Network Performance Analysis of the Limpopo TV White Space (TVWS) Trial Network

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***Abstract*—Television white spaces (TVWS) refers to vacant channels in the ultra-high frequency (UHF) band between 470 and 690 MHz assigned for television broadcast and can be used opportunistically by secondary users (SUs). Research has shown that when the spectrum allocation is managed appropriately, SUs can co-exist on the same radio frequency (RF) spectrum band with licensed networks. This paper introduces the Limpopo TVWS trial network, which provides a point-to-point Internet connectivity to five rural secondary schools. A set of 24 hours RF monitoring results of the TVWS trial network are presented which shows the behaviour of white space devices with respect to incumbent TV band services. The network performance results with respect to average throughput, average latency, and jitter are also presented. The performance results show that good throughput for each link which is in the magnitude of 4 to 8 Mbps and latency of less than 10 ms for typical packet sizes ranging from 32 to 1500 bytes are achievable.**

***Index Terms*—Limpopo, Mankweng, Performance, South Africa, Spectrum, Trials, TV white spaces.**

I. Introduction

Wireless communication networks are the most feasible and economically viable broadband solution for rural areas characterized with low teledensity and lack of fixed-line telecommunications infrastructure. However, wireless networks rely on the availability and affordability of radio frequency (RF) spectrum, which is a scarce natural resource. While few studies claim shortage of usable RF spectrum [1], many studies [2]–[5] assert that the utilization of the licensed frequency bands varies from 10% to 85% depending on the geographical location and time of the day [6].

There is a growing recognition that dynamic spectrum sharing, especially on TV white spaces (TVWS), has a potential to increase the availability and ubiquity of broadband access thereby addressing the digital divide in developing regions [7]. As a result, there has been a number of TVWS trials conducted around the world with the aim of demonstrating the feasibility of dynamic spectrum sharing on the TV spectrum bands. The next section provides an overview of TVWS trials. 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) [8], United Kingdom [9], and recently in Canada [10]. However, there are no defined or known TVWS regulations in the African continent.

978-1-4799-7492-4/15/$31.00

In South Africa (SA), the Council for Scientific and Industrial Research (CSIR) with its partners are conducting two TVWS trials (i.e. Cape Town TVWS trial [11] and Limpopo TVWS trial [12]). Details of these trials are presented in the sequel. The Cape Town TVWS trial started in 2012 and most of the technical results have been published and were recently used by the Federal Communication Commission (FCC), USA to motivate for the softening of the guard band requirements of the TVWS and TV channels [13]. We present the RF monitoring and network performance results of the Limpopo TVWS trial network. The results may contribute in the drafting of TVWS regulations in SA, and in other countries.

The remainder of the paper is organised as follows: Section II presents related work on TVWS trials. Section III discusses the Limpopo TVWS trial network. Section IV presents the network performance results. Section V concludes the paper.

II. Related Work

A. TVWS Trial: Global Overview

A number of TVWS trial networks have been deployed [14]–[16], for example, the Cambridge White Spaces Trial in UK [17], ran from June 2011 to April 2012. It included a number of scenarios, such as city centre, rural, and machine-to-machine (M2M) connectivity. A commercial pilot study in Singapore [18], started in 2013 considered a variety of commercial services that could be deployed using TVWS technology in a terrain where traditional wireless deployment would be difficult. These included various monitoring applications and video surveillance.

The NICT in Japan with support from King's College London [19] recently launched a trial network under the auspices of the Ofcom TV White Spaces Pilots [9], [20], [21]. A Long-Term Evolution (LTE) system extended to operate in TVWS realized mobile broadband communications 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 [22]. The IEEE 802.11af system established a 3.7 km point-to-point link using one TV channel, achieving a downlink throughput of over 2 Mbps. All devices used in the Ofcom TVWS pilots were required to satisfy the strict requirements on the spectrum mask and other characteristics [23]. A disaster recovery network based on TVWS was set up in Philippines. The network was set up and backhauled through Very Small Aperture Terminal (VSAT). It provided a two-way voice and data wireless communications for any user with a mobile device such as a laptop and tablet. The network was deployed at a cost of less than 1/10th of other solutions.

In Africa, the TVWS trials have been deployed in SA [3], [11], in Tanzania [14], in Malawi [24], in Kenya [14], [25], in Namibia [14] and in Ghana [14]. The Namibian trial network with coverage of 9,424 km^2 is currently the largest in the world. The network covers several regional councils and a number of schools in the northern part of Namibia. It uses Adaptrum's white spaces radios, with link distances of 8 km to 12 km, and achieves 5 Mbps to 10 Mbps.

The trial in Kenya combines various license-exempt bands with TVWS. The project has demonstrated the technical viability of this model of delivery, using point to multi-point TVWS base stations with coverage of up to 14 km at 2.5 W Effective Isotropic Radiated Power (EIRP). The base stations can achieve up to 16 Mbps on a single 8 MHz TV channel.

B. TVWS Trials in Cape Town: South Africa

Cape Town trial [3], [11] is the first large scale TVWS trial in Africa. The trial was set up to demonstrate that TVWS is a viable technology for providing alternative means of reliable high speed wireless connectivity, and that it can coexist with TV broadcasting, the primary user (PU) of the band.

The Internet connectivity was provided to ten schools with over 9500 pupils and teachers, using three separate base stations located on the roof of the Tygerberg Hospital. The Carlson Wireless, USA TVWS manufactured equipment, showed throughputs as high as 12 Mbps and latencies as low as 100 ms. Usage of directional antennas with gains of about 11 dBi ensured good quality of links for distances up to 6 km and minimized the potential of interference. One of the schools had nearly non-line-of-sight link, yet it received full grade Internet. The TVWS connectivity has become the only means of connectivity for low income schools.

The trial utilized TV channels adjacent to the operational TV broadcasting channels. Despite this, no interference was reported for both analogue and digital TV reception. These results have prompted the regulator in SA to prepare for public discussions on TVWS legislation.

III. The Limpopo TVWS Trial

The Limpopo TVWS trial network connects the University of Limpopo (UL) TVWS test house to five high schools located within a radius of 10 km in Mankweng Township, Limpopo Province, SA. It is a collaboration between Microsoft, South African Council for Scientific and Industrial Research (CSIR), the UL and Multisource. The objective of the project is to demonstrate the feasibility of low-cost TVWS wireless broadband connectivity to rural schools. The five participating schools are a mixture of quintile 1 (poorest) and quintile 4 (least poor) schools which had no Internet connectivity [12].

A. The Trial Network Topology

The trial network is a star topology with a base station (BS) located on the rooftop of the UL library. Figure 1 depicts the configuration of the trial network's BS and Customer Premises Equipment (CPE) terminals in terms of distance, radio frequency channels, and allocated spectrum for each link. Due to lack of line-of-sight between the BS and Ngwanalaka High School (HS), Mapeloana HS repeats the signals from the BS to Ngwanalaka HS. The BS connects to six CPE terminals stationed at six different schools through point-to-point (P2P) communication links; as a result, communication between CPEs takes place through the BS. The network operates under this constraint owing to its design and configuration.

B. Network Monitoring and RF Spectrum Measurements

Figure 2 shows a 24 hour frequency scan collected by the Independent Communication Authority of South Africa (ICASA)'s monitoring station on the 8th August 2014. The mobile monitoring station consists of a Rohde & Schwarz ESN Monitoring receiver (9 kHz to 2050 MHz) that is connected to a Rohde & Schwarz HE500 antenna (20 MHz to 3 GHz). It is controlled by Rohde & Schwarz ARGUS monitoring software (AMS) for recording of measurement results. The AMS is also capable of capturing antenna characteristics as well as cable losses. Measurement parameters were pre-set for different measurements and selected for use in AMS. Timing of measurements was also controlled through AMS.

As shown in Figure 2(a), there is presence of a strong analogue TV signals in channels: 22, 44, and 56. They are identifiable by the specific profile of spectrum masks with distinct peaks corresponding to video and audio components. There is also a presence of a strong digital TV (DTV) signal in channels: 26 and 30. These transmissions can be identified by their near-rectangular spectrum masks and steady occupancy of the channels over time. Figure 2(b) shows that TVWS channels are used only when needed and this is shown by the trace and variation with time over a 24 hour period.

The monitoring station was able to pick six TVWS channels. These are: 25, 27, 29, 33, 36 and 40. This shows that the monitoring station was able to detect signals from the BS despite the use of directional antennas from the BS to each CPE. Furthermore, the monitoring station was stationed about 380 m away from the BS.

It can also be seen in Figure 2(a) that there are DTV channels operating adjacent to the TVWS channels. The UL TVWS network channel allocation was determined based on the national terrestrial analogue broadcast data, and did not consider the recent digital terrestrial broadcasting plan of 2013 [26]. The roll-out of DTV transmission network was undertaken after the TVWS network trial was deployed. It is for these reasons that TVWS channels 25 and 27 are adjacent to DTV channel 26, and TVWS channel 29 is adjacent to DTV channel 30. While there is no single case of interference to TV users, the use of geo-location spectrum database (GSDB) is implemented to ensure that TVWS network employs dynamic spectrum allocation (DSA) mechanisms to avoid interference

Figure 1. Limpopo TVWS Topology Showing all the participating CPE sites and base station at University of Limpopo

to PUs. Furthermore, research on the impact of operating TVWS network adjacent to DTV is being conducted.

IV. Limpopo TVWS Trial Network Performance

A. Methodology

Network monitoring was done at six CPE sites using the iperf bandwidth measurement tool. The performance measurements of the following: the network throughput, jitter and packet loss rate, were recorded. Additionally, latency was measured using the ping utility diagnostic tool. The primary objective was to measure the capacity and performance of both the down and up links. The throughput and latency tests were performed for each CPE link in turns while the other links were disabled in order to measure the peak performance of each link. The maximum achievable throughput, the average and maximum network latency measurements were captured.

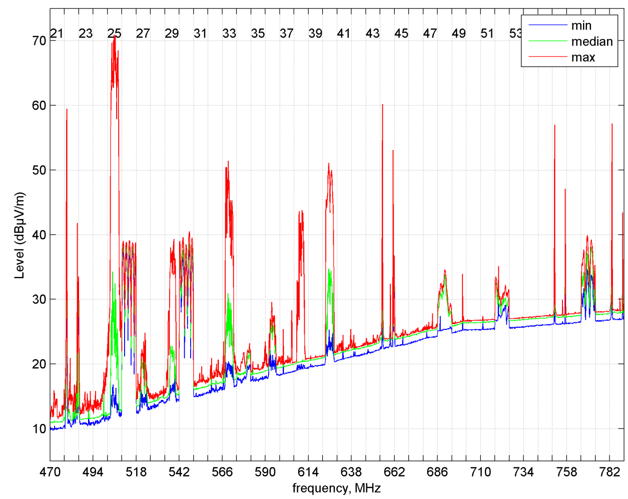
To effectively measure the uplink performance, the BS was configured as a sink node, while each CPE terminal was set up as a receiver for the downlink measurements in this case the traffic was generated by the BS for each CPE link. Figure 1 provides the details of the six CPE sites.

The measurements were performed in the Windows 7 operating system. The throughput and latency measurements were both run for 60 seconds for each links. The same set of parameters was considered for both downlink and uplink measurements. The default iperf variable packet rate was also considered for TCP throughput measurements.

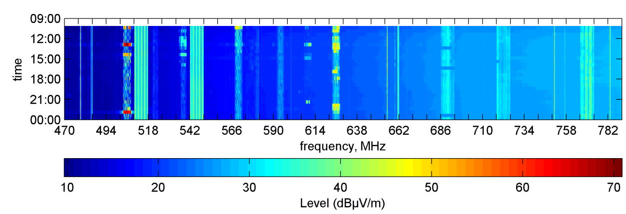
The TCP window was later changed to 80 KB while the bit rate was varied between 1 to 7 Mbps with a fixed 1470 bytes datagram for the UDP throughput measurements. We present and analyze network performance results in the next section.

B. Results

Figure 3 presents the average downlink and uplink TCP throughput performance results for each link. We observed



(a) minimum, median and maximum power level



(b) signal strength over a 24 hour day period

Figure 2. TV Band Frequency Monitoring at UL Test House

that links with shorter distances achieved higher average throughput as compared to longer links. The shortest link (0.38 km) achieved the highest average throughput rates of 7.21 Mbps and 7.81 Mbps in its downlink and uplink respectively. The longest link (7.58 km) achieved 5.41 Mbps and 4.37 Mbps in its downlink and uplink respectively. In general, the achievable throughput was determined by the link distance and

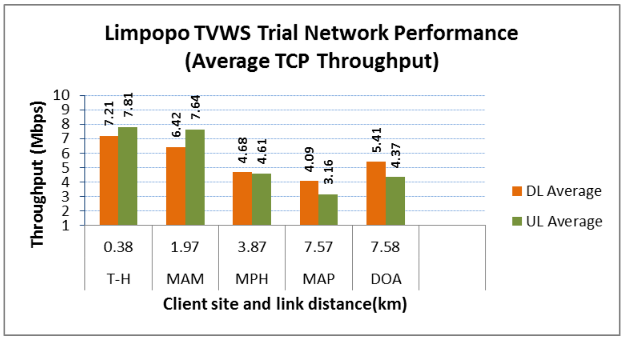


Figure 3. Average downlink and uplink TCP throughput rate achieved

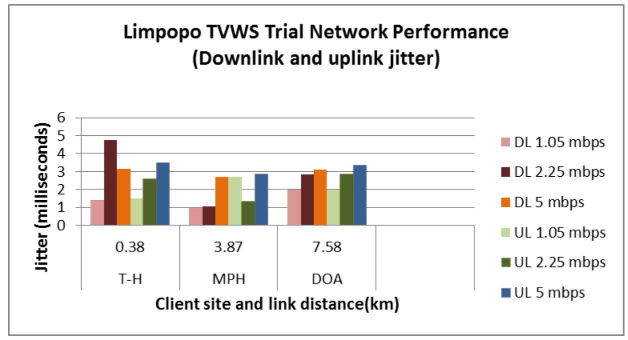


Figure 5. Downlink and uplink UDP jitter comparison results for selected links

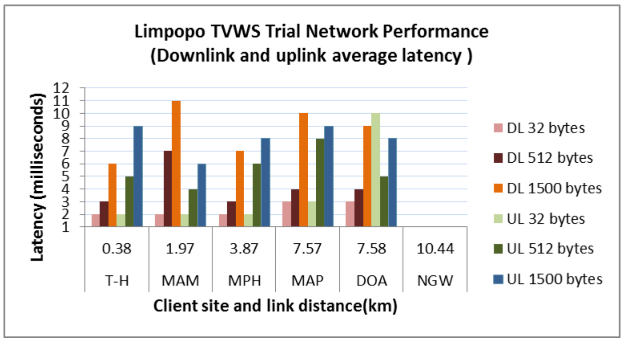


Figure 4. Average downlink and uplink latency comparison results per link

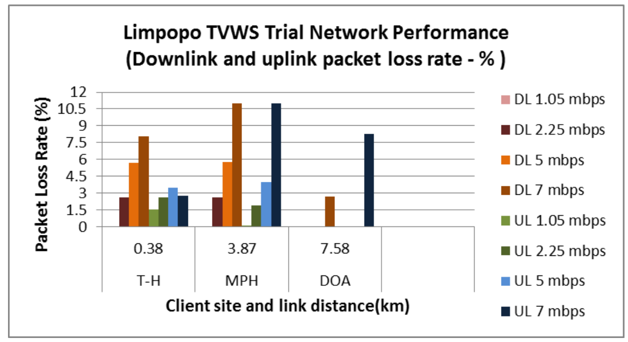


Figure 6. Downlink and uplink UDP packet loss rate comparison results for selected links

it decreased with the increase in link distance.

Figure 3 presents the average downlink and uplink 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 10 ms with typical packet sizes ranging from 32 to 1500 bytes. It was observed that the size of a packet had an effect on latency. For example, a 32 bytes packet recorded a latency of 3 ms. The effect of shadowing and distance on latency is evident in the obtained results; the differences in latency are marginal and are not proportional to the scale factor of link distances, therefore insignificant. The results show that delay-sensitive and real-time applications will perform well and that the effects of latency in relation to distance will be insignificant. The TCP results are therefore satisfactory; we now analyze the UDP results.

The UDP results are based on the shortest, average and longest links (0.3 km, 3.87 km and 7.58 km). The results are presented in Figure 4 and Figure 6. Figure 4 depicts the jitter results and Figure 6 shows the packet loss rate results.

A stream of fixed sized packets was generated and sent through each link at variable data rates ranging from 1 to 7 Mbps. The packets were 1470 bytes in size. The results show that the packet loss rate is proportional to bit rate. At the bit rate of 1 Mbps, all tested links performed well with packet loss rate below 1%.

Increasing the bit rate to 2.25 Mbps (which is 30% estimate of achievable throughput of the longest link) causes packets to be dropped at a rate above 2.6% for T-H and MPH links. DOA link appears to be more robust compared to the two links (T-H and MPH) as significant packet loss only occurs when the bit rate is set to 5 Mbps and above. The effects of shadowing are minimal on this link.

C. Discussions

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. Based on the measured results, shorter links achieved the highest throughput whereas longer links suffered a throughput loss at an estimated average of 0.35 Mbps per km. Furthermore, MAP link obtained the lowest throughput despite being equipped with a high gain antenna. Its poor performance can be attributed to shadow fading and distance. In the future, other factors will 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 (Voice over Internet Protocol), video streaming, real-time data, and voice due to the low latency and jitter. The results are comparable to the performance of Internet over Asymmetric Digital Subscriber Line (ADSL) (a predominant last mile technology used by most SA schools) which is capable of transmission speeds ranging from the magnitude of 4 to 8 Mbps. However, TVWS network yields higher and better ratio between downlink and uplink data rates as compared to ADSL.

V. CONCLUSION

This paper presents the network performance analysis of Limpopo TVWS trial project which is a point-to-point broadband network providing Internet access to five rural schools. The paper presents a brief overview of the network topology, and the results of the radio frequency (RF) monitoring station which monitors the RF activities over a 24 hour period. The overall network performance in terms of uplink and downlink throughput and latency are also discussed. The measurements show the throughput in the order of several Mbps, up to 8 Mbps. The latency was 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.

Due to the national migration to digital broadcasting, new terrestrial digital television (DTV) channels have been detected adjacent to the TVWS channels. Thus, our future work includes investigating the impact of operating TVWS adjacent to DTV channel, study the point-to-multipoint network performance and dynamic spectrum access using the geo-location spectrum database.

ACKNOWLEDGMENT

The authors would like to acknowledge support from the University of Limpopo TVWS centre staff, and financial support from SA Department of Science and Technology, the University of Limpopo, Council for Scientific and Industrial Research and Microsoft. This work is also based on the research supported in part by the National Research Foundation of South Africa for the grant, Unique Grant No. 94077.

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