Performance Analysis of Dual 5 GHz WiFi and UHF TV White Space Network Links

Mokwape M. Lamola
Computer Science Department
University of Cape Town
Cape Town, South Africa
maggielamola16@gmail.com

David L. Johnson
Computer Science Department
University of Cape Town
Cape Town, South Africa
david.lloyd.johnson@gmail.com

Albert A. Lysko
NGEI (formerly Meraka Institute)
Council for Scientific and Industrial Research
Pretoria, South Africa
alysko@csir.co.za

Richard Maliwatu
Computer Science Department
University of Cape Town
Cape Town, South Africa
rmaliwatu@cs.uct.ac.za

Melissa Densmore
Computer Science Department
University of Cape Town
Cape Town, South Africa
mdensmore@cs.uct.ac.za

***Abstract*—Commonly used WiFi is known to be ill-suited for penetrating vegetation and buildings and non-line-of-sight conditions. Television white space (TVWS) operates in ultra-high frequency (UHF) bands that overcome many of the penetration and line-of-sight challenges found in the 2.4 GHz and 5 GHz bands normally used by WiFi. The aim of this study is to report on the performance of WiFi technology in the 5 GHz band and the TVWS technology in the 600 MHz UHF TV band as well as a combination of both radios in two different scenarios, short-range clear line-of-sight, and non-line-of-sight conditions. A number of performance metrics, such as estimated throughput, bitrate, signal strength, noise, transmit power, transmit error, packet loss, and round trip time, are compared for varied distances and increasing levels of vegetation in the propagation path. Both TVWS and WiFi experiments showed increased sensitivity to noise as channel widths increased with TVWS being particularly susceptible to noise in nearby channels from powerful TV transmitters. Aggregating the WiFi and TVWS radios proved to have the best performance improvements when the WiFi and TVWS links had similar throughput in line-of-sight conditions.**

***Index Terms*—5 GHz WiFi, television white space, TVWS, performance, link aggregation.**

I. Introduction

Internet access is commonly recognized as one of the catalysts for economic growth and competitiveness in low income and developing countries. However, improving Internet accessibility in these regions remains difficult to achieve due to the high cost of back-haul, lack of local ICT skills and lack of reliable power. Low-cost wireless technologies such as WiFi and TV White Space (TVWS) [1], [2] have been shown to provide affordable access and a viable alternative to cellular technology. With various advancements in wireless technologies, there is a growing pool of wireless radio access technologies to use in order to improve the end-user experience. This has led to more devices using multi-radios for communication. This thus, increases the need to use the existence of these technologies to improve network. As such, other researchers investigated the use of multi-radio networks for bandwidth aggregation in this regard [3] [4]. Different aggregation techniques are evaluated in [4], in order to understand aggregation at different TCP/IP layers using different aggregation techniques. With an existence of the current radio technologies, researchers consider aggregating heterogeneous network for the benefit of increasing the data traffic in the overall network. In this paper we consider the behavior of aggregated WiFi and TVWS links with respect to the environmental effects around them and evaluate the degree to which aggregated links improve or degrade the overall performance of the network.

This work studies the behavior of a 5 GHz WiFi and TVWS links in different scenarios that involve line-of-sight (LOS) and non-line-of-sight (NLOS) [5] conditions. The 5 GHz and TVWS radios are aggregated and performance improvements are compared to individual 5 GHz and WiFi links. The work investigates the effects of parameters (channels, channel width, and power levels) for single and aggregated links, in different operating conditions. These results aim to provide a guideline on optimal parameters to use for WiFi and TVWS in single and aggregated link conditions that lead to improved connectivity. Ultimately low-cost and widely available connectivity will allow users in under-served areas to become active citizens in the digital economy [6], [7].

II. STUDY METHODOLOGY

The measurements are conducted in two locations for collecting single link and aggregated link performances. The main objective of the measurements conducted in these locations was to deduce performance constraints of single WiFi and TVWS links in LOS and NLOS conditions and aggregated

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WiFi and TVWS links in LOS conditions. The measurements in this study are conducted under different distances, and environmental conditions to establishing parameters such as throughput, signal strength, noise level, packet loss and round trip time.

A. Equipment Used

Meraka White Space Mesh Nodes (WSMNs) are used for all experiments in this study. The nodes consisted of a Mikrotik Routerboard and Doodle lab DL509-78 broadband transceivers (470-784 MHz TV bands). Each node was assembled with two antennas: one for TVWS and the other for WiFi. The equipment descriptions are specified in TABLE I.

TABLE I
SPECIFICATIONS OF EQUIPMENT USED.

TVWS
TVWS Radio Specifications 1. Outdoor use 2. UHF supported frequency bands Frequency Max : 860 MHz Frequency Min : 470 MHz Antennas **Product Details:** 1.Sealed F connector dipole housing 2.18 mm boom construction 3. Quick assembly and set up Specifications 1. Wideband 2. Frequency R : 470-862 MHz 3. Forward gain : 9 -11.5 dB 4. Elements : 12 5. Channel numbers : 21 -69 6. Assembled length: 860 mm TVWS Card 1. Doodle lab card DL509-78 2. TV band devices : 174 - 784 MHz
WiFi
WiFi Radio Specifications 1. Supports all 802.11 a,802.11 b and 802.11 g data rates 2. Type III - B miniPCi card, 6.0 cm x 4.5 cm (L x B) 3. U. FL antenna connectors on upper right corner 4. Weight : 20 g 5. Operating temperature :- 20 degrees to degrees) Antennas **Product Details:** 1. Meraka HPN 5.1 - 5.85 GHz 2. High gain 22dBi, intergrated in enclosure 3. Manufacturer : Poynting Specifications 1. WLM54SAG High power : 20 mW 802.11 a/b/g mini PCI card 2. 802.11 a/b/g Super AG High Power wireless mini PCI card 3. IEEE 802.11 a/b/g compatible WLAN 4. Benefits: Up to 108 Mbps (high-speed data rate) and : Up to 200 mW transmit power 5. High output power up to 23 dBm at a/b/g band 6. Dynamic frequency selection 7. 2.4 / 5 GHz IEEE 802.11 a/b/g standard

B. Measurement Setup

The experiments are initially run indoors and then recreated outdoors to meet the specified scenarios above, namely LOS and NLOS. The outdoor setup consisted of the same WSM nodes and adjusted at different distances at the University of Cape Town's (UCT) rugby fields and near the UCT tennis court. Fig. 1 depicts the rugby field where LOS measurements were conducted on the further right and the area near the tennis court where the NLOS measurements were conducted. In the outdoor setup the LOS scenarios varied over three distances: 163 meters, 245 meters, and 251 meters. The TVWS antennas on each node are positioned 2.34 meters above ground and WiFi antenna positioned at 1.84 meters above ground, as shown in Fig. 2. These measurements created a baseline for the aggregated performance measurements conducted in Fish Hoek area near Cape Town, depicted in Fig.3.

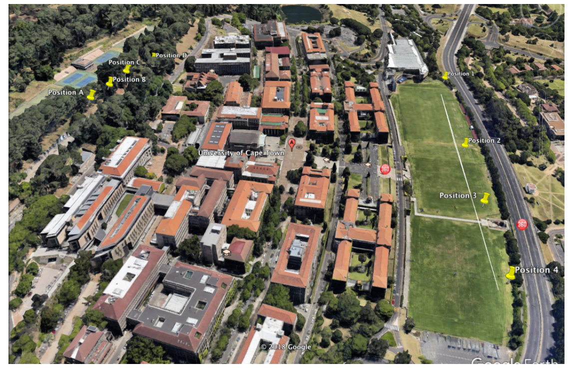

Fig. 1. Top Google Earth view of the outdoor locations at the UCT's rugby fields (*right*) and near tennis courts (*left*).

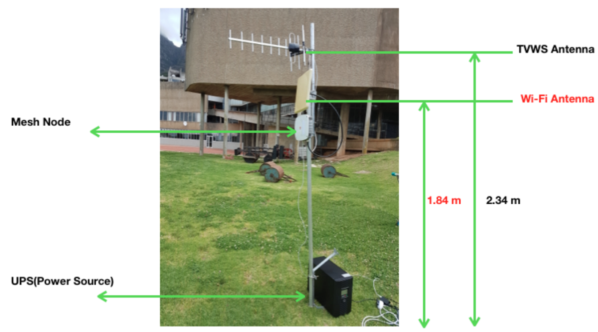

Fig. 2. The trial setup for measuring the performance of the links at different locations with different obstructions.

C. Measurement Procedure

Prior to each performance measurement, spectrum scans were conducted and weather conditions were recorded. The spectrum scans were collected over the 5 GHz WiFi channels and UHF TV channels using R & S FSH4 spectrum analyzer. The measurement procedure was two-fold, initially, the experiments capture the single link measurements and secondly, the aggregated links between WiFi and TVWS channels. The procedures for both are described below:

1) Single Link Measurements Procedures: With single link measurements, four channels were selected for both radios. Where channels 1, 4, 7 and 11 are selected from a pool

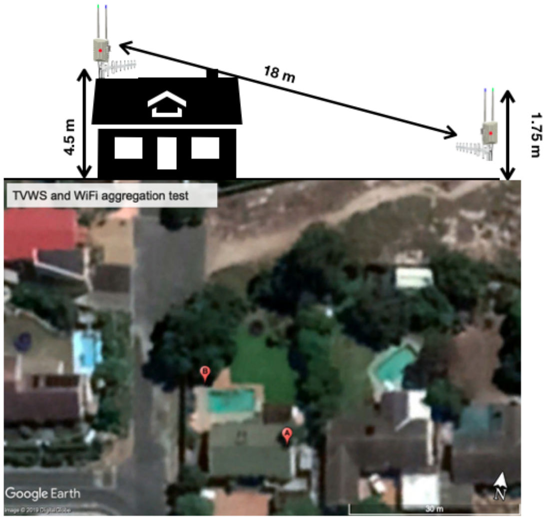

Fig. 3. Short range aggregation network setup.

of channels available with the Doodle lab cards, channels corresponding to 540 MHz, 555 MHz, 570 MHz, and 590 MHz center frequencies. Channels 36, 40, 44, and 46 are selected for WiFi test, corresponding to 5180 MHz, 5200 MHz, 5220 MHz, and 5240 MHz center frequencies. The main objective of these experiments is to deduce the behavioral performances of single WiFi and TVWS links over the specified channels. The measurements variables are controlled and set on a laptop, running a script that defines the experiment procedures. The link performance was measured using *iperf* and *ping* measuring tools over different three independent variables, namely channel; channel width and transmit power. The independent variables are then collected against throughput, packet loss, signal strength, noise level, bitrate, transmitted packets, received packets, and delay. Each test spans through these channel widths values 20 MHz, 10 MHz, and 5 MHz and transmit powers settings 20 dBm, 15 dBm, 10 dBm, and 5 dBm as shown in Fig. 4.

2) Aggregated Link Measurements Procedures: The measurement attributes are controlled and adjusted on the radios remotely via a secure terminal login. Aggregated link performance measurements were preceded by single link performance measurements at different channel widths and a combination of channels. In this experiment, the overview of the procedure followed is shown in Fig. 5. The links were tested using an 18m short range LOS link. This is to avoid environmental impacts to this section of the study that was essentially trying to understand the internal scheduling protocol issues when WiFi and TVWS radios with varying degrees of throughput differences are aggregated. Distance and environment changes would only affect the absolute performance values and not the relative performance differences with aggregation. The need to aggregate links is realized using performance differences between WiFi and TVWS. In order to achieve this, the experiment uses a channel bonding

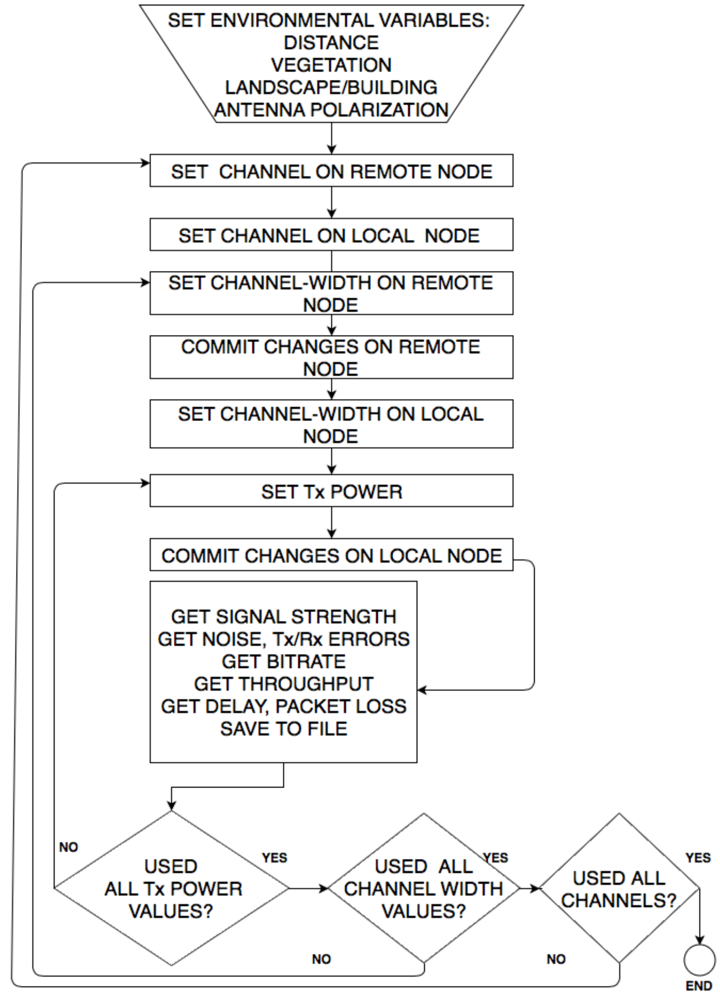

Fig. 4. The flowchart of all the implemented single link measurement steps of the script.

feature of the Better Approach To Mobile Adhoc Networking (B.A.T.M.A.N) routing protocol [8]. For this experiment, only three channels are selected for each radio. Doodle lab channels 1, 8, 11 are selected, corresponding to 540 MHz, 575 MHz, and 590 MHz center frequencies and WiFi channels 36, 44, and 48 with the corresponding center frequencies 5180 MHz, 5220 MHz, and 5240 MHz. The link performance is tested for the following permutations: WiFi frequencies of 5180 MHz, 5220 MHz, and 5240 MHz and TVWS frequencies of 540 MHz, 575 MHz, and 590 MHz with channel widths for both radios set to 5 MHz, 10 MHz, and 20 MHz. The transmit power in this experiment was kept constant at 20 dBm.

III. RESULTS AND DISCUSSIONS

1) Outdoor Single Line-of-Sight Links: Figs. 6-7 describe the relationship between link quality and transmit power over different channel widths. The results present throughput results of frequencies 540 MHz, 590 MHz, 5180 MHz, and 5240 MHz with nodes 251 meters apart. TVWS shows a gradual decrease in throughput performance with an increase

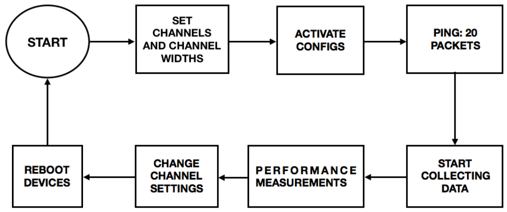

Fig. 5. A flow of measurement procedure used in the aggregated experiment.

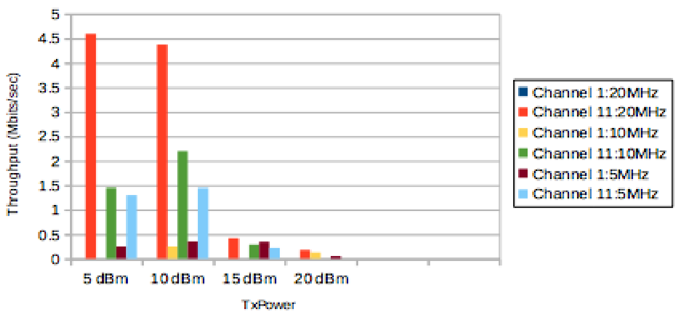

Fig. 6. TVWS transmit power vs throughput graph recorded at the rugby field.

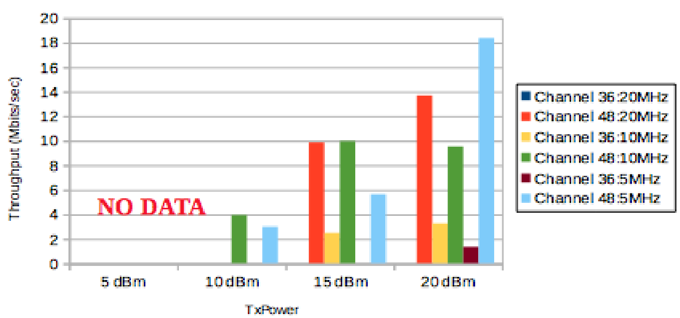

Fig. 7. WiFi transmit power vs throughput graph recorded at the rugby field.

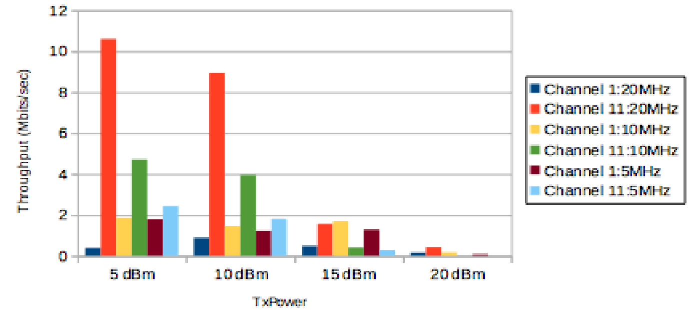

Fig. 8. TVWS transmit power vs throughput graph recorded near the tennis court with at least two trees between the nodes.

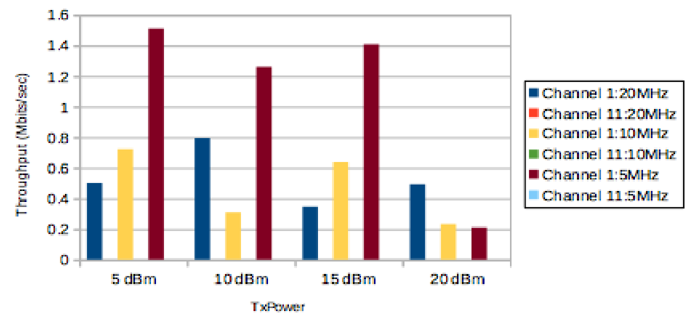

Fig. 9. TVWS transmit power vs throughput graph recorded near the tennis court with at least eight trees between the nodes.

in transmit power at both channels, showing channel 11 (freq: 590 MHz) performing better than channel 1 (freq: 540 MHz). This may owe to the fact that channel 1 is not available or interfered by adjacent channels in this area. Fig. 7 shows an inverse relationship between WiFi channels compared to TVWS channels, the link performance increases with an increase in transmit power, wherein in channels there is little to no recorded data of throughput in low power budgets. It is also worth noting that we experienced some saturation in the power budget with respect to the devices used. The measurements are then used as a baseline to understand how saturated the data is and the results are hence not used for general scientific conclusions in this paper.

2) Outdoor Single Non-Line-of-Sight Links: The results collected in this scenario are described in Figs. 8-10. The measurements were set up in such a way that pine trees were used as the main source of obstruction between the WSM nodes. Tree count was incremented from just one tree between the nodes to at least eight trees in between. Figs. 8-10 present results collected at two and eight tree counts. Figs. 8 and 10 present data collected at setups with at least two trees in between the nodes 64 meters apart for WiFi and TVWS channels. At short distances and negligible line-of-sight to the antenna on the opposite end, WiFi links show a rather positive performance at greater transmit powers compared to WiFi and TVWS shows a poor performance with an increase in power budgets. Similar to behaviors of LOS links channel 11 (freq: 590 MHz) shows a rather better performance compared to channel 1 (freq: 540 MHz). The maximum performance recorded for the 5 GHz WiFi link was at least three tree count and the link simply breaks after that point, while TVWS links continue to show positive throughput performance at counts of at least eight.

3) Outdoor Single and Aggregated Line-of-Sight Links: We are also interested in presenting the possible improvement benefits for aggregated link performance. Figs. 11-13 depict a relation between single 5 GHz WiFi and UHF TVWS links, by conducting a permutation between frequencies, channel width with transmit power kept constant at 20 dBm for all experiments. Similar to all the experiments conducted in this paper, the throughput is used as the main parameter for analysis. Figs. 11-13 show a rather inconsistent relationship between links aggregated at asymmetric link capacities. The relationship shown in Figs. 11-13, where WiFi occupies a large portion

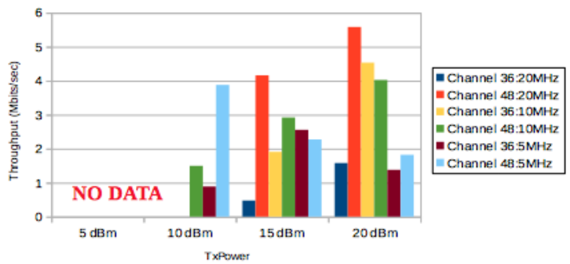

Fig. 10. WiFi transmit power vs throughput graph recorded near the tennis court with at least two trees between the nodes.

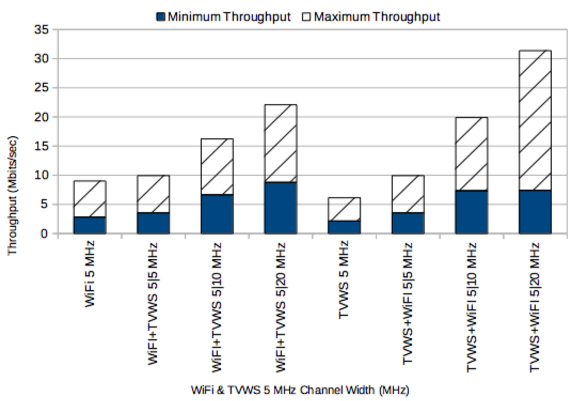

Fig. 11. Throughput performance at a 5 MHz WiFi-TVWS link.

of the aggregated channel width shows a rather better link performance compared to cases where TVWS occupies the larger portion of aggregate link capacity. The results also show an exponential improvement in symmetric link aggregation from 5 MHz to 20 MHz. Although this may be the case where the capacity increment does not always provide better performance over single link usage. In cases where increasing the link capacity also increases the chance of adjacent channel interference as regulated channel capacities less than the set channel capacity in this experiment. We conduct such an experiment to be able to determine the improvement in ink capacity when aggregating links.

IV. Proposed Mitigations for Link Quality Improvement

1) Metric selection for link quality: When analyzing the performance of a link, it is beneficial selecting a metric that will help provide at least an optimal channel to use in a given area. This is owing to the fact that TVWS channels are mainly based on availability in different regions and even different antenna polarization. Therefore it is imperative to select a parameter to be able to select a channel with less clutter or noise. With that being said, we need to run thorough spectrum scans for all frequencies in use to weigh out clean channels. We need to collect round trip time (RTT), received signal strength (RSSI) and signal to noise ratio (SNR) tests to measure the level of transmissions of the link being used prior to its usage. In assessing and thorough analysis of these

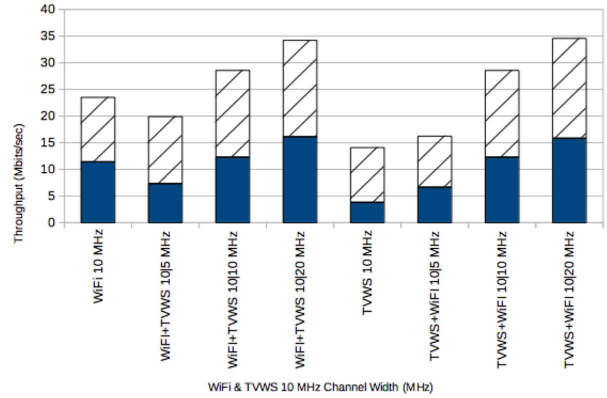

Fig. 12. Throughput performance at a 10 MHz WiFi-TVWS link.

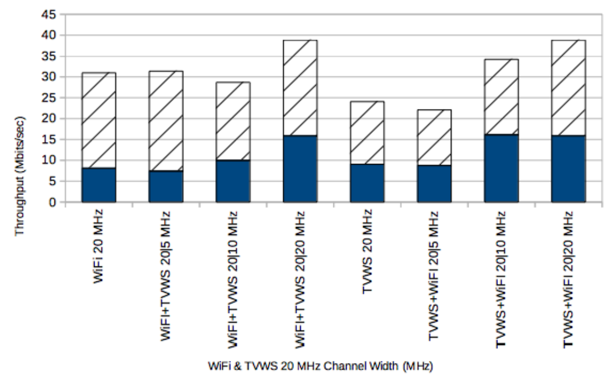

Fig. 13. Throughput performance at a 20 MHz WiFi-TVWS link.

metrics are extremely vital in weighing the viability of a link, this follows the work done in [9]. With these experiments, we have found throughput value to provide sufficient information to conclude on the performance of a link against different power budgets in different channel widths.

2) To aggregate or not to aggregate?: Increasing the link capacity does improve the performance of the network, but the answer to the question: ”Does it benefit the overall network performance?” is not apparent with just simple data collection. This paper aims to provide the necessary tools to help network designers make informed decisions in this regard. Considering different radio channels against different channel widths, we need to consider how much of an improvement is the aggregated link providing. We consider this very imperative to consider since in other cases using aggregated links puts a strain on the available resources, wherein using a single WiFi or TVWS links relieves either WiFi link or TVWS link to be used by other nodes in the network. For instance Fig. 12 shows a good example of such behavior, where a WiFi link with 20 MHz capacity is aggregated with a TVWS link with a 10 MHz capacity link and TVWS link at 20 MHz capacity and WiFi at 10 MHz capacity. A single 20 MHz WiFi link seems to perform better than an aggregated link at WiFi 20 MHz and TVWS at 10 MHz capacity, and inversely, a single 20

MHz TVWS links shows a poor performance compared to its aggregated link at TVWS with 20 MHz capacity and WiFi at 10 MHz capacity. Therefore, we generate a threshold that can be incorporated into an algorithm that calculates how much of an improvement the aggregated link is playing in optimizing the network performance.

V. CONCLUSION AND FUTURE WORK

The results show that WiFi and TVWS radios complement each other and work well as a combination when rolling out networks with a mix of terrains and geographical constraints. Each wireless interface should be profiled to check signal strength, noise level, delay, and packet loss before selecting the optimal radio.

Aggregating the WiFi and TVWS radios generally provided improved link performance. The optimal increase in throughput was achieved when both links had similar channel widths. Although there is an attractive performance improvement in the use of aggregated links, the overall network performance is not guaranteed. Therefore, when considering aggregated links vs single radios links in a network, a careful decision should be made to determine if the increase in performance benefits all the resources used in the network.

Future work will involve more in-depth link performance analysis of environmental effects such as weather and more complex terrain and interference environments in rural and urban areas of South Africa. Additionally, future work could look at designing an algorithm that helps each node in a network to select or combine radios to achieve the best balance between individual and overall network performance for various regions studied in this paper.

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