at the CPEs using the Agilent N9340B RF Spectrum Analyzer. Note that a portable RF Explorer can also be used but a calibration and the corresponding compensation are required. Signals travelling in the environment as an electromagnetic wave are suffered from path loss. These waves are not aware of the exact route to the receiver. Once they propagate in the direction where the antenna directs them. The receiver captures a certain fraction of transmitted power depending on different factors, such as distance, obstacles, etc. Path loss L_P can be expressed by the relationship between the powers of transmitted signal P_T and received signal P_R as

$$L_P = \frac{P_T}{P_R}. \quad (1)$$

The average power of received signal determines the probability of bit detection error or Bit Error Rate (BER) at the receiver. Estimating the path loss within a given real-world terrain/geography is not a simple problem. It is impacted, among other things, for instance, by the height of the transmitter and receiver antennas, whether there is Line-of-Sight (LoS) or Non-Line-of-Sight (NLoS), the geography/terrain in terms of hills, mountains, the vegetation in terms of attenuation by foliage any type of construction, and if so, the type of materials used in that construction, the height of the buildings, their distance, and the frequency used. Lower frequencies like UHF and VHF generally expose better NLoS characteristics than higher frequencies (COST 259, 2001).

Although the Okumura-Hata model is one of the most extensively considered those mentioned factors using empirical propagation models (COST 259, 2001) and is a well-established model for the Ultra High Frequency (UHF) band as it supports the frequency range from 150 to 1500 MHz it cannot be applied in our case due to the out-of-range height of the BS antenna

(30-200 m). One of the most widely used propagation prediction models that take account of the terrain irregularity is the Longley-Rice (L-R) model (COST 231, 1999, Radio Mobile, 2014). The L-R path loss model $L_{P, L\text{-}R}$ supporting the frequency range from 20 MHz to 20,000 MHz is also known as Irregular Terrain Model (ITM) and used through Radio Mobile (Radio Mobile, 2014). It uses the path geometry of terrain profile and the refractivity of the troposphere. It also accounts for climate and subsoil conditions when predicting the path loss. Because of the level of detail in the model, it is generally applied in the form of a computer program that accepts the required parameters and computes the expected path loss (Radio Mobile, 2014). In practice, we can compute the actual path loss L_P from (1) and compare with those from the models.

Besides LoS or actually visual LoS, the other factor, which has impact on the strength of the received signal, is Fresnel effect, which is actually included in so-called radio frequency LoS. In other word, for radio communications to work properly, an additional area around the visual LoS needs to remain clear of obstacles and obstructions. This area around the visual LoS is known as the Fresnel zone. The concept of Fresnel zone clearance may be used to analyze interference by obstacles near the path of a radio beam as a confocal prolate ellipsoidal shaped region in space, centered around the line of the direct transmission path. The first zone must be kept largely free from obstructions to avoid interfering with the radio reception. However, some obstruction of the Fresnel zones can often be tolerated. The radius of an ellipsoid at a point between the transmitter and the receiver or the n^{th} order Fresnel zone is given by the following formula (Westcott & David, 2012):

$$R_n = \left[\frac{n\, c d_1\, d_2}{f(d_1 + d_2)} \right]^{1/2}, \qquad (2)$$

Where c is the speed of light equal to 3×10^8 m/s, f is the frequency (MHz), and d_1 and d_2 are the distances (km) between transmitter and receiver at the point where the ellipsoid radius (m) is calculated.

As a rule of thumb for best practice the maximum obstruction allowable is 40% meaning that we should maintain at least 60% of the first Fresnel zone radius free of obstructions to avoid fading of the received signal, but the recommended obstruction is 20% or less (Westcott & David, 2012).

3. Network Performance Monitoring

Network monitoring is done at three CPE sites using the monitoring tool called Internet Performance working group (Iperf) to measure network throughput, packet loss rate, and jitter. Additionally, round-trip latency is measured using the ping utility diagnostic tool. Network throughput is the amount of data moved successfully from one place to another in a given time period, and typically measured in bits per second (bps). Packet loss occurs when one or more packets of data travelling across a network fail to reach their destination. It is either caused by errors in data transmission, typically across wireless networks or network congestion. Packet loss is measured as a percentage of packets lost with respect to packets sent. Jitter is the deviation from true periodicity of a presumably periodic signal, often in relation to a reference clock signal. It is a significant and usually undesired factor in the design of almost all communications links. Finally, round-trip latency, a.k.a., Round-Trip Delay time (RTD) or Round-Trip Time (RTT) is the length of time it takes for a signal to be sent plus the length of time it takes for an acknowledgement of that signal to be received plus the propagation times for the paths between the two communication endpoints.

The objectives of this study are as follows:

1. For point-to-point measurements we measure the addressed performance metrics of both the downlinks (from the BS to each CPE) and uplinks (from each CPE to the BS). The tests are performed for each CPE link in turns while the other links are disabled in order to measure the peak performance of each link. The measurements are both run for 60 seconds for each link. The same set of parameters is considered for both downlink and uplink measurements. The default iperf fixed packet size of 1,470 bytes is considered for Transmission Control Protocol (TCP) throughput, and User Datagram Protocol (UDP) packet loss rate, and jitter measurements, while the packet size varies as 32, 512, and 1500 bytes for the average round-trip latency measurements. A stream of fixed sized packets is generated and sent through each link at variable data rates for the packet loss rate and the jitter measurements.

2. Besides the point-to-point measurements, point-to-multi-point measurements are also done when all links are on. In addition, the case that the TVWS network (Link#2 is connected to our existing Wireless Mesh Network (WMN). We present and study network performance results in the next section.

Results : Data Analysis

In this section we investigate the above mentioned powers of the received signals and the network performance metrics. According to the specification of RuralConnect® Gen 3 Carlson TVWS radio system, the transmit power is equal +21 dBm or 0.126 Watt. The measured power of received signals P_R at each CPE using the Agilent N9340B RF Spectrum Analyzer is reported in Table 1 along with the corresponding path losses and the radius of first order Fresnel zone. The received signal power of each link P_R is measured to guarantee the link functionality. We can see that the considered L-R path losses and even the ideal free space path losses well fit the actual path losses. However, this might not be a sufficient conclusion since it contains only three different positions. Moreover, all links have acceptable radius of the first order Fresnel zone.

In addition to the powers of the received signals, we investigate the effect of polarization of the antenna. Using horizontal polarization we are able to receive not only the TVWS signals but also the DTV signals since the commercial DTV and radio stations use horizontally polarized antennas. The received powers from TV signals are quite strong so that we can clearly see increased power levels of the spectra. On the other hand, using vertical polarization we do not receive the DTV signals, but we receive only the TVWS signals.

Table 1 Power of received signal P_R, actual path loss L_P, free space L_{PF}, L–R path loss $L_{P\ L\text{-}R}$, and radius of the first order Fresnel zone L_1 of each link

	Link#1	Link#2	Link#3
P_R (dBm)	-62.94	-64.61	-65.8
L_P (dB)	83.94	85.61	86.8
L_{PF} (dB)	81.87	87.39	91.79
$L_{P\ L\text{-}R}$ (dB)	81.50	87.60	98.1
R_1 (m)	7.052	9.692	14.22

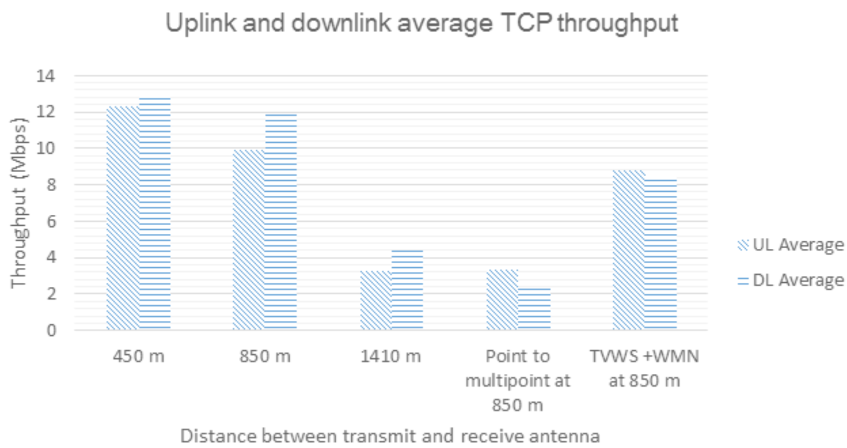
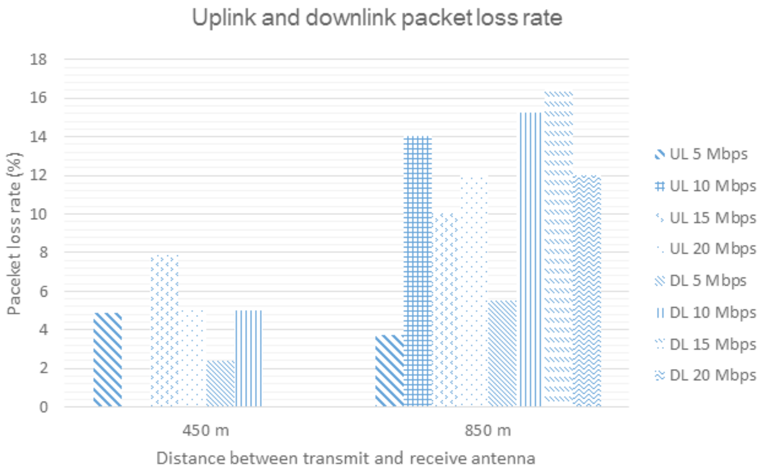
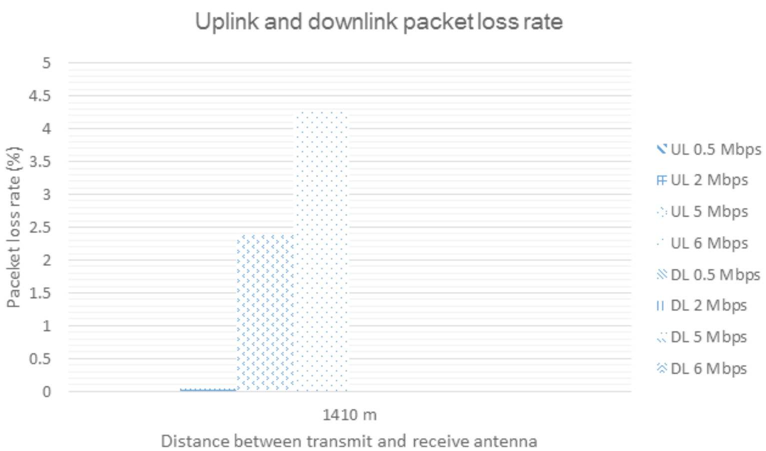


Figure 2 Throughput of Link#1, Link#2, Link#3, overall TVWS, and Link#2+WMN

Figure 2 shows the average downlink and uplink TCP throughput performance results for all cases. From the point-to-point results, we observe that links with shorter distances achieved higher average throughput as compared to longer links. The shortest link (0.45 km) achieves the highest average throughput rates of 12.9 Mbps and 12.3 Mbps in its downlink and uplink respectively. The longest link (1.41 km) achieves 4.39 Mbps and 3.59 Mbps in its downlink and uplink, respectively. The point-to-multi-point throughput is measured by generating traffic in the BS to CPE Moo 1 link and then measuring the throughput in the BS to CPE Moo 9 link. As compared to the case of point-to-point at 850 m, the throughputs are reduced from 11.8 Mbps (downlink) and 9.89 Mbps (uplink) to 2.34 Mbps (downlink) and 3.32 Mbps (uplink). This is because the same sector and channel is shared by more than one CPE. Finally, we measure the throughput of TVWS connected to WMN at CPE M9 location. The reduction in throughput can be accounted for the traffic in the WMN. In general, the achievable throughput is inversely proportional to the distance, i.e., it decreases with the increase in distance.



a) Links#1 and #2



b) Link#3

Figure 3 Packet loss of a) Link#1, Link#2, and b) Link#3

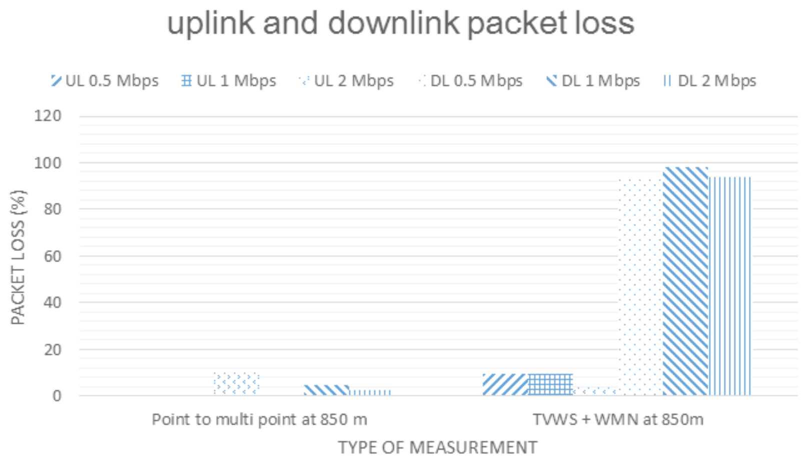


Figure 4 Packet loss of overall TVWS, and Link#2+WMN

The UDP results in terms of packet loss rate are shown in Figures 3 a) and b) and 5. A stream of fixed sized packets of 1,470 bytes is generated and sent through each link at variable data rates ranging as 5 10 15 and 20 Mbps for the case of Links#1 and 2 and 0.5 2 5 and 6 Mbps for the case of Link#3. At the bit rate of 5 Mbps, all tested links performed well with packet loss rate not more than 10%. Links#1 and #2 appears to be more robust compared to Link#3 as significant packet loss only occurs when the bit rate is set to 10 Mbps and above. Link#3 cannot support for bit rate at 6 Mbps and above and gives 100% packet loss. Therefore, we study the packet loss of Link#3 at lower data rates, i.e., 0.5 Mbps 2 Mbps 5 Mbps and 6 Mbps. The packet loss for both the point-to-multipoint and TVWS plus WMN cases cannot be carried out at 5 Mbps. Thus, we decrease the set of the data rate from 5 Mbps to 20 Mbps to 0.5 Mbps to 2 Mbps as shown in the Figure 4. Both the uplink and downlink packet loss rates are satisfactory at these data rates for both point-to-multi-point and TVWS plus WMN cases except only for the downlink of TVWS plus WMN where the packet loss is very large. This is likely because of high traffic in the WMN in downlink at the time of measurement. We need to see if this is the case for long duration of time.

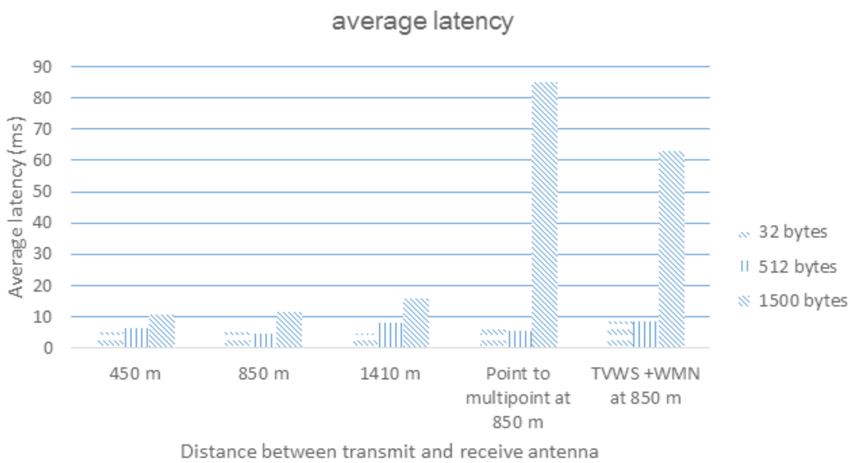
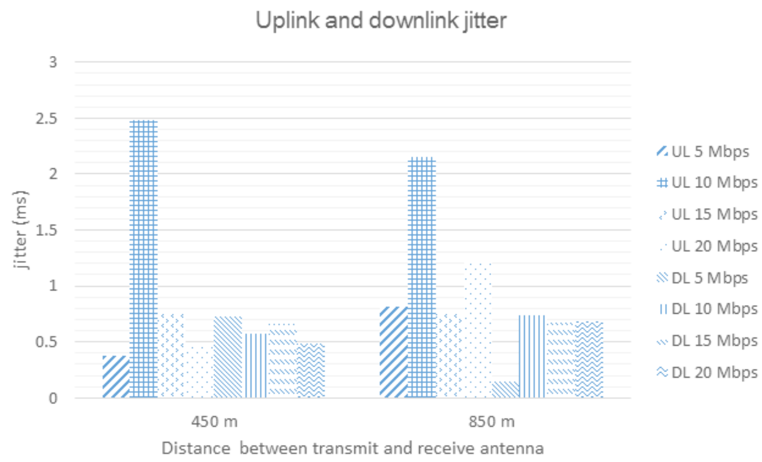
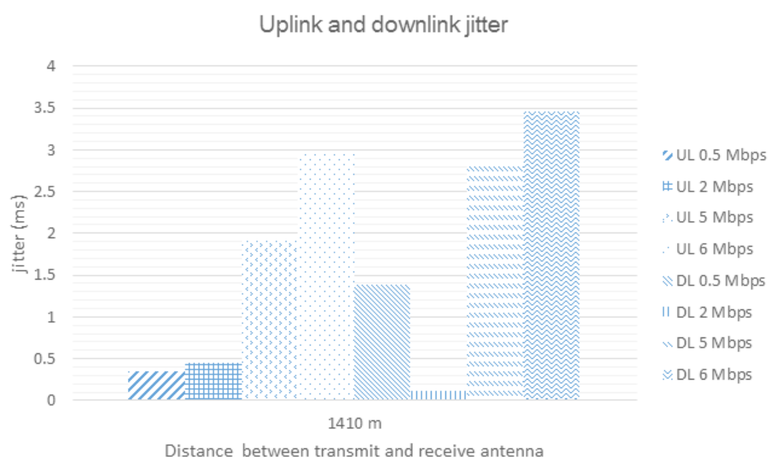


Figure 5 Average round-trip latency of Link#1, Link#2, Link#3, overall TVWS, and Link#2+WMN

Figure 5 shows the average downlink and uplink round-trip latency results in relation to variable data packet sizes. The results show that all the links exhibited excellent average latency results which are less than 16 ms with typical packet sizes ranging 32 512 and 1,500 bytes. It is observed that the packet size affects the latency. For instance, at Link# 1, a 32 bytes packet has a latency of 5.238 ms while a 1,500 bytes packet has a latency of 10.561 ms. Shadowing and distance have an impact on latency. However the differences in latency are not proportional to the scale factor of link distances and insignificantly varied by the distances. We are only able to measure the uplink latency using ping command. The downlink latency cannot be measured as we are not able to ping from the BS to the CPEs which can only be done in bridge mode, which is the simplest way to extend networks requiring no Internet Protocol (IP) routing or Network Address Translation (NAT) between networks. According to the overall round-trip latency results, we can say that delay-sensitive and real-time applications can perform well in a TVWS based network since they still meet less than the Quality of Service (QoS) requirements of voice, video, and real-time data, i.e., 300 ms (Chris & Steve, 2006).



a) Links#1 and #2



b) Link#3

Figure 6 Jitter of a) Link#1 and Link#2, and b) Link#3

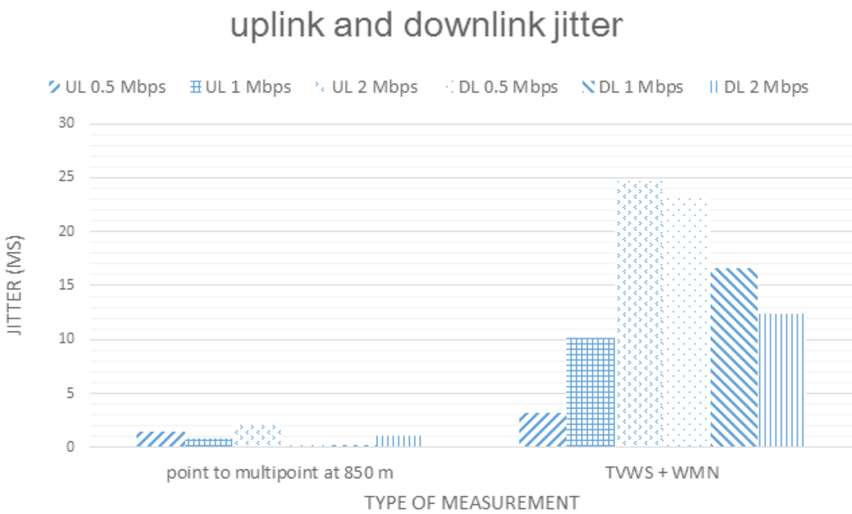


Figure 7 Jitter of overall TVWS, and Link#2+WMN

Similar to the packet loss measurements the point-to-point jitter measurements are carried by generating stream of fixed sized packets and sending through each link at variable data rates ranging from 5 to 20 Mbps. Figures 6 a) and b) show the jitter for the point-to-point case. Links#1 and #2 appears to be satisfactory with jitter less than 3 ms for all uplink and downlink, while Link#3 is unstable at and above 5 Mbps so the measurements could not be performed. Similar to the packet loss measurements we need to further study the jitter of Link#3 at lower bit rate including 0.5 Mbps, 2 Mbps, 5 Mbps, and 6 Mbps as shown in Figure 6 b). The jitter for both the point-to-multi-point and TVWS plus WMN cases cannot be carried out at 5 Mbps. The jitter performance of point-to-multi-point case seems to be more robust and much lower than the one in the TVWS plus WMN case as shown in Figure 7. Overall, the jitters of the almost all cases are very small, less than 2.5 ms, except the case when we connect TVWS to WMN, the jitter becomes more significant. However, it is still acceptable since it meets the Quality-of-Service (QoS) requirements of voice video and real-time data, i.e., 30 ms (Chris & Steve, 2006).

Discussion

The results presented above demonstrate that distance and other factors such as signal fading have a notable effect on the throughput achievable by the CPE terminals. In the future, other factors can be investigated including the properties of the antenna and its capabilities.

The overall achieved performance results depict good network performance which is suitable for Internet telephony, i.e., Voice over Internet Protocol (VoIP), video streaming, and real-time data due to the low latency and jitter. The results are comparable to the performance of Internet over Asymmetric Digital Subscriber Line (ADSL) as a predominant last mile technology, which is capable of transmission speeds ranging from the magnitude of 4 to 8 Mbps. Although the performance of a TVWS system cannot be compared to an optical fiber network a TVWS system still can be a good solution for rural parts of the country, where houses are located randomly here and there and separated by a huge distance or by physical barriers like hills and mountains. It is very difficult to connect every household in such areas using cable and fiber optics. TVWS can alleviate the situation of the people living in those rural areas as TVWS can travel up to 10 km across physical obstacles like buildings and vegetation unlike typical Wi-Fi signals.

Conclusion

This paper presents the network performance study of Thailand TVWS pilot project which is a point-to-multi-point network providing Internet access to three rural locations. First, the received signal power of each link was measured to guarantee the link functionality. Moreover, the vertical antenna polarization must be used so that only TVWS signals, meaning no DTV signals can be received. The overall network performance in terms of average throughput, round-trip latency, packet loss rate, and jitter were discussed. The measurements showed the throughput in the order of several Mbps, up to 13 Mbps. The latency and the jitter were found to be typically around a few milliseconds, despite the long distances. The performance is excellent and suitable for voice, video and real-time data.

Suggestion

Since a number of rural communities have problem with the poor broadband performance they receive from currently available commercial services. Their experience are not unusual in other rural areas around the world even in developed countries. The key attraction of TVWS in this application is the enhanced range which lower frequencies enable compared to the higher frequency bands traditionally used for wireless broadband access. This extended range translates into fewer BSs being required to cover a given area, but with lower coverage costs. In addition, it is a license-exempt access. Beside the rural area use, urban broadband TV white spaces can be used to fill broadband access gaps and provide a way of offloading data traffic from congested mobile broadband networks. This is essentially similar to WiFi but with larger cell sizes called "Super WiFi" with greater penetration into buildings. The Internet of Things (IoT) or M2M communications embraces a wide range of emerging applications with the potential to enhance the quality of daily life and increase sustainability. A vast number of possible applications have been suggested in many literatures, for example, from environmental sensors to traffic management and healthcare applications, to smart grid and metering. Implementing IoT or M2M applications in a future trial can demonstrate how it can be enabled with relatively sparse infrastructure operating at low power levels using the TVWS.

Currently, use of geo-location databases is the preferred method for detecting TVWS by White Space devices including our device, i.e., RuralConnect® Gen 3 Carlson TVWS radio system. This can protect TV transmitters and receivers from interference sufficiently by keeping a record of the TV transmitters' information, and mostly relying on propagation models to determine the protection area of the TV transmitters. The radio of the BS selects a channel from the list of available channels using the Protocol to Access White Space Databases (PAWS) to communicate with the geo-location database. However, such a database is still not available in Thailand. Thus, a channel for each radio was selected based on spectrum occupancy measurements and analysis done in the work in this paper. For future work, geo-location databases and PAWS can be done. An efficient dynamic spectrum access technique using the geo-location spectrum database is also a challenging research topic. A future trial can be done for examining how TVWS system could complement the coverage obtained with conventional WiFi hotspots.

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