Experimental analysis of 5 GHz WiFi and UHF-TVWS hybrid Wireless Mesh Network back-haul links

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Abstract. This paper reports on the experimental analysis of hybrid back-haul links comprising WiFi operating in the 5 GHz and Ultra High Frequency Television White Space bands. Possible link permutations are highlighted. Performance results show that overall network optimisation requires a combination of frequency division and time division duplexing.

Keywords: multi-radio · dynamic spectrum access · TV white space · wireless mesh network · 5 GHz WiFi.

1 Introduction

Alternative network deployments [1] such as community wireless networks [2] are said to hold the most hope in meeting the goal of extending connectivity services to rural and unconnected communities. However, as currently deployed, realising the required scale has been hampered primarily by WiFi's operating frequency propagation characteristics. The clear line-of-sight required by 2.4/5 GHz bands limits its use cases. Furthermore, the limited transmission radius at the access layer results in prohibitive costs when attempting to provide ubiquitous coverage.

This paper builds on the foundation laid in prior related work [3] for optimal use of Television White Space (TVWS) and 2.4/5 GHz industrial, scientific and medical (ISM) bands for back-haul Wireless Mesh Networks (WMNs) across rural and urban areas, and the region in between. We conducted performance measurements of 5 GHz and Ultra High Frequency (UHF) TVWS links to study the performance of hybrid links in different environmental settings. Prior related work on hybrid links (*see section 2*) has been in the context of infrastructure-mode cellular networks where a client simply connects/disconnects from the base station or access point, which is much more straight forward whereas, for multi-point-to-multi-point multi-radio ad-hoc type networks, the connectivity decision is a non-trivial task in that the choice of connectivity has to be synchronised on both ends of a link. The main contributions of this paper are as follows: (i) Report on the performance of UHF-TVWS and 5 GHz WiFi links in different deployment scenarios using different transmitter/receiver parameter settings; (ii) insight into UHF-TVWS based network deployment; and (iii) a new perspective on multi-radio enabled nodes' link configuration.

2 Background and related work

Network capacity and performance can be improved by using multiple channels simultaneously, which requires multiple transceivers. Basic multi-channel capable nodes can be built using one of the following architectures: (i) *Multiple hardware platform* where two or more single-radio nodes are connected via Ethernet to form one logical multi-radio mesh router; (ii) *Single hardware platform* where a single node has multiple transceivers fitted; or (iii) *Single-chip multi-transceivers* where multiple transceivers are integrated into one wireless chipset on a router [4]. This study focuses on nodes fitted with 5 GHz and UHF-TVWS transceivers to realise multi-band-multi-radio nodes. The ISM band is suitable for densely populated urban areas, whereas UHF-TVWS is ideal for sparsely populated rural areas, which also happen to have significantly more TVWS compared to urban communities.

When confronted with diverse population densities, there exists a grey region (sometimes referred to as peri-urban) that is characteristically a cross between rural and urban regions from a spectrum requirement standpoint as shown in Figure 1. Combining ISM and TVWS bands is appropriate in this region of intersection. Research [3] has shown that in such scenario, the gains of using a combination of the two bands are much larger compared to using either spectrum band by itself.

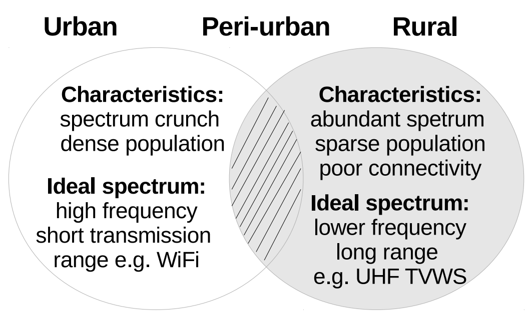


Fig. 1: Spectrum requirements by region.

Applications of WiFi can be categorised coarsely into *access-tier* and *back-haul-tier* network architectural components. The problem of optimal use of TVWS and ISM bands for back-haul connectivity amid diverse population densities is highlighted in WhiteMesh [3]. Other researchers have proposed combining TVWS with 5G infrastructure for rural coverage where traditional cellular coverage models are less economically viable due to low user density and subsequent revenue [5]. The work on TVWS with 5G considers the cost and analyses the feasibility of using TVWS for rural Internet access in 5G, but does not provide any test results of TVWS performance for the proposed architecture.

Regarding the performance of WiFi-like access points operating in TVWS, the benefits of larger coverage area and better obstacle penetration are challenged when inter-access point interference is considered [6]. The lower operating frequency of TVWS results in larger cell sizes and the overlap in contention domains among interfering access points significantly reduces the link data-rate. Therefore, it may be said that the wider coverage range provided by TVWS is considered best suited to rural settings because degradation due to inter-access point interference is minimal because of low access point density. However, a few judiciously well placed TVWS radios spaced far apart in urban areas can offer lower data-rate coverage filling and better building penetration, which is useful in bridging the gaps among clusters of radios operating in the 2.4/5 GHz band.

3 Network architecture

One of the biggest challenges in rural communities is the extension of connectivity from the nearest point-of-presence (POP) to the houses. These areas are typically characterised by sparse population and rugged terrain, which makes it economically and technically impractical to lay down copper or optical fibre cables. Moreover, vegetation and other obstacles along the signal propagation path results in obstructed line-of-sight.

Owing to the known advantages and drawbacks of *high* and *low* operating radio frequencies, this work considers using a combination of 5 GHz and TVWS for *first-mile* connectivity. We define "first-mile" as the stretch from the location of the remotest user to the closest POP. Figure 2 illustrates the envisioned application scenario. The architecture comprises nodes with radios operating in the 2.4 GHz, 5 GHz and UHF-TVWS bands strategically deployed at key community sites such as schools, clinics, libraries, office parks and houses. The 2.4 GHz radio serves the access-tier whereas the 5 GHz and UHF-TVWS radios interconnect the nodes in mesh mode to form the back-haul-tier.

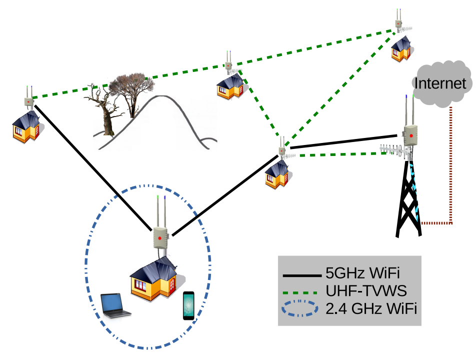


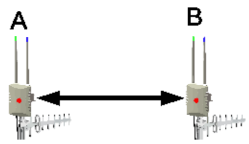
Fig. 2: TVWS, 2.4 and 5 GHz combined to extend broadband connectivity.

4 Problem description and formalisation

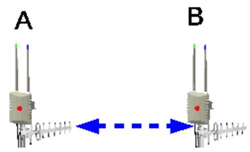
Given the combination of radios described in section 2, there are nine possible link configurations as the Alice & Bob topology illustrates in Figure 3.

To generalise, we first consider two wireless devices, node A and node B. Each of these devices has a number of wireless interfaces, which can form connections between the two devices in a variety of configurations and permutations. Consider the different options of technology and band that can be used, and possible combinations of these links with parallel links and link aggregation as shown in Figure 3. Each individual interface-to-interface link is modelled as a directed edge E in the graph model. An edge can be in one of a number of states, for example we may define the possible states as incident or transmitted. If we assume the wireless devices have a uniform number of radio interfaces, the total number of possible link configurations n is given by

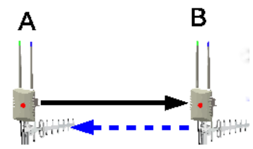
$$n = (p^r - 1)^k \quad \text{for } p, r, k \in \mathbb{N}$$



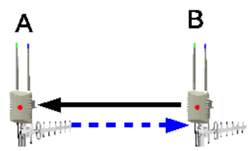
(a) select 5 GHz



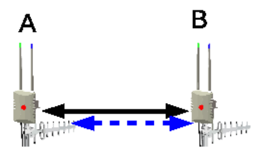
(b) select TVWS



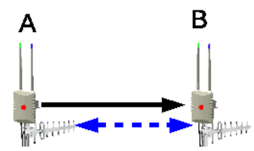
(c) use 5 GHz to transmit and TVWS to receive



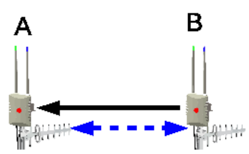
(d) use TVWS to transmit and 5 GHz to receive



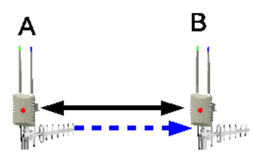
(e) aggregate 5 GHz and TVWS into a single logical link to transmit/receive



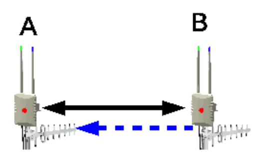
(f) use 5 GHz to transmit only and TVWS to transmit and receive



(g) use 5 GHz to receive only and TVWS to transmit and receive



(h) use 5 GHz to transmit and receive, TVWS to transmit only



(i) use 5 GHz to transmit and receive, TVWS to receive only

Fig. 3: Possible options when using 5 GHz and UHF-TVWS hybrid links. The black solid line and blue dashed line respectively represent 5 GHz and UHF-TVWS radio links.

where p is the number of possible edge states, k is the number of nodes and r is the number of wireless interfaces. The "-1" term is to remove the empty set, which is not a valid link configuration.

The system aims to find the set of link configurations:

$$\begin{gathered} S = \{S_j\} := \{y_{ji}\} \mapsto \min_i z_{ji}(x) \\ \text{where } j = 1, 2, ..., N-1 \text{ and } i = 1, 2..., n \end{gathered} \tag{1}$$

where x = amount of data to be served, y = link, z = transmission time, which depends on interference, congestion, etc. and is handled by the MAC protocol, and n = number of possible links, which is dependant on the number of radios per node.

4.1 Single point-to-point

It is very easy to determine the optimal link in one of two extreme deployment scenarios: (i) in an area where there is no TVWS available, 5 GHz remains the only option; (ii) when the node spacing is beyond 5 GHz transmission distance capability, TVWS becomes the only option because UHF-TVWS attenuates less compared to 5 GHz as explained by Friis path-loss model [7]. The focus of this paper is on a typical scenario where both 5 GHz and TVWS radios are operable with performance subject to prevailing spatial/temporal spectral and environmental conditions.

For a one-hop scenario i.e. two wireless radio devices communicating only with each other (local optima), the link selection scheme chooses a link configuration y_i from the set of possible link configurations of size n to transmit a data package of size x in the minimum possible time. The time taken for that package transmission on that specific link configuration is $z_i(x)$.

$$y_i \mapsto \min_i z_i(x) : \quad i \in 1, 2, ..., n$$

For a multi-hop system of N identical radio devices, the link selection method chooses a link configuration for each hop S_j, $j \in \{1, 2, ..., N-1\}$ such that the total transmission time is minimised. The total link selection set is denoted

$$S = \{S_1, S_2, ..., S_{N-1}\}$$
$$S_j \in S := y_{ji} \mapsto \min_i z_{ji}(x) \ : \quad j, i \in \mathbb{N}$$

In section 6 we show that performance depends highly on the combination of parameter settings such as channel, transmission power (txpower), channel width, modulation and coding scheme (MCS), and environmental factors.

4.2 Point-to-multi-point

Suppose there are three nodes A, B and C connected as shown in Figure 4. When node A has a queue of data destined for node B and another queue for node C, it can aggregate the links, send to node B and thereafter send to node C. Alternatively, node A can split i.e. send to node B on one interface and send to node C on the other interface. We choose a set of link options $\{S_j\}$ where, in this case, $j = 1, 2, ..., N-1$ for N-1 nodes connected to a single node.

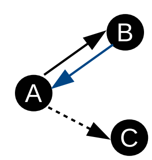


Fig. 4: Transmission options for a point-to-multi-point link.

$$S_j := y_j \mapsto \min_i z_{ji} + \tau \tag{2}$$

where τ = delay associated with media contention.

5 Experimental setup

The objective of the study was to investigate the performance of the different 5 GHz and UHF-TVWS radio settings, namely channel, channel-width, and txpower under different environmental conditions such as trees/vegetation, building structures and landscape that tend to affect line-of-sight. Figure 5 shows the node specifications and physical setup. The measurement process involved setting up the nodes on two ends of a site to set the environmental variable. Performance was measured using *iperf* and *ping* tools for different combinations of channel, txpower and channel width settings. The process was controlled from a laptop (not visible in the picture) connected to the node over a dedicated 2.4GHz WiFi access connection. We also conducted performance measurements using an indoor setup to establish baseline performance prior to setting up the experiment outdoors. The indoor setup comprised nodes set up inside the lab such that node A and node B were 21 m apart, and 1 m, 0.9 m and 4.5 m away from the wall sides while the TVWS antenna stood at 0.36 m below the ceiling.

5 GHz radio:

i) System board: Mikrotik RB435G
ii) Operating system: OpenWRT
iii) WNIC: Atheros-based 802.11 a/b/g mini PCI adapters.
iv) Driver: Ath5k
v) Antenna: Brand: made/distributed by scoop (www.scoop.co.za); Model: ANT-P523; Gain: 23 dBi; Frequency: 5150 - 5850 MHz; Cable type and length: coax, 1 m.

TVWS radio:

i) System board: Mikrotik RB435G
ii) Operating system: OpenWRT
iii) WNIC: Doodle labs DL509-78 Broadband Radio Transceiver for the 470-784 MHz TV band.
iv) Driver: Ath5k
v) Antenna: Brand/Model: Maxview, MXR0053 TV Aerial -10 element Forward Gain: 8 dB; Front to back ratio: 10-20 dB; Acceptance angle: 25; Frequency range: 470-860 MHz; channel 21-69; Cable type and length: coax, 1.55m.

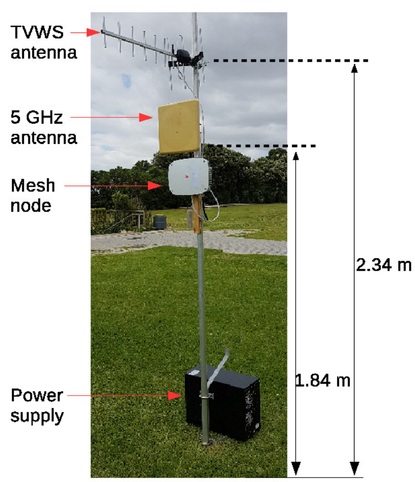


Fig. 5: Node specifications and physical setup.

6 Results and discussion

6.1 Indoor performance

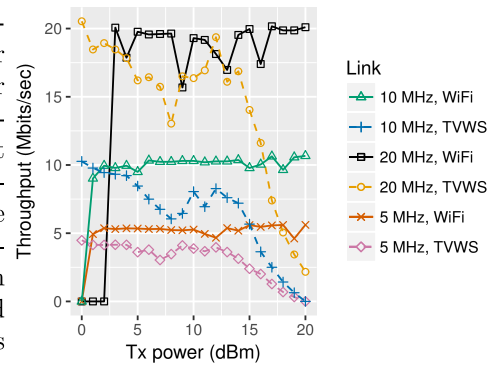
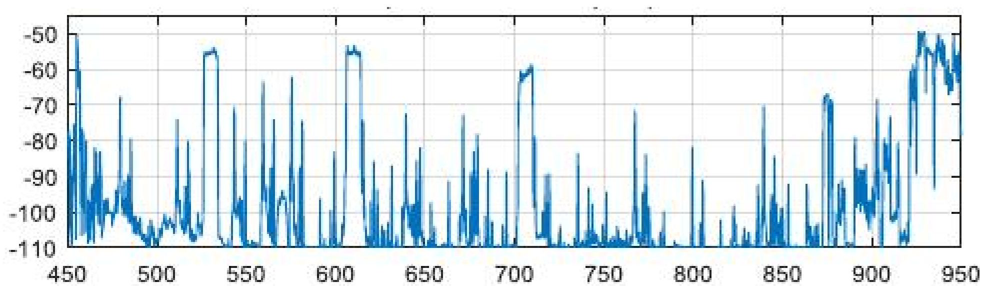


Fig. 6: Throughput vs txpower.

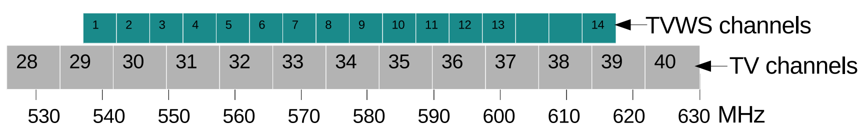
Figure 6 shows the relationship between throughput and transmit power observed from the indoor setup. For the 5 GHz WiFi radio, throughput slightly increases with transmit power. We would expect in an outdoor real-world setup there would be a more marked increase in throughput owing to the expected increase in SNR but we suspect that the reduced distance between the nodes reduces the possible range of throughput values. Very surprisingly and counter-intuitively, once the transmit power surpasses 10 dBm for TVWS, the throughput in fact decreases rapidly, which completely contradicts Shannon's Law. This is owing to the input signal level at the receiver being well above its recommended range, causing saturation of the electronics and distortion of the signal. The DL509-78 transceiver is quoted to have a recommended input signal strength range of -40 to -80 dBm, while on the TVWS interface the input signal levels were measured to reach above -30 dBm, even climbing to +9 dBm in one measurement and above -20 dBm for a transmit power of 20 dBm in several measurements. Such high input power values cause the signal responses of the RF receiver front-end electronics to become distorted. The operational amplifiers cannot output a voltage above their supply voltage in response to a higher input power - i.e. they saturate at such high input signal levels - so they are unable to reflect the variations in the received signal accurately, causing signal distortion and inability of the system to decode the signal correctly. On the other hand, for the same transmit power values, the receiver-side 5 GHz WiFi card showed lower input signal strength measurements, all falling below -40dBm, so saturation and the resulting decreased throughput was not observed in the experiments on the 5GHz radio under the same conditions. This observation underscores the point that considering signal strength alone can be misleading when assessing link quality or determining optimal operating parameters as it clearly fails to reflect possible link failure/deterioration due to phenomena such as power saturation.

6.2 Outdoor performance: clear line-of-sight

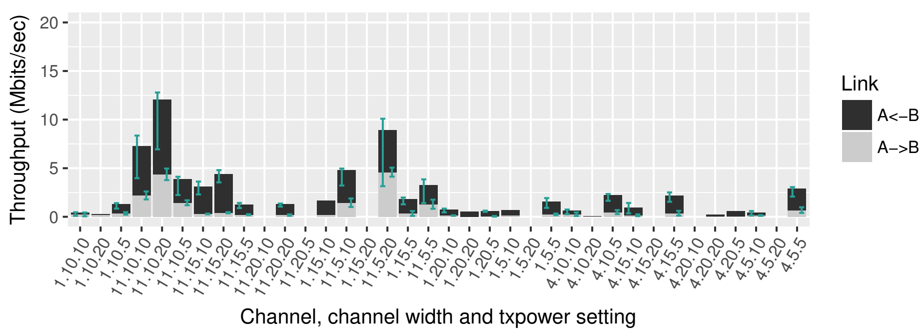
Figures 7c & 7d show the link performance at the University of Cape Town rugby field for the channels tested. Figure 7b shows the TVWS channel mapping to UHF. Performance difference between TVWS channels was due to frequencies mapped to channel 1 & 11 being busier than channel 4 as Figure 7a shows.



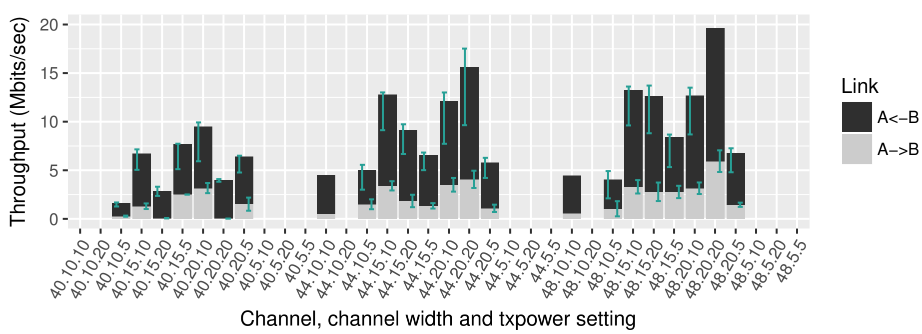
(a) TVWS band spectrum scan. Vertical axis: uncalibrated signal strength; horizontal axis: frequency in MHz.



(b) Down-converted WiFi mapping to UHF-TVWS channels.



(c) TVWS



(d) 5 GHz

Fig. 7: Link performance for each of the channel, txpower and channel width settings at one location. The bars are labelled x.y.z where x, y and z respectively represent the channel, txpower (dBm) and channel width (MHz) settings. The absence of a bar at a point e.g, '44.5.20' implies that channel 44 was inoperable with channel width set to 5 MHz and txpower set to 20 dBm. The blue lines indicate the *standard error* calculated as $(\textit{standard deviation}) \div \sqrt{(\textit{sample size})}$.

6.3 Outdoor performance: line-of-sight obstructed by trees

One node was fixed on one end while the other was positioned such that a tree obstructed the line-of-sight and repositioned such that there was an incremental number of trees in between. The site had pine trees with trunks typically 2 m in circumference and spaced as follows: 20 m, 28 m, 7 m, 9 m, 5 m, 18 m, 25 m.

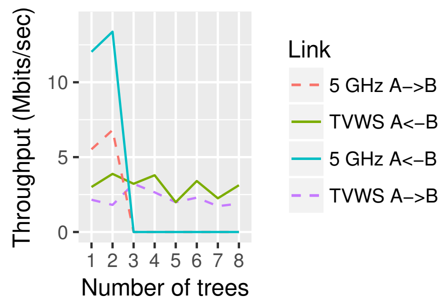


Fig. 8: TVWS and 5 GHz WiFi throughput through trees.

Multiple data samples were collected for different combinations of settings. We considered the combination of channel, channel-width and txpower that gave the best results at the highest tree count and used that at all the other tree counts. The rationale is that it is better to have a low-throughput link that works end-to-end than a high-throughput link that breaks mid-way along the path. For the TWVS radio this turned out to be channel=7, chanbw=5MHz, txpower=5dBm whereas for 5 GHz it was channel=44, chanbw=20MHz, txpower=20dBm. Figure 8 shows the average forward and reverse throughput. From the results it is evident that a 5 GHz WiFi link breaks completely as soon as the link is obstructed by more than two trees. On the other hand, a TVWS link is operable with as many as eight trees obstructing the line-of-sight.

6.4 Summary of observations and implications

i) **Optimal operating parameters.** Each channel appears to perform differently with different settings as shown in Figures 7c and 7d . The optimal setting is time and location dependent, and there seems to be an interesting interplay among channel quality, txpower and channel width settings. The task of determining optimal operating parameters is a complex and relevant problem. The immediate implication is that though throughput is generally directly proportional to txpower and channel width, keeping the txpower and channel width at its max does not always maximise performance. Some data points in Figures 7c and 7d are missing throughput readings (e.g. TVWS channel = 11, chanbw = 20 MHz and txpower=10 dBm) because the link became inoperable for that setting at that point in time, which underscores the importance of preceding channel selection with spectrum analysis.

ii) **Effects of environmental factors.** Objects between or around the nodes affect performance in two ways: (i) obstructing the line-of-sight, thereby impinging on the Fresnel zone clearance, (ii) signal reflections off of objects around the node, which is more pronounced in TVWS compared to 5 GHz due to differences in antenna characteristics. This may account for some of the the performance variations between 5 GHz and TVWS radios.

iii) **Txpower vs throughput.** At short distances with nodes in close proximity to walls, the 5 GHz link throughput is generally directly proportional to txpower, whereas the TVWS link throughput is inversely proportional to txpower as observed in Figure 6. This discovery suggests that for indoor applications, the current TVWS state-of-the-art will require low txpower for optimal performance.

iv) **Link asymmetry.** More often than not links are asymmetric as Figures 7c and 7d show. This is caused by a combination of factors ranging from interference sources to imperfections in hardware. Routing protocols need to factor in this link characteristic.

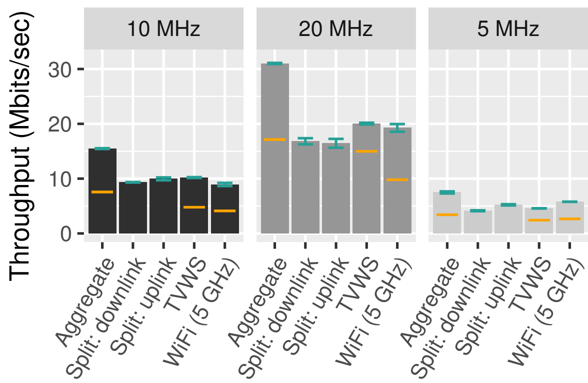
v) **Vertical vs horizontal polarization.** There were performance variations observed between vertical and horizontal polarization, which may be attributed to differences in channel quality subject to polarization due to other transmitters using a specific polarization. For example, a channel may be vertically occupied, but horizontally vacant or vice-versa. Besides channel quality, there is no statistical evidence to suggest a difference in obstacle penetration/circumvention capability between vertical and horizontally polarised radio antennas.

7 Multi-link performance

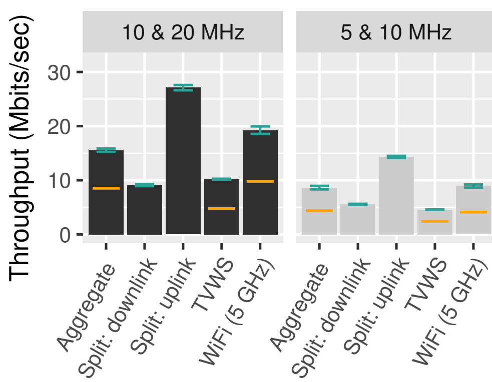
Link aggregation was realised by distributing outbound frames over the 5 GHz and TVWS interfaces, while link splitting was implemented by alternating frame sending and receiving tasks between the two radios using Batman-advanced mesh protocol [8]. Batman-advanced was used because of its inherent support for multi-link optimisation. The data-rate was set by varying the channel width from the set of supported values, which are are 20 MHz, 10 MHz, and 5 MHz.

When the radios' data-rates are approximately equal, aggregating provides the best performance in terms of throughput and round trip time (RTT) as shown in Figures 9a and 9c. The increases in throughput when aggregated ranges 44.5 - 61.8 %. The benefit of splitting compared to selecting either radio is not immediately clear unless we consider throughput in the forward as well as reverse direction. The horizontal orange lines in Figure 9a mark the throughput in the reverse direction. Splitting achieves optimal throughput consistently in either direction, whereas a single radio may have significantly lower throughput in one direction as shown in Figure 9a.

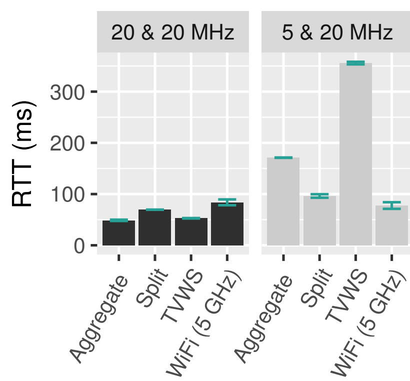
For links with unequal data-rates, the resultant throughput when the 5 GHz and TVWS links are aggregated is higher than the throughput of the link with a lower data-rate, but less than that of the individual link with higher data-rate as shown in Figure 9b. Therefore, layer-2 link aggregation is most beneficial when the radios have uniform data-rates. For radios with unequal data-rates, link splitting provides better performance as observed from the RTT in Figure 9c. The poor performance of aggregation involving non-uniform data-rates is due to an increase in the number of frames arriving out of order, which exacerbates delays in fragment reassembly at the receiving end. On the other hand, when the uplink and downlink are split between the two radios, there is a significant improvement in throughput relative to individual radio performance as shown in Figure 9b. The improved performance of a split link sometimes going beyond theoretical expectation may be attributed to the minimised contention delay and subsequent efficiency in the store and forward mechanism, and the sending/receiving of acknowledgement packets.



(a) Uniform data-rate.



(b) Non-uniform data-rate



(c) Average round trip time (RTT).

Fig. 9: Performance of individual radios, aggregate and split link from the indoor setup. The orange horizontal lines in (a) and (b) mark the link's reverse direction or downlink throughput. To determine RTT, 500 packets were sent with a wait interval of one second and a packet size of 65507 bytes. The maximum transmission unit (MTU) on each interface was 1532 bytes.

8 Conclusion and follow on work

The results confirm the theoretical expectation, which is that high operating frequencies such as 5 GHz band are suitable for short to medium distance with clear line-of-sight whereas for medium to long distance and obstructed line-of-sight, lower operating frequencies such as UHF-TVWS band out-perform higher frequencies. The choice of spectrum could make or break a wireless link. Further work is needed to understand the intricate interplay among operating parameters, namely txpower, channel width, channel quality and how the surrounding environment influences the choice of optimal operating parameter -especially in a mesh network environment with interdependencies between links.

Future work will include an exploration into effects of weather conditions such as rainfall on link performance. In addition, an expansion of the test-bed is imminent for further investigation into the performance of aggregate and split links as the node count and subsequent traffic flows increase. Furthermore, the next node design iteration will include the following features: (i) Dynamic antenna polarization for efficient spectrum utilisation and clean/optimal channel selection; (ii) Inbuilt mechanism for auto-adjusting operating parameters such as txpower; and (iii) Auto-adjusting radio selection and operating parameter in a multi-hop mesh environment described in sections 4.1 and 4.2.

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