Connecting Africa Using the TV White Spaces: From Research to Real World Deployments

(Invited Paper)

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***Abstract*—More than 4 billion people are not connected to the Internet. This is either because there is no infrastructure or because Internet access is not affordable. This digital divide is extreme in Africa. At Microsoft, we have been investigating various technologies to bridge this divide. In this paper we describe our research around the TV White Spaces, and how we have leveraged it, and worked with our partners to connect communities in Kenya, Tanzania, Ghana, Botswana, Namibia and South Africa.**

I. INTRODUCTION

Reliable, low-cost, and robust broadband connectivity is often not present in many emerging markets. A 2014 study concluded that approximately 2.7 billion people worldwide are connected to the Internet [5], with a subset of those consumers using broadband connections. That leaves approximately 4.3 billion of the worldwide population yet to be connected. And, even with availability, broadband access remains unaffordable for at least half the world's population. The problem is particularly acute in growth markets, such as in Latin America, Africa, and South and Southeast Asia, and especially in areas that lack reliable electricity. In Africa alone, over 600 million people lack electricity [4]. Furthermore, cost is an issue: for more than 60% of Africans, handset-based mobile broadband is unaffordable and costs more than 5% of household expenditure [5].

To address the connectivity challenge, we have been investigating a new approach to spectrum utilization, called Dynamic Spectrum Access (DSA). Using this technology, it is possible to significantly reduce the cost of wireless broadband access by leveraging two key elements: (i) availability of high quality spectrum below 1 GHz, and (ii) non-exclusive unlicensed access to this spectrum. DSA is a term used to describe a set of technologies enabling radio communications devices to opportunistically transmit on available radio spectrum without interfering with transmissions from licensed users like broadcasters. The first globally-harmonized opportunity to use DSA technology will be in the unused TV band frequencies, also called the TV white spaces (TVWS).

TVWS can enable a variety of use cases ranging from low-power in-building media distribution to machine-to-machine applications, but they are particularly well-suited for delivering low-cost broadband access to rural and other unserved communities. Radio signals in the TV bands, in particular the 470 MHz to 698 MHz range of UHF frequencies travel over longer distances and penetrate more obstacles than other types of radio signals, enabling non-line-of-sight wireless connectivity and requiring fewer base stations to provide ubiquitous coverage.

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When combined with regulations allowing unlicensed or license-exempt access to unused TV band spectrum (such as those that exist in the spectrum bands typically used by Wi-Fi technologies today), white space technologies can create new opportunities for individuals, as well as new competitors, to create low-power and/or long-range wireless connections. This regulatory model eliminates the need to obtain expensive spectrum licenses and lowers barriers to market entry. The United States and Canada are the first countries to implement an unlicensed spectrum access model for TVWS. Singapore and the United Kingdom have recently announced similar regulations. Several other countries, such as Japan, South Korea, South Africa, Malawi, the Philippines and New Zealand, are also considering this change.

While current white space radios use proprietary technology implementations, various standards involving devices and databases are being developed. The IEEE 802.11af task group has recently completed a Wi-Fi standard for white spaces access and major Wi-Fi chipset vendors are developing products. Eventually Wi-Fi devices implementing the 802.11af standard will likely include multi-mode chips offering TVWS (470-698 MHz), 2.4 GHz, and 5 GHz Wi-Fi connectivity. Such standardization will enable the white space device marketplace to scale, thereby minimizing unit costs.

Due to these attributes of good propagation, unlicensed access, and industry progress, TVWS is a powerful technology for broadband access in developing regions. It can increase the bandwidth, reduce the cost, and extend the coverage of wireless broadband. When combined with other low cost and complementary wireless technologies such as 5.8 GHz backhaul and 2.4 GHz Wi-Fi hotspots, TVWS has the potential to enable creation of new and disruptive business models that could be particularly well-suited for price-sensitive consumers, such as those disproportionately located in emerging markets, such as in Africa.

White spaces technology has been in development for over a decade and has been extensively tested in trials and pilots conducted by Microsoft and others. Over this time, we have made the transition from basic research (as part of our KNOWS program [3]), to lab and field trials assessing technical feasibility, to commercial pilot projects that are now validating different business models.

We make the following three contributions in this paper:

- Although prior work has focused on lab and field trials of TV white space networks [8], there is little information on real world commercial deployments, such as, what radios are available? How does one connect them to antennas? What distances can be covered at good throughputs? What antennas should be used?
- To the best of our knowledge we are the first to highlight the usefulness of TVWS as a point-to-multipoint backhaul technology. We also describe a multi-frequency architectural approach in which this technology is used in conjunction with point-to-point microwave links to provide connectivity in a given region.
- We present five use cases of how TVWS can be used as an effective (and inexpensive) technology to connect remote regions of Africa, and bring connectivity to several communities that previously had not been affordably connected to the Internet.

II. TVWS Network Architecture

A TV white spaces radio uses location-aware devices and online TVWS databases to deliver low-cost broadband access and other forms of connectivity to consumers. This approach is rooted in the idea that devices with greater knowledge of their electromagnetic surroundings can opportunistically use available radio spectrum. There are many TV broadcast channels that are unused in nearly every location in the world.

A. Benefits of TV White Spaces

Using TV broadcast spectrum for broadband connectivity has three main advantages.

Greater Distances: As shown in prior work, TVWS signals can easily cover large regions. This is primarily because it trasmits in the lower frequencies. In typical applications, a strong Wi-Fi signal can cover approximately 100 meters while a TVWS signal at the same power level can easily travel 400 meters and with higher power can cover several kilometers. In our deployments, we have been able to cover 14+ kilometer distances at 10 Mbps user level throughputs, while operating within FCC mandated transmission parameters.

Penetrates Common Obstructions: Wi-Fi transmissions do not pass through walls, while TVWS radios operate in lower frequencies, and its signals can easily penetrate walls and obstructions. In a simple experiment in our building (spanning a usable area of 222,000 sq ft over 4 floors) that has 150 Wi-Fi Access Points to provide high speed access, we were able to cover all parts of the building using a single TVWS base station operating at 20 dBm with a 2 dBi gain antenna. The lowest received signal strength over a 6 MHz channel was -79 dBm.

Greater Efficiencies: Since the TVWS signals travel farther than Wi-Fi, a TVWS deployment would cost less, and would consume less power than Wi-Fi or mesh based topologies

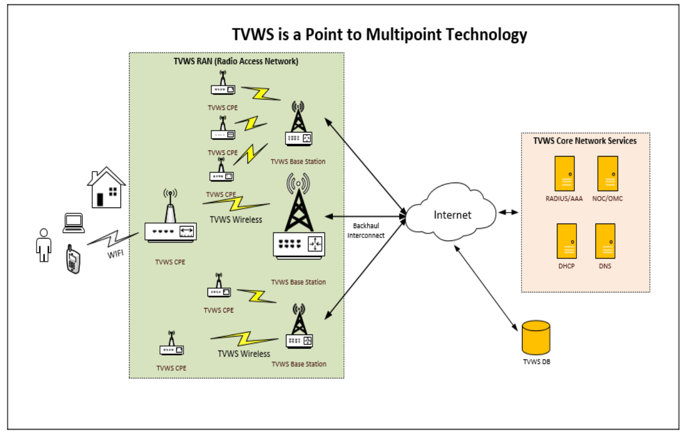

Fig. 1. TVWS Network Architecture

to cover sparsely populated communities in Africa. As we show later in this section, TVWS deployments are also more economical than LTE for these scenarios.

B. How it Works?

The most common implementation of TVWS networks are accessed using smart, radio-enabled devices that report their location to a cloud-based TVWS spectrum database. The database informs the device about the available TVWS channels, and the maximum power level it is permitted to use at its current location. The database maintains a list of all protected TV stations and frequencies across a country, so the devices can avoid causing interference to TV broadcasts and wireless microphone signals. This technology is truly dynamic: as different TV channels become available, TVWS devices can opportunistically switch from one group of channels to another. TVWS translates to greater network capacity, allowing a greater number of users in a given area while, at the same time, protecting television reception from interference. All of this engineering is invisible to the consumer, who simply experiences more ubiquitous broadband connectivity.

Figure 1 depicts a block diagram of a typical TVWS network. From left to right, the components include off-the-shelf 802.11 b/g/n/ac Wi-Fi access points (APs), which connect directly to the TVWS customer premise equipment, or CPE; using standard Cat5 or Cat6 cable. Because of the ubiquity of end user devices using the 802.11 family of protocols, this is the least common denominator for remote connectivity. At this point in time, there are no dual mode Wi-Fi/TVWS CPE, however, such a product is under development. The CPE, in turn, communicates with the TVWS basestations (BS) through a TVWS air interface protocol, e.g. IEEE 802.11af, which can be located within several hundred meters of the CPE or many kilometers away, depending on the use case, availability of mounting radio facilities, and the location of fiber access.

The CPE site configuration is simple and easy to install: a high gain directional UHF antenna is pipe or mast mounted at the service location. The TVWS radio attaches behind the antenna to the same pipe mount and an RF jumper connects to the antenna while Cat5 cable drops to the Wi-Fi AP or

Ethernet switch. Radio power is provided via Power over Ethernet (PoE). Because of the low power draw (typically $<$ 20 W) of the CPE (or BS) radios it is possible to use a solar power system in the event that electricity is not present at the site.

Each TVWS BS can consist of one or multiple sectors and radios. A typical BS configuration would have multiple sectors, just like any GSM or LTE BS, in order to illuminate 360 degrees around the site, which is ideal for point to multipoint implementations of white spaces. If the capacity requirement calls for more than one channel per sector, a duplexer can be used to multiplex another radio onto an existing sector antenna. Once channel bonding is available as a radio feature, duplexers can be eliminated. Given that the TVWS Effective Isotropic Radiated Power (EIRP) is limited to 36 dBm or 4 Watts, and the conducted power of a present day TVWS BS is only 100 mW per radio, high gain panel antennas are used to help boost the effective signal in the directions of interest. The gain of antennas can be reduced for radios that can transmit at higher power.

The BS equipment configuration is also minimal: just like with the CPE, pipe or mast mounts for the antennas and radios. The output of each BS radio is connected to a site aggregation router, and the output of the router points towards the Internet, whether locally available, or hundreds of miles away using fiber or a point-to-point or even VSAT backhaul systems.

As a rule of thumb, each TVWS radio can produce approximately 10 to 12 Mbps at the TCP layer per 6 or 8 MHz carrier, under ideal radio conditions. From an architectural perspective, there is an advantage to mounting the BS as close as possible to the CPE. Furthermore, given the low cost of high quality, high capacity unlicensed microwave backhaul radios, there is good reason to keep TVWS access equipment within a confined area. This is not to say that long range TVWS communications is not possible or even desirable, just that there are the typical telecommunications tradeoffs involving cost, performance, and feasibility that always need to be made. The use cases below will help to highlight such tradeoffs.

On the backend, any commercial TVWS deployment will require core services, including some sort of Radius/AAA for customer provisioning and billing; Network Operations Center and Operation and Maintenance Center tools for network management and control; and DHCP/DNS for IP addressing allocation and management. Finally, the regulator in each country will either own or outsource TVWS database functionalities to ensure that all assigned UHF channels are accounted for and protected from interference. When a TVWS radio queries the DB for channel availability at its location, only usassigned channels are returned.

C. TVWS Radios

Today there are multiple commercially viable TVWS radio manufacturers. Typical of this class of product is Adaptrum's (San Jose, CA) ACRS2.0 platform [2] shown in Figure 2 and 6Harmonics (Ottawa, Canada) GWS radios [1] shown in Figure 3. Both radios are FCC certified and can produce

Fig. 2. The Adaptrum Radio ARCS 2.0. It measures 8.5 x 7.5 x 1.5 in

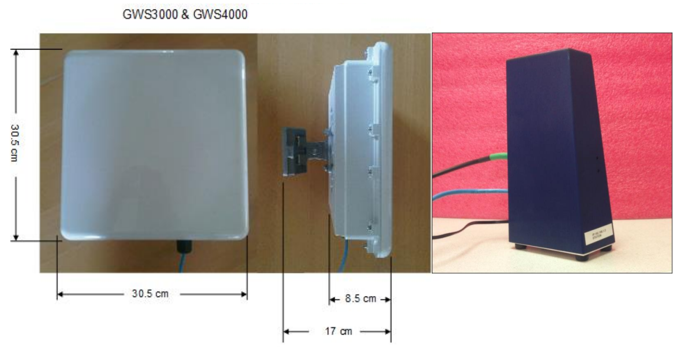

Fig. 3. The 6Harmonics TVWS radio

data rates of 10+ Mbps at long distances. The Adaptrum radios use a TDD MAC with an OFDMA PHY, while the 6Harmonics radios use a Wi-Fi like MAC protocol with an OFDM PHY. Both these radios have support for telemetry and have performed very reliably in our test deployments described in Section IV.

Other key radio features include power over ethernet, low power consumption, low latency, PAWS compliant interaction with TVWS databases, automatic gain control and channel scanning capability. In the future we expect to see channel bonding, MIMO and high power operations.

D. Planning a TVWS Network

When designing a TVWS network all the traditional radio network planning tools and procedures apply. To address coverage, we get a good visualization of the network and terrain characteristics by plotting the proposed fiber POP, BS towers and CPE endpoints using any of a myriad of planning tools, such as Radio Mobile, Atoll, or EDX. In many cases the fiber POP will be located some distance from the area which is intended to be served by TVWS. Extending the POP is cheap and easy as there are many affordable high quality and high capacity point to point licensed and unlicensed microwave solutions. Once plotted, we use the path profile tool to verify Line of Sight (LOS) on all links. Even though TVWS operates in the UHF band, those signals will not penetrate mountains and can still be blocked. If terrain or man-made obstacles appear challenging on a path, we always verify LOS with a physical path survey. Another method we use is to erect a test transmitter and conduct a field survey. We also optimize the link by raising BS and CPE antenna heights as much as possible. The same tools mentioned above generally also can calculate a link budget to ensure that the terrain and link range allow ample signal strength at the receiver to provide the desired throughput.

Inputs (green boxes are drop downs)	Range	Values	Units
LTE Spectrum POP (millions)	10 to 250	150	million
LTE Spectrum Bandwidth (MHz)	10 to 100	20	MHz
Number of Subscribers (drop down or manual input)	1 to 10 MM	1,000,000	
Backhaul: Leased Line to MW ratio	40::60 to 100::0	90 :: 10	
CAPEX Depreciation (years)	4 to 10	5	years
Average Throughput per subscriber	0,25 to 5 Mbps	1	Mbps
Over-Subscription/Contention-Ratio	10::1 to 50::1	50::1	
Monthly Usage per subscriber	0.5 GB to 50 GB	2	GB
Daily Traffic in Busy Hour	8% to 15%	7%	

Fig. 4. A snapshot of the input parameters of our analysis tool

Assuming LOS or adequate NLOS connectivity can be achieved, a simple capacity analysis is required to dimension the number of sites and radios to support the traffic demand and quality of service desired. Given the number of subscribers we intend to serve at each venue in the TVWS network, including the minimum throughput per subscriber (T), the number of concurrent subscribers (U) and the over-subscription ratio (O), we calculate the baseline network design:

$TotalCapacity(C) = (U * T)/O$

$Num\_TVWSRadios = C/Avg\_Tput\_Per\_Radio$

The above parameters are specific to each installation site.

E. TVWS vs. LTE for Connecting Unserved Regions

TVWS and LTE are complementary technologies. While LTE has several in-built mechanisms to handle mobile devices, the current TVWS standards are best for nomadic, or mostly stationary, deployments. TVWS technology is being deployed on a license-exempt (or unlicensed) basis and supports mechanisms to coexist with other users of this spectrum, while LTE is being deployed by leveraging exclusive use licenses.

We did a simple cost comparison for both of these technologies, comparing capex, opex, and spectrum costs (when applicable) between large scale (in terms of monthly usage and number of subscribers) TVWS and LTE networks. Making the assumption of current generation TVWS equipment (not 802.11af products at scale) and comparing that to current generation, multi-band / multi-mode LTE products, at scale, using the parameters in Figure 4, the cost per GB/MB result is depicted in Table I.

The Low Capacity configuration for TVWS uses a 1-1-1 (3-radios per site) setup. Cost Estimates include 6 hour battery backup, site router, basic telemetry, antenna and peripherals. This is the basic setup close to or at carrier grade. This cost estimate also assumes lower average costs for Site Leasing, Backhaul Leasing, Maintainence (NOC, Basic Billing and backoffice support). Service costs, such as radio network planning, transport network design and core network configuration are included in capex estimate. The High Capacity Configuration is a 2-2-2 (6 radios per site) setup. An EIRP of 1 to 2 W is assumed for TVWS installations, which is well below the permitted power of 4W EIRP in the US.

The Low Capacity Configuration for LTE is 2x10MHz FDD single band LTE radio setup with 1-1-1 (3-radios per site) configuration. This is the basic carrier grade setup, and the cost estimate is the average cost of two major global LTE vendors. The capex estimates include similar components as for TVWS deployments. The High Capacity configuration for LTE assumes a 2x10MHz FDD dual band LTE radio setup.

TABLE I
DIFFERENCE IN COST OF GB/DATA FOR TVWS AND LTE FOR THE LOW CAPACITY AND HIGH CAPACITY CONFIGURATIONS.

Subscriber Per Site	TVWS Low Cap.	TVWS High Cap.	LTE Low Cap.	LTE High Cap.
Cost Per GB ($) (incl. spectrum cost)	1.67	3.62	6.35	39.48

This configuration is the basic configuration with 2-2-2 (6-radios per site) setup. A 20W to 40W EIRP is assumed for LTE deployments.

The model calculates the capex and opex associated with the number of TVWS and LTE sites required to support the traffic load (Figure 4). A key difference in cost per GB is due to the cost of licensed spectrum for LTE. Without it, and even though the price of capex between the two systems is very different, the cost comparison between similarly sized TVWS and LTE networks comes into alignment (1.35 $/GB for Low Capacity LTE, and 4.48 $/GB for High Capacity). TVWS is a powerful tool to leverage for connectivity in small and large-scale deployments. For example, the cost of an off-the-shelf TVWS BS radio is only 1/10th of an LTE base station radio. The relative cost benefits of TVWS technology will become more apparent as new features, such as non-contiguous channel aggregation and higher power transmission, are added to TVWS systems and as low-cost equipment becomes available at scale. Given their complementary nature, we envision network operators deploying either or both TVWS and LTE topologies when and where appropriate.

III. LEARNINGS FROM THE RESEARCH DEPLOYMENT

At Microsoft Research, we developed the WhiteFi system [6], and deployed it in a mobile campus testbed in 2009 [8]. We used discone wideband antennas, and deployed 2 base stations – on two tall buildings on Microsoft's campus in Redmond, WA. The CPEs were on campus shuttles. We tested our system with Wi-Fi as well as WiMax based PHY and MAC protocols. This system was showcased to several governments' regulators worldwide, including the US FCC Chairman. We also developed a TVWS database as documented in the paper [8].

However, when moving from the research deployments to the real world setting, we learnt some lessons that we outline below:

Collocate base station and the antenna: Since most commercial radios transmit at a max power of less than 30 dBm (usually 20 dBm), any loss in the RF cables connecting the base stations to the antennas significantly reduces our ability to transmit at the FCC allowed maximum transmit power of 4W EIRP.

Use sectorized high gain antennas: This helps solve two concerns. First, it helps us amplify the radio's transmit power to reach the FCC's permissible limit of 4W EIRP. Second, it improves the uplink from the mobile node to the base station. We will elaborate on this a bit more. The base station is allowed to transmit at 4W EIRP (typically done by adding a power amplifier (PA)), while a personal portable device is allowed to transmit only up to 100 mW. This leads to an asymmetry in the link as was shown in a recent paper [7]. We can partly overcome this asymmetry by adding a high gain antenna at the base station.

Restructure TVWS database to be extensible: Once we started deploying TVWS networks outside the US, such as in Singapore and UK, we quickly realized that we needed to make our TVWS database extensible. In particular, our terrain database was for the whole world, but we also needed to add country-specific information about TV towers, their height, transmit power, etc. Different regulators sometimes also had country specfic regulations, so we had to modify the database to make a template for existing rules, while making the parameters configurable.

Support for network management and statistics in TVWS radios: The campus network was a demo testbed, which we turned on and off on demand, and a number of steps were manual because of our proximity to the demo location. However, for deployments in Africa we needed to automate and manage these networks. So in addition to network management software, we required radios to support network management functions.

Need for periodic scanning: The TVWS database returns a list of channels that have not been assigned, and therefore are available. However, not all channels are equal, even when declared free by the database. Various other transmitters in these bands, such as wireless MICs or other (likely) authorized transmitters, or intermodulations from other wireless equipment can sometimes lead to degradation of a channel. Therefore, the radios should be capable of periodically scanning the spectrum and selecting the cleanest of all available channels.

IV. Deployments in Africa & Business Models

As described earlier, the TV white spaces are a unique enabler for providing Internet access in Africa. We have been working with local governments and business in various African countries to build out TVWS networks and connect several communities. We briefly describe some of our deployments in this section.

Kenya: In 2013, Microsoft, in collaboration with the government of Kenya's Ministry of Information and Communications, and Mawingu Networks, launched a pilot TVWS project called Mawingu (Cloud in Swahili) for delivering low-cost wireless broadband access to previously unserved locations near Nanyuki, Kenya. The network utilizes TVWS radios from Adaptrum and 6Harmonics and solar-powered base stations to deliver broadband access and create new opportunities for commerce, education, healthcare and delivery of government services. The initial installation near Nanyuki currently includes seven customer locations: the Burguret Dispensary (healthcare clinic), Male Primary School, Male Secondary School, Gakawa Secondary School, Laikipia County Government Office, the Red Cross office in Nanyuki, and the first Mawingu charging and bandwidth agent. The Mawingu team is currently adding new locations to the network. In the next year, an additional 30 end-user locations will be added

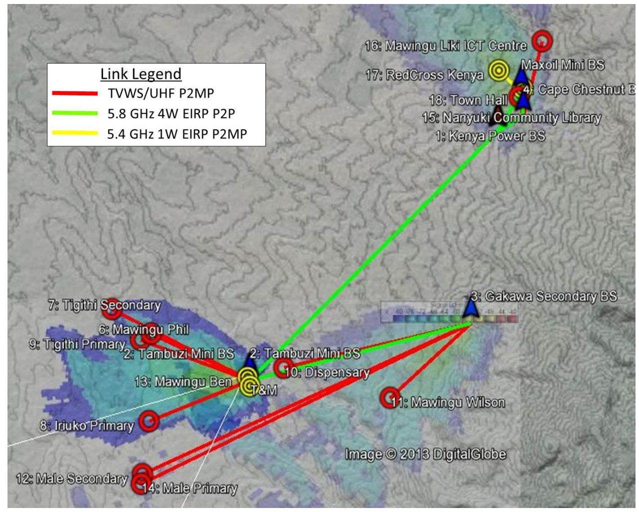

Fig. 5. Mawingu network overview

TABLE II

Weekly network usage from Oshana site (Namibia)

Application	Usage	Percentage Usage
Non-web TCP	2.03 GB	25.0%
Youtube	1.78 GB	21.9%
UDP	1.40 GB	17.2%
Software Updates	769.2 MB	9.3%
Miscallenous Web	580.1 MB	7.0%
microsoft.com	501.7 MB	6.0%
apple.com	281.7 MB	3.4%
Facebook	221.4 MB	2.7%
Misc. secure web	148.7 MB	1.8%
BitTorrent	105.3 MB	1.3

to the network, including several more schools, Mawingu agents, and businesses in the area. USAID, through the Global Broadband and Innovations (GBI) initiative, has agreed to provide funding for solar charging stations for the end-user locations. In Laikipia County, the network covers a diversity of end points across a broad area as shown in Figure 5. The green 5.8 GHz point to point unlicensed microwave link is in excess of 20 km in length and the longest red UHF link is approximately 16 km.

Our Mawingu deployment has had many technical achievements. First, we showcased an interference free point to multipoint coverage of up to 16 kilometers from TVWS base stations operating at only 2.5 Watts power (EIRP measurement). Second, we achieved approximately 235 km^2 of TVWS coverage using multiple 90 degree base station sector antennas. Third, we demonstrated Internet speeds of up to 16 Mbps on a single 8 MHz TV channel, at a distance of up to 16 kilometers. Fourth, our deployments are being actively used. We get approximately 7 and 10 GB of data consumption per day on average at Gakawa Secondary School. We have demonstrated support for various media protocols, such as streaming videos, emails, FTP, Skype voice and video conferencing, and high speed VPN services. Finally, we have shown that it is possible to successfully deliver network connectivity in areas with no source of electricity; indeed, the majority of the endpoints are running on standalone solar power systems, a clean and renewable source of energy.

Tanzania: Microsoft recently launched a project in collaboration with the Tanzania Commission for Science and Technology (COSTECH) and UhuruOne, a Tanzanian ISP, to provide affordable wireless broadband access to university students and faculty in Dar es Salaam using TVWS radios from 6Harmonics. The partnership will enable UhuruOne to offer a laptop or tablet, wireless broadband connectivity, and applications and services. UhuruOne's initial plan is to cover a student population of about 50,000 at four universities: the Institute of Financial Management, the Dar es Salaam School of Journalism, the Institue of Social Work and The Open University – and to then expand coverage to several other universities across Tanzania, so that eventually a student population of 189,000 is covered with low-cost connectivity.

Ghana: Microsoft and SpectraLink Wireless launched a commercial TVWS network at Koforidua Polytechnic, a university with 8,500 students, faculty and staff on January 26, 2015. This deployment uses radios from 6Harmonics. Similar to Tanzania, the connectivity program in Ghana is designed to provide low-cost Internet access in urban university campuses. SpectraLink will sell bundles of Internet access along with smartphones, tablets, and Office 365 to the university students and the surrounding community.

Namibia: In partnership with MyDigitalBridge Foundation, the Namibian pilot, called Citizen Connect, consists of a network of TVWS sites deployed over a 62km by 152km (9,424 km^2) area. It uses radios from Adaptrum and covers three regional councils: Oshana, Ohangwena, and Omusati in northern Namibia. The network delivers connectivity at three regional offices, 28 rural schools, 7 education circuit offices, with a link ranges from 8km to 12km and typical speeds from 5Mbps to 10Mbps, which is sufficient for a host of user applications, including voice, video, and data.

Usage from the Oshana cluster for the first week in February 2015 was a total of 8.13 GB of traffic, with 7.6 GB attributed to the downlink and 537.5 MB on the uplink. The top applications by usage are summarized in Table II.

South Africa: In July 2013 Microsoft launched a project to deliver high-speed and affordable broadband to five secondary schools in underserved parts of the Limpopo province, South Africa, using TVWS technology. The focus of the pilot is to prove that TVWS can be used to meet the South African government's goals of providing low-cost access for a majority of South Africans by 2020. The pilot is a joint effort between Microsoft, the Council for Scientific and Industrial Research (CSIR), the University of Limpopo and Multisource, and uses radios from 6Harmonics.

Since the secondary schools are geographically oriented around the BS location on the University of Limpopo campus, the network consists of one multi-sectored BS at the University of Limpopo library, as shown in Figure 6. A 6th site located near the library is used for test measurements.

Fig. 6. Network in South Africa

The schools have the number of learners and teachers, with 5 sites having 1861 (Mtn View), 937 (Doasho), 829 (Mamabudusha), 1322 (Mphetsebe), and 366 (Ngwanalaka) total users respectively. About 4% of users on each site are teachers. Depending on link range the TVWS network delivers multi-megabit service to each site. Learners and teachers interact with the network using desktop computers and Tablet devices and WiFi APs installed in each school.

V. Conclusions and Future Work

Several countries in Africa have low penetration of Internet connectivity. In this paper we have described how TVWS technology can be used to bridge the digital divide, and share experiences connecting communities in 5 different countries. Moving forward, we are deploying TVWS networks in several countries worldwide. We are also exploring two new research directions. First, we are investigating ways to achieve higher speeds on a TVWS link using a single radio, e.g. using channel aggregation and MIMO. Second, we are exploring ways in which other parts of the spectrum can be reused using DSA techniques.

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