Head to head battle of TV White Space and WiFi for connecting developing regions

David Johnson, Natasha Zlobinsky, Albert Lysko, Magdeline Lamola, Senka Hadzic, Richard Maliwatu, Melissa Densmore

Meraka, CSIR,
{djohnson,nzlobinsky,alysko,mlamola}@csir.co.za
Computer Science Department, UCT
{shadzic,rmaliwatu,mdensmore}@cs.uct.ac.za

Abstract. TV White Space networks are gaining momentum worldwide as an important addition to the suite of wireless protocols available for connecting developing regions. However, there has been no thorough investigation of scenarios where TV White Space performs better or worse than alternative low-cost wireless technology such as WiFi. This paper analyzes the performance of 5 GHz WiFi links and TV White space links using down-converted WiFi, typically used as wireless backhaul for poorly connected regions, in different scenarios including line-of-sight links and links obstructed by trees and structures. The experiments make use of 802.11a/b/g WiFi and TV White Space equipment that down-converts standard 802.11 a/b/g WiFi from the 2.4 GHz band into the UHF band. The paper finds that 5 GHz links outperformed TVWS where clear line-of-sight is available and point-to-point links are required. TVWS however is a clear choice where there are obstructions and where wider coverage is needed. Some interesting observations on the negative effect of TV transmissions in adjacent channels a few channel-hops away from the channel being used for TVWS are also provided.

Keywords: TV White Space, 802.11, rural connectivity

1 Introduction

According to www.internetworldstats.com [1] as well as other sources [1]–[3], the African continent has the lowest internet penetration rate of all, with a mere 28.6% of the population having internet access compared to the world average of 46.4% [2,3]. The second lowest is Asia with 40.2%. By far the main contributors to low access rates are rural areas. For example, the ITU research found that in Africa the 3G coverage of the rural population was 29% while the coverage in urban areas was a significantly higher 89% [4]. Statistics South Africa also found in 2014 that 27.5% of households with internet access were in metropolitan and urban areas while only 2.4% were in rural areas [5]. The reason for the persistently low rates is that internet access is not affordable for a large portion of the population.

Expanding access in rural areas has been typically achieved using a mix of commercial mobile operators, satellite and licence-free WiFi backhaul and access networks [6,7] Internet access offered by mobile operators and satellite is usually very costly and only allows limited Internet to be used. WiFi access is far more cost-effective as no licence fees are required for access to spectrum and low-cost equipment is readily available. Many of these WiFi networks are adapted for long distances using high-gain antennas and a modified MAC to handle long distances [8]. However, WiFi only works well when line-of-sight is available.

TV White spaces is an emerging communication technology that offers many of the low-cost benefits of WiFi but with improved coverage - especially in mountainous areas and areas with vegetation that require very high masts to achieve line-of-sight. Early trials of TVWS show that respectable throughput (up to 12 Mbps) can be achieved at distances of 6 km [9] with 802.22 promising speeds up to 22.69 Mbps and a maximum distance of 100 km [10]. 802.11af-based equipment, due for release this year, can achieve rates up to 569 Mbps when used with four spatial streams and four bonded 8 MHz channels [11]. TV White spaces can only use spectrum not used by TV broadcasters and the performance of the link will also be related to the amount of available spectrum.

The performance of WiFi and TV White space is linked to a number of factors: the amount of available spectrum, the level of interference for a specific chosen channel, the antennas being used and the propagation environment. The choice between TV white space and WiFi is not always obvious; if no interference is present, WiFi will usually be best for line-of-sight links with clear Fresnel zones and TV white space will usually provide better performance than WiFi where there is not clear line-of-sight. But there are various shades in-between these extremes once interference from TV transmitters in adjacent channels, different antenna types, multi-path and degree of Fresnel zone obstruction are factored in.

This paper uses a set of theoretical predictions and real-world measurements in different environments to illuminate the subtle shift between the choice of TVWS and WiFi for a specific link. We also show how well the theory correlates to what could actually be expected by users in terms of throughput and propagation. In Section 3 we discuss popular simplified propagation models and the results that can be expected from these. The following sections show both idealized laboratory testing results and outdoor "real-world" test results, together with analysis and recommendations based on our discoveries.

2 Related work

In order to keep deployment costs low, most alternative rural networks rely on license free or license exempt frequency bands, such as the 2.4 GHz ISM band or 5 GHz U-NII band. Wireless Mesh Networks (WMNs) are often seen as an affordable solution to bring wireless connectivity into rural and remote regions [6]. Several deployments using long range IEEE 802.11 links have been rolled out in sub-Saharan Africa using WiBACK technology [12, 13].

Low-cost WiFi-based Long Distance (WiLD) networks have been deployed in India, Ghana and the San Francisco Bay area [8]. With links up to 100 km, WiLD networks seemed a promising connectivity solution for rural areas. However, real-world deployments of such networks showed very poor end-to-end performance, thus the same authors proposed WiLDNet – a system with modified 802.11 MAC protocol and an adaptive loss-recovery mechanism for improved link utilization [14]. In [7] a multi-hop long-distance WiFi network has been designed, and the solar-powered system deployed in a remote village in Borneo, connecting six nearby villages to the telecentre for Internet access. An important aspect of long-distance WiFi deployments is the low cost due to the use of off-the-shelf devices.

Cognitive radio technology enables utilization of unused UHF frequencies originally assigned to TV broadcast, referred to as TV white spaces (TVWS). TVWS based last mile access has received a lot of attention in the research community and several systems have been deployed in rural areas and developing countries such as India [15], Malawi [16], Southern Africa [17] and rural Malaysia [10]. Preliminary results of a TVWS deployment in rural Malawi report coverage distances of up to 7.5 km, maximum throughput of 2 Mbps and average latency of 120 ms [16]. Wide coverage and availability of white spaces particularly in sparsely populated regions make this technology an attractive solution for last mile access in rural areas. While deployments in cities and densely populated areas inevitably depend on geolocation spectrum databases, in rural areas most of the spectrum is underutilized. Therefore, a spectrum database is not technically essential. Furthermore, spectrum mask requirements for the low cost equipment can be looser, since there are usually only few TV stations deployed in rural areas in developing countries, leading to very low channel occupancy [18].

However, trials performed in one of the suburbs of Cape Town, South Africa showed that TVWS can provide interference free Internet even in urban areas, with speeds up to 12 Mbps for downlink and 5 Mbps for uplink, and average latency 120 ms [9].

An overview of deployment trends for last-mile connectivity in rural areas is given in [19]. To the best of our knowledge, there is no reported performance comparison between long-distance WiFi and TVWS in terms of throughput and propagation characteristics.

3 Background

WiFi and TVWS spectrum have different advantages and disadvantages that make it relatively difficult to select one or the other technology. TVWS has the obvious technical advantage of wider coverage (up to 30 km [13]) which means fewer radio devices are required per unit area than in the case of shorter range equipment, and make TVWS particularly suitable to rural backhaul applications. Greater penetration and less absorption by buildings, trees and other obstacles are further technical advantages, enabling a signal to be received even in non-line of sight situations. TVWS is well suited to areas with low population densities [13]. On the other hand, the greater propagation range and penetration could also result in higher interference effects between TVWS nodes. TVWS is also a comparatively immature technology in the market. In contrast the WiFi properties of shorter propagation range and higher sensitivity to obstacles result in less interference, but the consequence is that the technology requires more nodes per unit area as well as line-of-sight. A further technical advantage is that Fresnel zones have smaller radius so less clearance (height) is required to avoid attenuation. Additionally, WiFi is a mature and well known technology that is readily available, and high gain WiFi antennas up to 30 dBi are common.

It is generally assumed that operating WiFi in TV bands would provide reliable connections with greater speeds. In free space, in the absence of other impairments, the main effect on the performance from a theoretical perspective is path loss. Using the Friis path loss equation where P_r is receive power, P_t is transmit power, G_t is transmit antenna gain, G_r is receive antenna gain, d is distance between antennas and f is frequency:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{c}{4\pi d f}\right)^2$$

If the TVWS frequency (f_{TV}) is set to 700 MHz and the 5 GHz WiFi operating frequency (f_{WF}) is set to 5600 MHz then $f_{WF} = 8f_{TV}$

The change in path loss in dB when moving from 5 GHz WiFi to TVWS with the same receive and transmit antenna gains and the same transmit power and distance is

$$10Log\left(\frac{P_{r_{TV}}}{P_{r_{WF}}}\right) = 10Log\left(\frac{G_t G_r \left(\frac{c}{4\pi d f_{TV}}\right)^2 P_t}{G_t G_r \left(\frac{c}{4\pi d f_{WF}}\right)^2 P_t}\right) = 10Log\left(\frac{\frac{1}{f_{TV}}}{\frac{1}{f_{WF}}}\right)^2$$

$$= 20Log\left(\frac{\frac{1}{f_{TV}}}{\frac{1}{8f_{TV}}}\right) = 18.06\ dB$$

Hence TVWS would generally have approximately an 18 dB advantage compared to 5 GHz WiFi when using exactly the same RF parameters. The reality, however, is that 5 GHz WiFi antennas can be built with a gain of up to 30 dBi whereas UHF antennas usually have a gain of no more than 12 dBi. When the transmit and receive gains of these maximum gain antennas are combined, TVWS has a combined maximum antenna gain of 24 dBi and UHF has a combined maximum antenna gain of 60 dBi. For the same distance TVWS will now be 18 dB weaker when building point to point links with high gain antennas. This is the reality for narrow-beam point-to-point links, however if point-to-multipoint links are required TVWS is more ideal as its lower gain antennas have a wider beam width. The antennas we use in our experiments (22 dBi 5 GHz WiFi antennas and 12 dBi UHF antennas) result in similar received signal strengths for line-of-sight links with antennas pointed directly at each other. However, the TVWS antennas will have a wider horizontal beam width and coverage and provide better links in a point-to-multipoint scenario. Multipath fading will also result in variation of the received signal and this paper makes use of real world experiments to compare TVWS and WiFi more accurately.

4 Methodology

4.1 Description of equipment used

The measurements made use of the Meraka White Space Mesh Node (WSMN) which consists of a Mikrotik Routerboard RB435 running OpenWRT and Atheros-based 802.11 a/b/g mini PCI adapters as well as a Doodle labs DL509-78 Broadband Radio Transceiver for the 470-784 MHz TV band.

The WSMN setup used the following antennas

- 22 dBi 5GHz Panel antenna (connected directly to enclosure with pigtail)
- Static unit: 13 dBi MaxView MXR0025 Yagi TV antenna (connected via LMR400 1.5m low-loss cable)
- Mobile unit: 10 dBi Ellies AA15EE4/69 15 Element VHF / UHF Yagi TV antenna
- The WSMN also has two 8 dBi omnidirectional antennas for 2.4 GHz and 5 GHz bands but these were not used.

The Doodle lab transceiver uses a transverter that down-converts the 2.4 GHz WiFi band to the UHF band (550 MHz to 650 MHz).

4.2 Measurement process

Before carrying out the measurements, scans were carried out in the 5 GHz WiFi band and the UHF band. We selected a channel in WiFi and TVWS which resulted in the lowest noise level in the channel or lowest level of interference. To test the performance of the links the *iperf* tool was utilized to test the TCP throughput in both directions. Three measurements over 60 seconds were taken to ensure that variability in the channel is captured. To test the latency and packet loss we make use of the *ping* tool and again take three 60 second measurements. Performance of the radios for different channel widths (5, 10, 20 MHz) was tested to check if interference in neighboring channels was having any effect on the performance.

4.3 Setup for cabled measurements

Figure 1: Cabled measurement setup using 60 dB of attenuation and a splitter to check performance of devices without interference and with various levels of attenuation

Baseline experiments were conducted to determine the best performance possible on the TVWS and WiFi radios, in the absence of the effects of the wireless channel (e.g. noise, interference, fading). For the baseline experiments the network card of one interface was physically connected to the network card of a similarly kitted board through each board's antenna pigtail, RF cable, two 30 dB attenuators and appropriate connectors. (This is illustrated in Figure 1 above for clarity.)

4.4 Setup for outdoor measurements

For outdoor measurements, one WSMN was statically mounted at the apex of the roof of a house in Fish Hoek, Cape Town (shown in Figure 2 (a)) and another WSMN was a mobile device powered by an uninterruptible power supply and placed at various points to test specific scenarios (shown in Figure 2 (b, c, d)) below.

Figure 2: Outdoor measurements setup: (a) Static installation on roof (b, c) Mobile installation 500m up the road (d) Mobile installation 2.2 km away behind a tree

Figure 3: Location of outdoor test sites in Fish Hoek, Cape Town

The 5GHz WiFi and TVWS antennas of the static WSMN were 5 m above ground level. The antennas of the mobile unit were 1.5 m above ground level. Two outdoor scenarios (shown in Figure 3) were tested (1) a line-of-sight test 500 m from static site shown in Figure 2(b,c), and (2) a longer range 2 km test with line-of-sight and a 2.2 km non-line-of-sight test obstructed by a tree shown in Figure 2(d).

5 Results and analysis

In this section we summarize all the measurements taken with respect to distance and environment. Take note of the following abbreviations used:

- S/N: Signal to Noise Ratio
- M->S: Mobile Node-to-Static Node
- S->M: Static Node-to-Mobile Node

5.1 Baseline cabled measurements

A summary of the baseline results is shown in Table 1. There is a fairly linear average throughput relationship as channel width increases, which is to be expected. WiFi has a slightly higher throughput than TVWS in the absence of environmental effects, with a difference of about 1.7 Mbps. The latency variation is insignificant. The slightly worse throughput of TVWS is most likely due to the extra distortion added by the transverter of the TVWS radio.

Table 1: Cabled measurements results for establishing baseline performance

	Wi-Fi		**TVWS**	
Channel width	***Throughput (Mbps)***	***Latency (ms)***	***Throughput (Mbps)***	***Latency (ms)***
	Min/Avg/Max	***Min/Avg/Max***	***Min/Avg/Max***	***Min/Avg/Max***
5 MHz	1.2/6.1/7.3	1.1/1.3/4.0	2.8/4.4/5.1	1.1/1.5/5.0
10 MHz	6.9/11.8/13.0	0.8/1.0/3.7	6.0/9.8/11.4	0.8/1.1/4.5
20 MHz	13.6/22.4/24.6	0.7/0.8/3.3	18.1/20.6/22.5	0.7/0.8/2.7

5.2 Short-range 500m Line-of-sight measurements

Spectrum scans revealed that channel 36 (5180 MHz) was the best WiFi channel to use and 575 MHz was the best frequency to use for TVWS. The SNR for WiFi was

-52/-102 dBm for all channel widths and the signal strength of TVWS was -44/ -93 dBm, -44/-90 dBm and -46/-89 dBm for 5,10 and 20 MHz respectively. The latency variation was insignificant and averaged between 1.1 and 1.2 ms for WiFi and 1.1 and 1.7 ms for TVWS. The throughput variation is shown in Figure 4 below. TVWS performance followed the same trend as the cabled measurements for 5 MHz and 10 MHz, where its performance was slightly poorer than WiFi but at 20 MHz, the interference from a strong DTV transmission in a nearby adjacent channel caused the performance to degrade significantly due to the weak input filter of the Doodle lab radio.

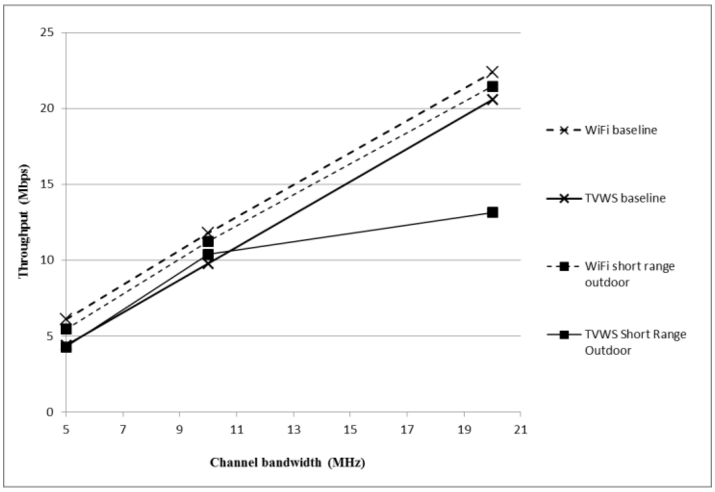

Figure 4: Comparison of average throughput of WiFi and TVWS for baseline and outdoor measurements

5.3 Long range measurements with and without obstructions

The results of the long range measurements are given in Table 2. For this experiment, spectrum scans also revealed that WiFi channel 36 (5160 MHz) and 575 MHZ for TVWS had the least amount of interference. These experiments were only carried out with 20 MHz channel width. We obtained significantly higher throughput for the TVWS link compared to WiFi. In case of a 2.2 km NLOS link, the SNR of the WiFi link was too low to establish connectivity between the two nodes. For the TVWS link we were able to achieve 5.18 Mbps throughput even with a tree obstructing line-of-sight.

In the line-of-sight case, the WiFi performance was also weaker than the TVWS. We would have expected the WiFi to perform better in this scenario but this may be due to us not being able to perfectly align the panel antennas which had a much narrower beam width than the TVWS antennas. This may also have been due to some intermittent WiFi interference in the 5 GHz band.

Both the static to mobile and mobile to static throughput is captured as this is often not symmetrical. The lack of symmetry is due to different noise levels at each site. Typically, higher sites experience more noise. In this experiment, the mobile site was at a higher elevation than the static site and we therefore would expect the mobile to static throughput to be better than the static to mobile throughput – this is confirmed by the measurements.

Table 2: Long range outdoor measurements

	Wi-Fi 5180 MHz M->S (S->M)			**TVWS 575MHz M->S (S->M)**		
Scenario	***RSSI***	***Throughput Avg (Mbps)***	***Latency (ms)***	***RSSI***	***Throughput Avg (Mbps)***	***Latency (ms)***
	S/N: M->S (S->M)	*M->S (S->M)*	*Avg*	*S/N: M->S (S->M)*	*M->S (S->M)*	*Avg*
2 km LOS	*-72/-102* (-74/-103)	*1.45* (1.52)	1.804	*-50/ -89* (-49/ -91)	*7.26* (6.85)	1.043
2.2 km NLOS	*-99/ -102* (unknown)	none	none	*-62/ -92* (-61/-91)	*5.18* (3.1)	2.175

6 Conclusion

The results show that there are various parameters and environments that influence whether WiFi or TVWS has superior performance. Owing to the range of possible conditions, it would appear that an optimal implementation should have devices fitted with both WiFi and TVWS radios where the best link is selected automatically based on prevailing conditions. Such a node would continually monitor link conditions and switch to the best performing radio whenever necessary.

From our analysis so far, WiFi performs better in short-range line-of-sight scenarios and our theoretical analysis shows that for very long range point-to-point links they will outperform TVWS but antenna alignment is challenging. TVWS performs best in NLOS scenarios and is well suited to point to multi-point scenarios where wider coverage is required. TVWS can however be negatively affected by strong TV signals even in adjacent bands a few channel hops away.

References

1. Internet World Stats, “Africa Internet Users, Facebook and 2015 Population Statistics.” 2015.
2. Neto, M. L. Best, and S. E. Gillett, “License-Exempt Wireless Policy: Results of an African Survey,” Inf. Technol. Int. Dev., vol. 2, no. 3, pp. 73–90, 2005.
3. R. Thanki, “The Economic Significance of Licence- Exempt Spectrum to the Future of the Internet,” no. June, 2012

4. B. SANOU, “ICT Facts & Figures. The world in 2015.,” Itu 150 Años (1865 - 2015), p. 6, 2015.
5. Office for National Statistics, “Census 2013,” General Household Survey, no. May. p. 78, 2013.
6. M. Kretschmer, C. Niephaus, T. Horstmann and K. Jonas, "Providing Mobile Phone Access in Rural Areas via Heterogeneous Meshed Wireless Back-Haul Networks," 2011 IEEE International Conference on Communications Workshops (ICC), Kyoto, 2011, pp. 1-6.
7. K. Ab-Hamid, C. E. Tan and S. P. Lau, "Self-sustainable energy efficient long range WiFi network for rural communities," 2011 IEEE GLOBECOM Workshops (GC Wkshps), Houston, TX, 2011, pp. 1050-1055.
8. L. Subramanian, S.Surana, A.Sheth, S. Nedevschi, R. Patra, M. Ho, and E. Brewer, “Rethinking wireless for the developing world,” In ACM Hotnets 2006.
9. A. A. Lysko et al., "First large TV white spaces trial in South Africa: A brief overview," 2014 6th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), St. Petersburg, 2014, pp. 407-414.
10. M. H. Omar, S. Hassan and A. H. M. Shabli, "Feasibility Study of Using IEEE 802.22 Wireless Regional Area Network (WRAN) in Malaysia," Network Applications Protocols and Services (NETAPPS), 2010.
11. W. Lee, et al., "TGaf PHY proposal". IEEE P802.11. Retrieved 2013-12-29.
12. M. Kretschmer, C. Niephaus, D. Henkel and G. Ghinea, "QoS-Aware Wireless Back-Haul Network for Rural Areas with Support for Broadcast Services in Practice," 2011 IEEE Eighth International Conference on Mobile Ad-Hoc and Sensor Systems, Valencia, 2011, pp. 758 764.
13. D. Henkel, S. Engländer, M. Kretschmer and C. Niephaus, "Connecting the unconnected - Economic constraints and technical requirements towards a back-haul network for rural areas," 2011 IEEE GLOBECOM Workshops (GC Wkshps), Houston, TX, 2011, pp. 1039-1044.
14. R. Patra, S. Nedevschi, S. Surana, A. Sheth, L. Subramanian, and E. Brewer, “WiLdnet: design and implementation of high performance wifi based long distance networks,” In Proceedings of the 4th USENIX conference on Networked systems design & implementation (NSDI'07). USENIX Association, Berkeley, CA, USA, 7-7.
15. G. Naik, S. Singhal, A. Kumar and A. Karandikar, "Quantitative assessment of TV white space in India," in Twentieth National Conference on Communications (NCC), Kanpur, 2014, pp. 1-6.
16. C. Mikeka et al, “Preliminary Performance Assessment of TV White Spaces Technology for Broadband Communication in Malawi,” in Humanitarian Technology: Science, Systems and Global Impact 2014, HumTech2014, Volume 78, 2014, Pages 149-154.
17. Moshe T. Masonta, David Johnson, and Mjumo Mzyece, “The White Space Opportunity in Southern Africa: Measurements with Meraka Cognitive Radio Platform,” in Volume 92 of the series Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, pp 64-73(e-Infrastructure and e-Services for Developing Countries).
18. M. Zennaro, E. Pietrosemoli, and A. Sathiaseelan, “Architecting a Low Cost Television White Space Network for Developing Regions,” in Proceedings of the Fifth ACM Symposium on Computing for Development (ACM DEV-5 '14). ACM, New York, NY, USA, 113-114.
19. S. Nandi et al., "Computing for rural empowerment: enabled by last-mile telecommunications," in IEEE Communications Magazine, vol. 54, no. 6, pp. 102-109, June 2016.