

# TV White Space Based Wireless Broadband Internet Connectivity: A Case Study With Implementation Details and Performance Analysis

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**ABSTRACT** Even at the current age of sophisticated communication systems, remote rural communities with low user density throughout the world lack broadband Internet service of good quality. Traditional ways fall short to meet the demand of those regions due to technological or geographical challenges as well as less economic viability. Since the unlicensed operation of spare TV (Television) spectra was approved by the authorities in many countries of the world, various applications of those spectra, known as TV White Space (TVWS), have been researched. In many literature and implementations, TVWS has been found to be feasible in providing quality broadband Internet service to deprived rural communities. Penetration through obstacles, good non-line-of-sight connectivity, long-distance transmission, wider horizontal beam-width, and abundance of unused TV channels in remote rural regions are some of the promising features of TVWS which can be leveraged to connect rural communities to broadband Internet and related digital services. We made a comprehensive effort to evaluate TVWS based broadband Internet connectivity through laboratory testing and outdoor testing with a measurement campaign at Stillwater, Oklahoma and by providing live Internet service to a client in the rural area of Tillman County, Oklahoma, USA. Radio frequency (RF) coverage heatmaps have been created over the geographical map using the received signal data measured. Also, profiles of received power, signal to noise ratio (SNR) and throughput have been analyzed against antenna directionality. The purpose of this study is to provide the details of our TVWS trial and lessons learned from it, followed by performance analysis, comparison of results with theory and future directions.

**INDEX TERMS** Television White Space (TVWS), dynamic spectrum access, cognitive radio, broadband Internet, digital divide.

## I. INTRODUCTION

ENSURING quality telecommunication services in remote rural communities is always a challenging task in most of the countries of the world. Due to the lack of quality broadband Internet and associated digital services, the remote areas are facing a situation known as “digital divide” [1]. Optical fiber based broadband Internet service providers and mobile operators usually do not have robust telecommunication and Internet infrastructure in rural regions because it is difficult and costly to expand their

network up to that far. The user density at those places is too low to ensure a sustainable profit margin too. Besides, there exist geographical challenges like tall trees, high hills, mountains, rivers etc. in remote localities which limit the number of technologies to be implemented there effectively.

In the last decade, Television White Space (TVWS) has turned out to be a promising method to provide broadband Internet connectivity to the remote unexplored zones. White spaces refer to the unused gaps between the occupied frequencies in a spectrum. In the United States of

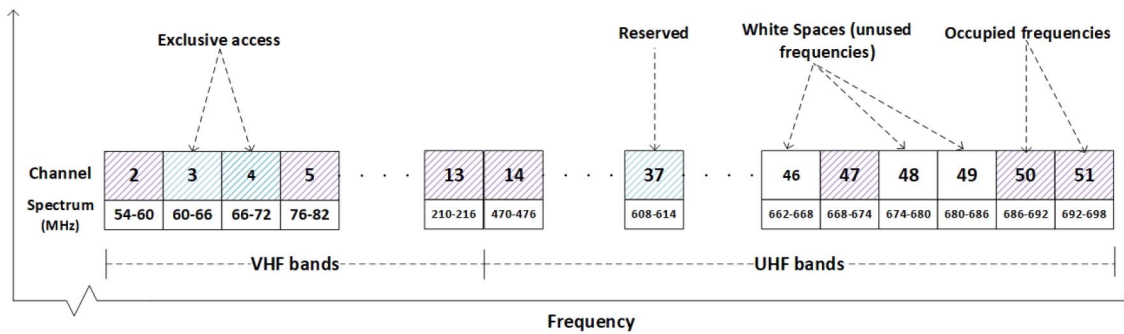


FIGURE 1. TVWS spectrum in USA.

America (USA), TV bands occupy very high frequency (VHF) low (channels 2-6, 54-88 MHz), VHF high (channels 7-13, 174-216 MHz), and ultra-high frequency or UHF (channels 14-83, 476-890 MHz) channels for broadcasting but leave some gaps within them which are known as white spaces. These unused spectra can be utilized by various wireless applications and devices using dynamic spectrum access [2], [3], an important application of cognitive radio technology [4]–[7]. After transition from analog to digital TV, known as digital switchover (DSO), was completed in various countries of the world, more TV spectra started to become free for other usage due to higher spectral efficiency of digital TV [8]. Federal Communications Commission (FCC) in USA proposed rules for opportunistic use of TV broadcast bands in 2004 and thus paved the way for TVWS to be used for Internet connection and other purposes in USA. They published the final set of rules in 2009, an additional notice in 2011 [9] and several amendments and revisions afterward regarding unlicensed use of TVWS.

Operation in TVWS can be licensed, unlicensed, or even hybrid. Licensed users or companies are known as primary users (PU), while unlicensed users are known as secondary users (SU). Unlicensed users can be either fixed or personal/portable. Fixed users transmit with higher power (30 dBm) than that of portable users (20 dBm or 16 dBm). SUs can operate either in independent mode where they must have to access the database to fetch local TVWS availability information or in client mode where they do not access the database, instead operate as a client of a fixed device with database access capability [10]. White spaces are abundant in both VHF and UHF zones (Fig. 1), but the following rules are followed for allocating channels to fixed and portable TVWS devices in USA [10], [11].

- Fixed devices are permitted to operate in the VHF channels 2-13 except channels 3-4 and the UHF channels 14-51 (470-698 MHz) except channels 36-38.
- Portable devices are allowed to use the UHF channels 21 to 51 (512-698 MHz), except channel 37.
- Excluded channels in the VHF and UHF bands are either reallocated or reserved for other purposes.

TVWS channel bandwidth is 6 MHz for single channel and 10 MHz for dual channel in USA [12]. TVWS

is often considered to be superior than Wi-Fi because it can provide wireless remote Internet connectivity similar to Wi-Fi but with enhanced capabilities like long-range transmission, penetration through multiple walls, non-line-of-sight connectivity by avoiding high terrain and trees and so on.

In a typical TVWS setup, there is a base station that consists of a base radio (signal transmitter) and antenna mounted on a cell tower or rooftop of a building. The base radio remains connected to the backhaul Internet network. Customer premises equipment (CPE) includes client radio (signal receiver) with directional antenna that is directed towards the base antenna. Currently, the white space spectrum database is managed by Nominet in USA [13]. The base radio remains registered to the spectrum database and communicates with it continuously to share its GPS location and receive the information of unoccupied channels in TV spectrum at that time and location. Once the base gets a channel (or multiple channels), it can establish TVWS based wireless connectivity with one or more CPEs. The client radios can be connected directly to a computer or a Wi-Fi router to provide Internet service.

After the digital switchover of analog TV in most of the countries was completed, numerous TVWS trial deployments had been done throughout the world between 2012 to 2015 [14], and also a few afterward by both academia and industries to evaluate the role of TVWS in alleviating the digital divide between urban and rural people. Multiple companies like Google, Microsoft, Facebook etc. and White Space Devices (WSD) providers like Adaptrum, Carlson, 6Harmonics etc. came forward with their partnership and support for these trials. It has been identified from literature that TVWS trials were conducted in South Africa, Malawi, Mozambique, Botswana, Kenya, Tanzania, Ghana and Namibia in Africa [14]–[24]; India, Singapore, Philippines, Japan, Bhutan, Taiwan and Oman in Asia [14], [25]–[27]; United Kingdom and Switzerland in Europe [14] and USA, Canada, Uruguay, Jamaica and Colombia in Americas [14], [15], [28]–[30].

In most of the TVWS trial projects, one or more TVWS base stations served multiple CPEs located within 10 km radius in star topology. Some of these trials published their

test results with network performance analysis characterized by throughput (download and upload), signal to noise ratio (SNR), latency etc. Network performance depended on multiple factors like backhaul Internet speed, number of simultaneously active CPEs, channel quality, channel width, distance of CPE from the base station, extent of line-of-sight availability, maximum throughput allowed by WSD and so on. Although it was difficult to directly compare network parameters among various trials due to these factors, the maximum achieved throughput so far was reported in the TVWS deployment project at Kenya in 2013 and Muscat, Oman in 2017, in the literature. TVWS was used to provide Internet connectivity to previously unserved schools, clinics, govt. offices and small business organizations in rural Kenya using point-to-multipoint coverage up to 14 km, achieving maximum 16 Mbps throughput on a single 8 MHz TV channel at a distance of 5.6 km from base station [18]. At 6.9 km away from the base station, download throughput of maximum 16 Mbps (average 5.21 Mbps), upload throughput of maximum 11.6 Mbps (average 2.3 Mbps) and SNR between 22 to 28 dB were achieved in the trial at Muscat [31]. “Citizen Connect” in Namibia was the biggest TVWS implementation project in terms of area coverage in which TVWS equipment of Adaptrum Inc. [32] was used to cover an area of 9424 square km and connect 28 schools in northern Namibia [22]. Among different TVWS trials, the network latency varied from less than 10 ms (achieved at pilot projects at Botswana [21] and Limpopo province of South Africa [33], [34]) to around 120 ms (achieved at Cape Town, South Africa [35] and Zomba, Malawi [36], [37]).

As part of Gigabit Libraries Whitespace Project [1], [14], [28], Microsoft’s Airband Initiative [38], [39] and a few other projects, TVWS trials were either conducted or planned in around 27 states of USA so far. To the best of our knowledge, no TVWS pilot project was undertaken in Oklahoma, though unused TV frequencies were amply available in this state [40]. In this paper, we demonstrated TVWS trial run at Stillwater (Payne County) and Tillman County in Oklahoma followed by the results, their interpretation and performance analysis. The main contributions of this study are as follows.

- 1) TVWS based Internet connectivity has been tested and monitored at Stillwater and Tillman County, Oklahoma.
- 2) Heatmaps of throughput, received signal power and SNR have been created covering an area of 50 square km (longest distance 10 km) based on the results from measurement campaign.
- 3) The effects of receiver antenna angles (azimuth and elevation) on received power, SNR and network throughput have been analyzed from measured data.
- 4) Performance analysis of the established TVWS networks characterized by download and upload throughput, SNR and latency has been performed. Throughput data have been compared with maximum throughput that can be achieved with the chosen WSD.



(a) Base.

(b) Client.

FIGURE 2. Adaptrum TVWS base and client radio devices.

TABLE 1. Hardware, software and GUI versions of base and client radio.

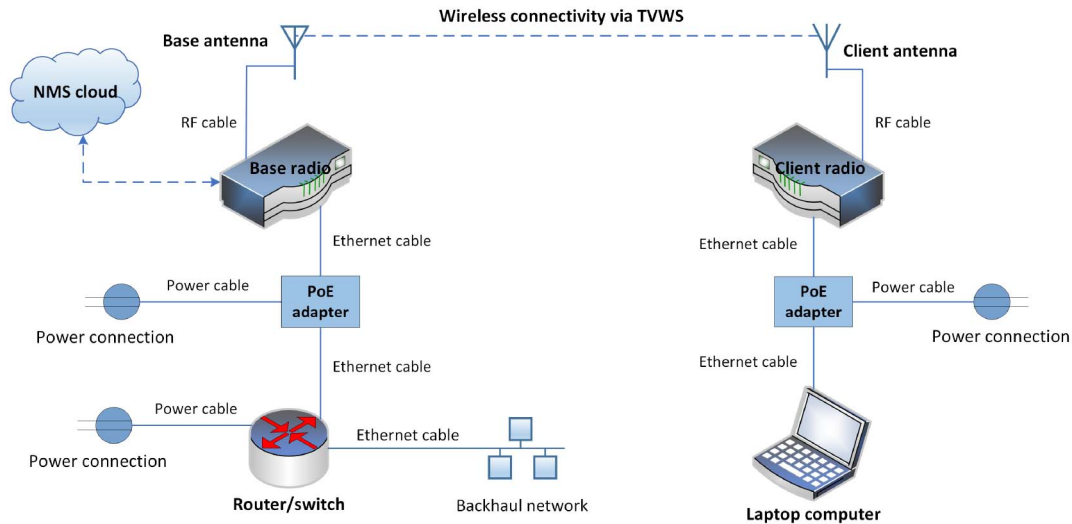
	Base radio	Client radio
Hardware version	R4.c4.0	R4.d4.0
Software version	S.1.2.86	K.7.12.78
GUI version	A2.2.8	3.6.0.67

- 5) Measured path loss has been compared with free space path loss model and the path loss exponent has been estimated.

The remainder of this manuscript is organized as follows. Section II presents the description of hardware (WSD) chosen for this TVWS trial. Section III includes the details of laboratory setup and testing. Section IV presents the details of base radio setup, client radio setup and measurement campaign for outdoor testing at Stillwater and lessons learned from it. Section V presents the details of how the live service was provided to the customer premises at Tillman County including test results and performance analysis. Section VI compares the results with relevant theory. Finally, Section VII presents the conclusions drawn from the whole effort and future directions.

## II. TVWS HARDWARE

TVWS starter kit of Adaptrum Inc. [32] was chosen for testing and live implementation. The kit contained one base radio of model ACRS2 B1000 [41], shown in Fig. 2(a), along with a panel antenna, two client radios of model ACRS2.0 [42], shown in Fig. 2(b), along with two Yagi antennas and other necessary accessories like power-over-ethernet (PoE) adapters, cables and a few mounting equipment. The hardware, software and graphical user interface (GUI) versions of base and client radios used are provided in Table 1. Base and client radios supported non-line-of-sight connectivity over a distance of 10 km. They were PoE devices that supported only passive PoE ports to get power from network equipment. They supported both single channel and dual channel operation. The maximum conducted power of the base radio and the client radio were 28 dBm and 20 dBm, respectively. The base antenna was a single-port full-panel antenna with  $11 \pm 1$  dBi gain and half-power horizontal and vertical beam-widths to be  $90 \pm 8^\circ$  and  $30 \pm 6^\circ$



**FIGURE 3.** Connection diagram of TVWS base and client radios.

respectively [43]. The client antenna was a log-periodic Yagi antenna which was vertically polarized and directional with a gain of 11 dBi [44].

### III. LABORATORY TESTING

Adaptrum TVWS devices were set up at OSU Wireless Lab in Oklahoma State University for indoor testing. The distance between the base antenna and the client antenna was kept nearly 4 m and the antennas were facing each other. A general connection diagram for TVWS base and client sides is shown in Fig. 3 which was followed in the lab setup.

#### A. BASE RADIO SETUP

Necessary IP addresses were configured in the base radio from the base GUI to connect it to the Internet using the OSU campus network. Adaptrum ACRS2 B1000 devices were not GPS enabled, hence the GPS coordinates of the lab (latitude 36.123764 and longitude  $-97.068307$ ) and also a height of 10 m were configured manually in it. From the database related page of the Web panel, it was verified that the base was connected to the spectrum database for selecting available channels. Adaptrum had a Web based network management system (NMS) that can be accessed at [www.nms.adaptrum.cloud](http://www.nms.adaptrum.cloud) for monitoring and managing its WSDs. The base radio was made connected to this NMS cloud using the credentials collected from Adaptrum. There was a page in the base GUI for channel selection and other related configurations where available channels at the surrounding area were displayed with their noise levels. In single channel mode (channel width 6 MHz), channels were listed one at a time. In dual channel mode (channel width 10 MHz), channels were listed in pairs. On that page, there was option (a button) for starting or stopping signal transmission too.

#### B. CLIENT RADIO SETUP

Client configuration software, provided by Adaptrum, was used for configuring the client radio. The client radio had

a default IP address which was hard-coded in it and could not be changed. At first, the client radio was connected to a laptop through the PoE adapter and the laptop was brought to the default IP network of the client radio for accessing its GUI. Similar to the base radio, the client radio did not have a GPS module in it, hence GPS coordinates and height were manually configured in it from the GUI. Base and client radios were fairly close to each other inside the laboratory, hence the same GPS coordinates and height like base radio were used in client radio too.

#### C. TEST RESULTS

A laptop computer was used to test TVWS based Internet connection. Internet connection and throughput were tested firstly in single channel mode and later in dual channel mode.

##### 1) SINGLE CHANNEL MODE

The base radio GUI was accessed using the configured IP address and credentials from a Web browser. The base radio was brought to the same network of the lab Wi-Fi already. Channel 21 (single channel of 512-518 MHz) was selected among the available channels displayed on the 'Channels' page of base GUI. Then, signal transmission was started.

In client GUI, channel 21 and a few other channels were selected, the settings were saved and the device was rebooted. From the GUI log, it was seen that the client radio was scanning the selected channels one after another and stopped at channel 21 because it received a signal that was strong enough to establish the Internet connectivity. Thus, the client radio became connected to the base radio using channel 21. From the base GUI, the client radio was found to be connected with  $-18.78$  dBm received download power and 48.52 dB download SNR as seen in Fig. 4.

For testing Internet using channel 21, the IP configuration of the laptop was updated to bring it to the same network of the Wi-Fi router or the base radio. Alternatively, dynamic host configuration protocol (DHCP) could also be used to let



## Clients

Name	Serial Number	Modulation (DL/UL)	Power dBm (DL/UL)	Noise dBm (DL/UL)	SNR dBm (DL/UL)	PER % (DL/UL)	
A2FJ1623		64QAM 5/6 / 64QAM 5/6	-18.78 / -24	-67.3 / -72	48.52 / 48	0 / 0	<a href="#">Detail</a>

REFRESH

FIGURE 4. Connected client and its received signal parameters as seen from base GUI.

the laptop choose an available IP address from the network. Then, after disconnecting lab Wi-Fi Internet from the laptop, Internet was accessed through TVWS. Using single channel, download throughput was found to be 10.7 Mbps tested by downloading large files from the Internet and simultaneously checking download throughput from Ethernet Adapter of the laptop.

### 2) DUAL CHANNEL MODE

In order to test Internet in dual channel mode, the channel width was set as 10 MHz in base radio. Channels 21-22 (center frequency 518 MHz) were selected from available channels list and signal transmission was started using that channel. Several pairs of channels including the one that was being used for transmission (channels 21-22) were selected in the client radio. After scanning a few channels, the client radio started receiving signal using channels 21-22.

Necessary IP addresses were already configured in the laptop. Internet was tested using dual channel and the download throughput was measured to be 18.6 Mbps maximum by direct downloading and checking from Ethernet properties of Windows task manager. The short range made the antenna pointing irrelevant, hence the same throughput was found when the antennas were kept pointing towards or opposite to each other.

## IV. OUTDOOR TESTING

After lab testing, TVWS base hardware was taken to a place called OSU feed mill for outdoor testing. The feed mill was located at 321 South Range Road, Stillwater, Oklahoma, USA, 74074 (latitude 36.118744, longitude -97.139919). The base radio and panel antenna were mounted on the top of a grain elevator tower there. After setting up the base station, a set of client radio and Yagi antenna were set up at the rooftop of OSU Willard Sparks Beef Research Center (commonly known as OSU feed lot) which was 3.08 km away from the base tower and the service was monitored by running a Python script in a Raspberry Pi placed at the client premises. The feed lot was located at North Sangre Rd, Stillwater, Oklahoma, USA, 74075 (latitude 36.136259, longitude -97.113285). Also, a measurement campaign was conducted with another set of client radio and Yagi antenna at 18 different places in Stillwater town. At those locations, various data like received power, SNR, throughput etc. were collected in order to analyze them later.



FIGURE 5. Base radio and antenna on OSU feedmill tower.

### A. BASE STATION SETUP

The base radio and base antenna were mounted at approximately 30.5 m height on the tower at OSU feed mill. A close-up picture of the mounted base radio and panel antenna on the tower is shown in Fig. 5. They were connected with each other through the Adaptrum provided RF-195 cable of length  $\approx 1$  m. The downtilt angle of base antenna was around  $0.5^\circ$  which was calculated online from [45] using transmitter height of 30.5 m, receiver height of 5 m, distance of 3.08 km and vertical beamwidth of  $30^\circ$ . The antenna was directed towards Stillwater Regional Airport, because the planned location of fixed client station was in that direction. Shielded Cat5e cable from TrueCable [46] was installed from the base radio at the tower to the feed mill office at the first floor over a distance of approximately 50 m. At the office, the cable was connected to the power socket via PoE adapter as per the connection diagram of base radio side in Fig. 3. The IP address of the base radio was changed to bring it to the OSU feed mill network. There was a Cisco switch (model: Catalyst 2960 WS-C2960S-48FPS-L [47]) installed by OSU at the office for Internet connectivity. The base radio was connected to a port of this switch and thus it became connected to the Internet.



**FIGURE 6.** Client antenna on van for measurement campaign.

Between the base radio and the switch, a programmable power-recycle device (Dataprobe iBoot-PoE-P [48]) was used so that the physical power of the base radio can be recycled remotely, if needed for any reason or problem. The power-recycle device was connected to the Internet through an IP address chosen by DHCP. The base radio was connected to its PoE output port which was a passive PoE port as needed. The device was programmed in a way so that it sent a ping to the base radio after every 5 seconds for 1.5 minutes and if all of those pings were failed, then it recycled the power of the base radio by resetting its PoE output port. If all pings were not failed, then it would repeat the ping cycle after waiting for a buffer time of 1.5 minutes to give time to the base radio to be turned on fully after a power recycle. In this way, the base radio was made more stable and the service quality was improved. The power-recycle device was added to iBoot cloud NMS (<https://iboot.co/>) for remote management. Finally, channels 35-36 (channel width 10 MHz, center frequency 602 MHz) were selected from the ‘Channels’ page of the base radio GUI and signal transmission was started using this dual channel.

### B. CLIENT STATION SETUP

The client radio and Yagi antenna were mounted on the rooftop of the main building at OSU feed lot on a tripod at approximately 5 m above the ground. The antenna was vertically oriented (polarized) and directed towards the base antenna. Cat5e cable was installed from client radio to the feed lot office where the radio was powered up through another PoE adapter similar to the one used at the base station. A TP-Link Wi-Fi router (Model: TL-WR1043ND [49]) was connected to the PoE adapter which would receive

IP address of OSU feed mill network through DHCP and became connected to the Internet.

A Raspberry Pi was connected to a port of the Wi-Fi router. It had a running Python script that measured the throughputs (download and upload) and latency of its Internet connection every 5 minutes, and then at midnight, saved all the test results as .csv file in a Google Drive folder. Another client radio and Yagi antenna were prepared for measurement campaign at various locations of the town. A light tripod was chosen for mounting the antenna temporarily at each location for controlling antenna azimuth angle, elevation angle and polarization as per requirement. A portable AC power box was used for powering up the client radio. The same laptop that was used for lab testing was needed to be used for testing Internet at OSU feed lot and other locations, with DHCP enabled so that it received IP address automatically from DHCP server of OSU network accessed at OSU feed mill.

### C. TEST RESULTS

The antenna with tripod was placed on the top of a van (at approximately 3.5 m height), polarized vertically and directed towards the base antenna (Fig. 6). The laptop received its IP address from the OSU feed mill network using DHCP and became connected to the Internet. The base radio GUI displayed various necessary real-time data of the client radio like received power, noise power and SNR for both download and upload links. These data were collected at 18 different locations in the town. Also, throughputs (download and upload speeds) were measured from [www.speedtest.net](http://www.speedtest.net) at each of those locations.

One of the locations visited was Life Church (latitude: 36.141234, longitude: -97.120342), which was 3.06 km away from the base tower and in the line-of-sight of the base antenna. Around 35 measurements were taken at that location by varying azimuth or elevation angles each time to see the effects of antenna direction on received signal power, throughput etc. Received signal power, SNR and throughput of the signal, for both download and upload, were plotted with respect to azimuth angle of the antenna in Fig. 7. The same parameters were plotted against elevation angle in Fig. 8. From both figures, it was noticed that signal parameters reached their peaks when the client antenna was aligned with the base antenna, in both horizontal (azimuth angle  $\approx 0^\circ$ ) and vertical (elevation angle  $\approx 0^\circ$ ) planes. At both sides of the peak, received power and SNR values decreased immediately, but throughput value, which was the most important parameter for users, remained at its peak within a range of  $-50^\circ$  to  $+50^\circ$  antenna angles at 3.06 km test distance. It indicates the extent of robustness of the system, because throughput is not being dependent on received signal quality within a certain range of antenna angles. Because of this property, clients will not incur additional loss of throughput due to multiple clients being present at different angular distances (within a certain limit) from the single base antenna.

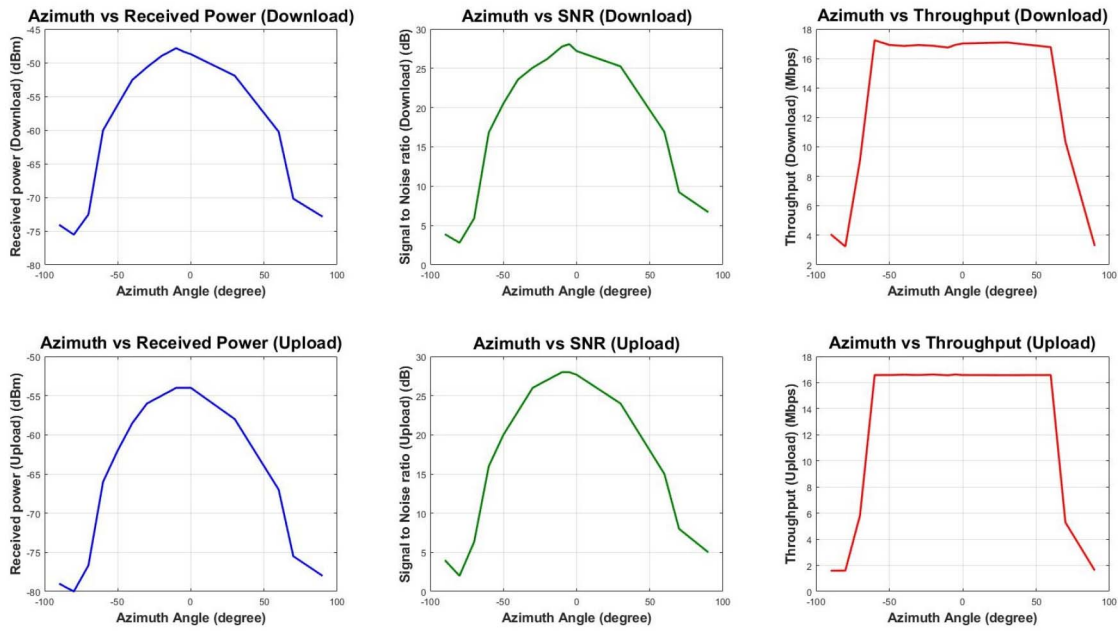


FIGURE 7. Signal parameters plotted against varying azimuth of client antenna.

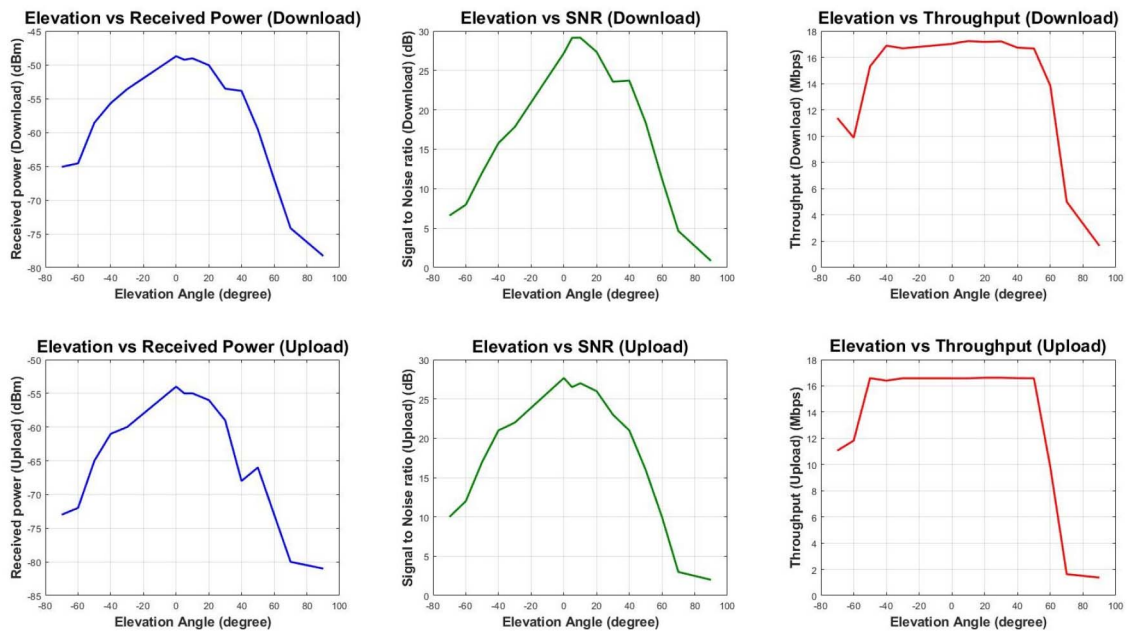


FIGURE 8. Signal parameters plotted against varying elevation of client antenna.

Received powers, SNRs and throughputs were measured 5 times at each location by varying azimuth and elevation angles by  $10^\circ$  at both sides of the center and the best data (with the highest throughput) were chosen for creating radio frequency (RF) coverage heatmaps. After data collection was done, the data were interpolated by MATLAB to generate four heatmaps - received power (download), SNR (download), download throughput and upload throughput. Fig. 9 to 12 show these four heatmaps.

The center frequency of the channel (602 MHz) was considered as signal frequency while creating the heatmaps.

The red pin on each heatmap denotes the location of the base radio, while the blue pins denote the test locations.<sup>1,2</sup>

1. While doing 2D interpolation of the throughput data, a few data at the edges of the covered area became negative, which were manually set to zero before plotting, because throughput cannot be negative.

2. At two locations at the busiest area of the town, no signal has been received. The GPS locations of those two sites were (36.159575, -97.069638) and (36.174701, -97.070747). For including those points in the heatmaps, we set throughput at those locations to be zero, received power to be  $-95$  dBm (which was around 20.64 dBm lower than the minimum power received in other locations) and SNR to be 0.1 dB (which was 3.8 dB lower than the lowest SNR received).



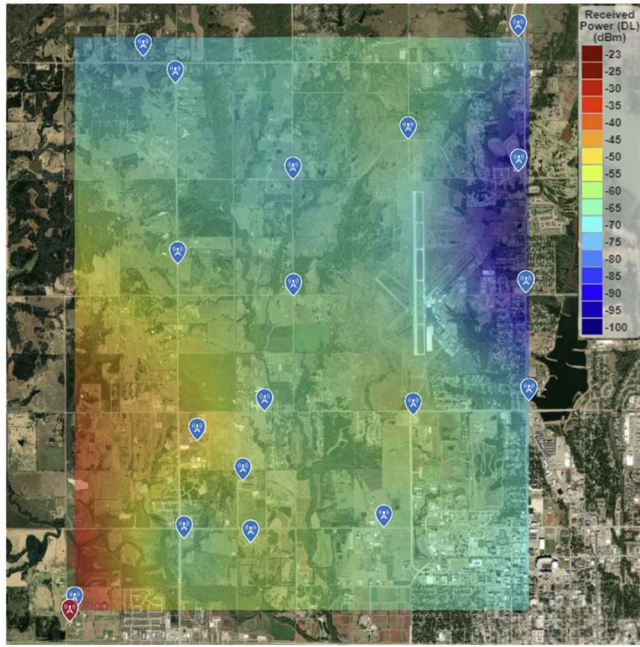


FIGURE 9. Received power (download) heatmap.

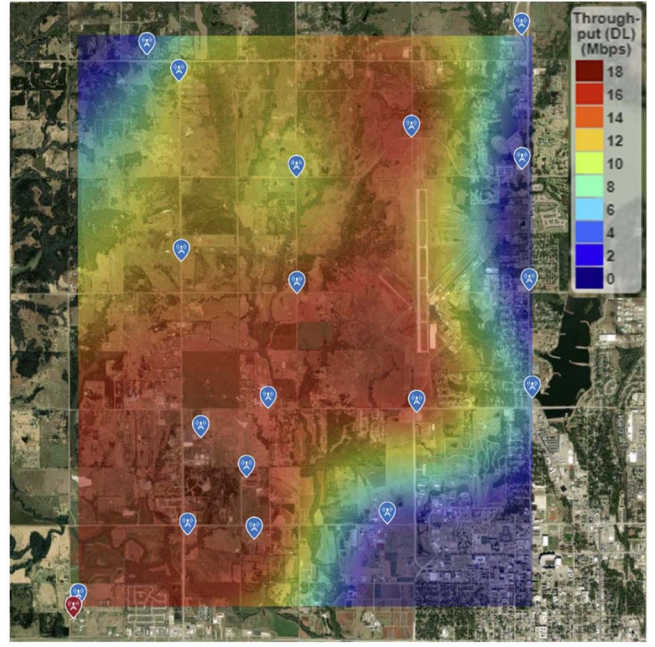


FIGURE 11. Throughput (download) heatmap.

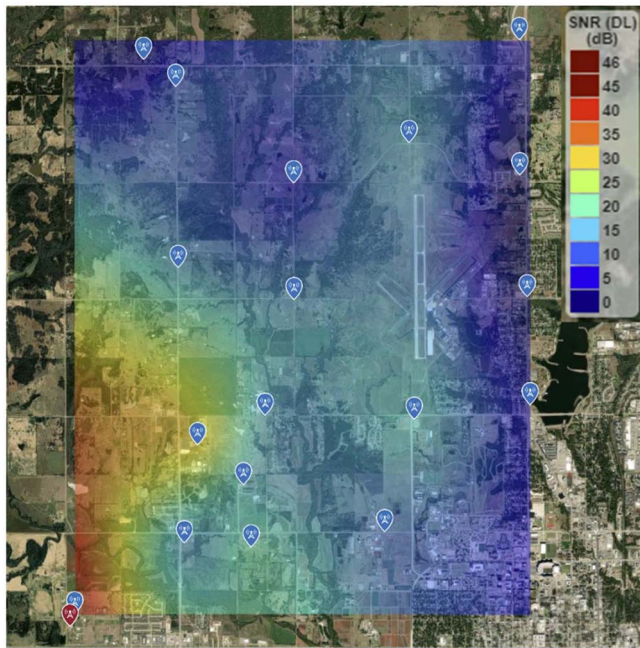


FIGURE 10. SNR (download) heatmap.

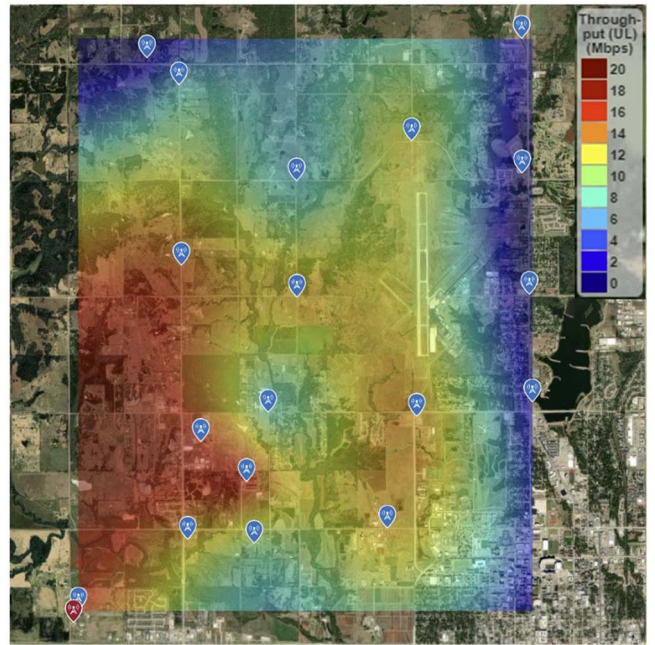


FIGURE 12. Throughput (upload) heatmap.

Also, the throughputs (download and upload) and latency data collected continuously by the Raspberry Pi at OSU feed mill were plotted for 48 hours in Fig. 13. Within that timeframe, the maximum, minimum and average throughput and latency data are presented in Table 2.

TABLE 2. Performance data collected at OSU feed lot on October 24–25, 2020.

Parameter	Maximum	Minimum	Average
Throughput (DL)	16.9976 Mbps	13.8404 Mbps	16.5426 Mbps
Throughput (UL)	16.0677 Mbps	9.8206 Mbps	14.0856 Mbps
Latency	37.542 ms	26.832 ms	28.1896 ms

### V. LIVE SERVICE

After lab testing and outdoor testing, we moved forward to provide TVWS based Internet service to a real client, Collin’s Cattle Inc., located at Tillman County, Oklahoma.

The address of the client was 23334 E 1800, Loveland, Oklahoma, USA, 73553. Two cell towers of Pioneer Telephone Cooperative Inc. [50] were identified near the



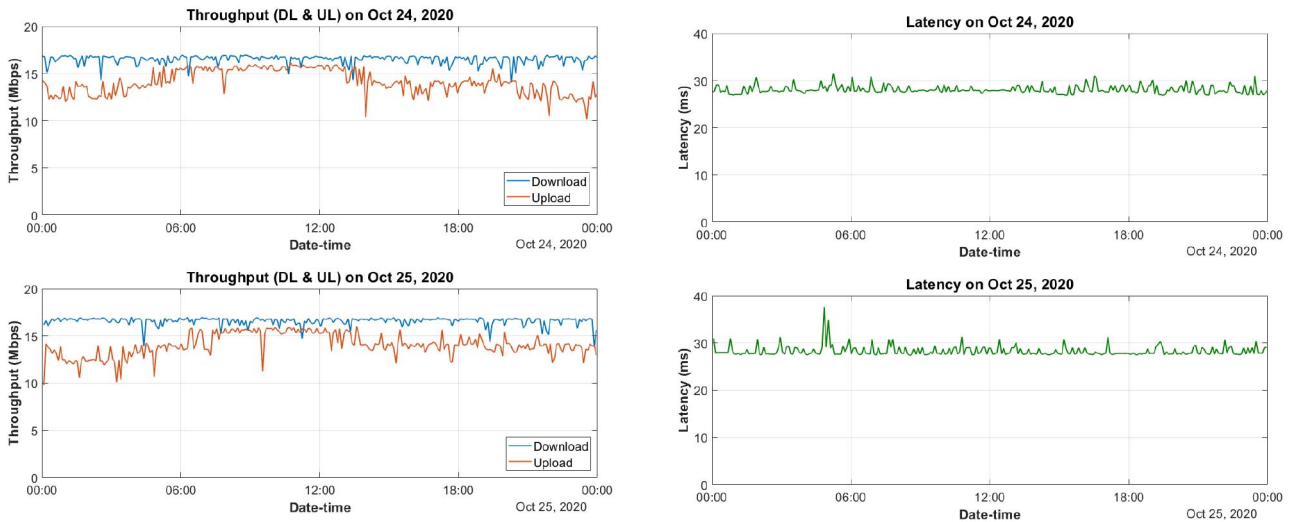


FIGURE 13. Plots of throughput and latency at OSU feed lot vs. time for 48 hours.

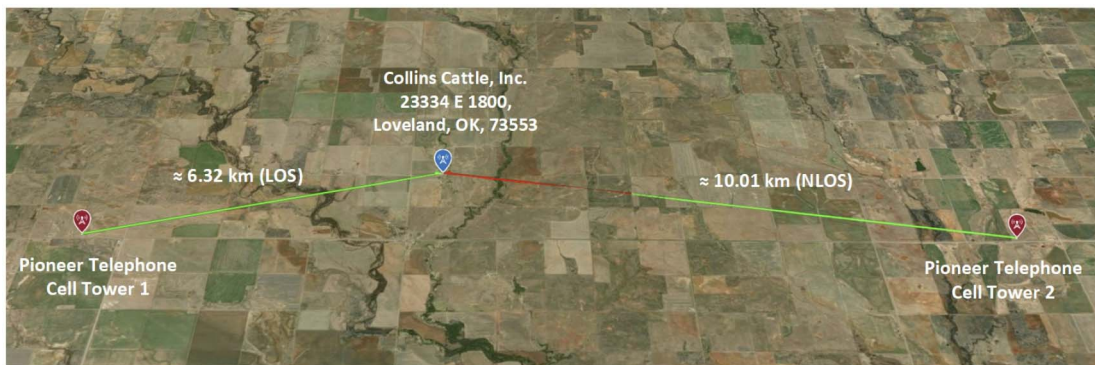


FIGURE 14. MATLAB LOS simulation result for Tillman County sites.

TABLE 3. Cell towers and client locations at Tillman County, Oklahoma.

Places	Latitude	Longitude	Aerial distance from farm
Collin’s cattle	34.406755	-98.812423	-
Cell tower 1	34.392556	-98.879167	6.33 km
Cell tower 2	34.391778	-98.704861	10.01 km

client location. The locations and their distances from Collin’s Cattle are shown in Table 3. In order to choose one tower, line-of-sight simulation was run in MATLAB using the location coordinates of sites, transmitter height of 30.5 m and receiver height of 5 m. In the simulation result (Fig. 14), the line-of-sight and non-line-of-sight portions were marked by green and red colored lines respectively. It was seen from the simulation result that only cell tower 1 had line-of-sight with Collin’s Cattle with chosen heights. Also, the distance between the transmitter and receiver was shorter for cell tower 1 which would ensure lower path loss. Hence, cell tower 1 (Fig. 15) was chosen for mounting the transmitter. There was 50 Mbps backbone Internet connectivity

available at the tower provided by Pioneer. Pioneer installed a new TP Link router (Model: R600VPN [51]) for managing our service. A public IP address provided by Pioneer was set up in this router for accessing it remotely. On the deployment day, the base radio along with the panel antenna was mounted at 68.6 m height of the tower. Pioneer provided Cat6 cable from base radio to the ground cabinet. Inside the cabinet, the base radio was connected to the Internet through the power-recycle device and PoE adapter, in a similar way it was done at OSU feed mill for outdoor testing.

The IP address of the base radio was changed to match the local network created by Pioneer at the tower. The power-recycle device got an IP address from the same network through DHCP. Once the base radio was connected to the Internet, port forwarding was done in the TP Link R600VPN router to access the power-recycle device and the base radio remotely from any Internet connection. From the list of available channels seen from the base GUI, channels 35-36 (center frequency 602 MHz), which was previously used for outdoor testing, was selected and signal transmission was started.



FIGURE 15. The chosen cell tower of Pioneer at Tillman County.



FIGURE 16. Client antenna at rooftop of client premises at Tillman County.

The client radio with Yagi antenna was set up at the rooftop of a garage of Collin’s Cattle (Fig. 16) at an approximate height of 5 m. The antenna was directed towards the base antenna at Pioneer cell tower. The Cat5e cable used for outdoor test setup at Stillwater was used to connect client radio to the indoor setup at the garage. The indoor setup included the Wi-Fi router [49] connected to the PoE adapter and a Raspberry Pi (for monitoring purpose) connected to the Wi-Fi router. Dual channels 34-35, 35-36 and 36-37 were selected at the client radio using its GUI. Once

TABLE 4. Performance data collected at Collin’s Cattle on March 06, 2021.

Parameter	Maximum	Minimum	Average
Throughput (DL)	16.9390 Mbps	13.1143 Mbps	16.2745 Mbps
Throughput (UL)	5.3508 Mbps	2.4701 Mbps	3.7472 Mbps
Latency	49.769 ms	32.226 ms	40.6887 ms

it received signal from the base radio, the Wi-Fi router and the Raspberry Pi received IP addresses from Pioneer network at the cell tower through DHCP and became connected to the Internet. The instantaneous values of signal parameters like received power, noise power, SNR etc. were seen from base GUI (Fig. 17). The throughput and latency for one day (March 6, 2021) collected every 5 minutes by the Raspberry Pi have been plotted in Fig. 18. Within that 24 hours, the maximum, minimum and average throughput and latency data are presented in Table 4.

## VI. THEORETICAL ANALYSIS OF THE RESULTS

The results of our TVWS trial were compared with theory and typical values to determine how closely the hardware performed to expectations. The measurement data were compared with a free space path loss model and the path loss exponent has been estimated. Also, the throughput data were compared with the maximum throughput that Adaptrum radios can provide under the testing condition.

### A. PATH LOSS MODEL

Path loss quantifies the loss of signal strength as the wave propagates in space. The received power (in watts) of the signal at a given distance  $d$  (in meters) from the transmitter is expressed as follows

$$P_r = P_t K \left( \frac{d_0}{d} \right)^\gamma, \tag{1}$$

where  $P_t$  is the transmitted signal power in watts,  $K$  is a unitless constant that depends on antenna characteristics and the transmission frequency,  $d_0$  is a reference distance in meters for antenna far field and  $\gamma$  is the unitless path loss exponent [52].  $K$  can be set to the free space path gain at distance  $d_0$  for omnidirectional antennas and in decibel, it becomes

$$K_{dB} = 20 \log_{10} \frac{c}{4\pi f d_0}, \tag{2}$$

where  $c$  is the speed of light in free-space ( $3 \times 10^8$  meters/second) and  $f$  is the frequency of the transmitted signal [52]. The value of  $\gamma$  is typically considered to be 2 in free-space propagation, but it can vary from 1.6 to 6.5 depending on the propagation environment [52]. Based on (1), path loss (in decibel),  $P_{L(dB)} = 10 \log_{10} \left( \frac{P_t}{P_r} \right)$  can be expressed by

$$P_{L(dB)} = -10 \log_{10} K + 10\gamma \log_{10} \left( \frac{d}{d_0} \right)$$

## Clients

Name	Serial Number	Modulation (DL/UL)	Power dBm (DL/UL)	Noise dBm (DL/UL)	SNR dBm (DL/UL)	PER % (DL/UL)
	A2FJ1595	64QAM 5/6 / QPSK 2/3	-52.44 / -58	-78.24 / -69	25.8 / 11	0 / 0.00163

FIGURE 17. Received signal parameters as seen from client site at Tillman County.

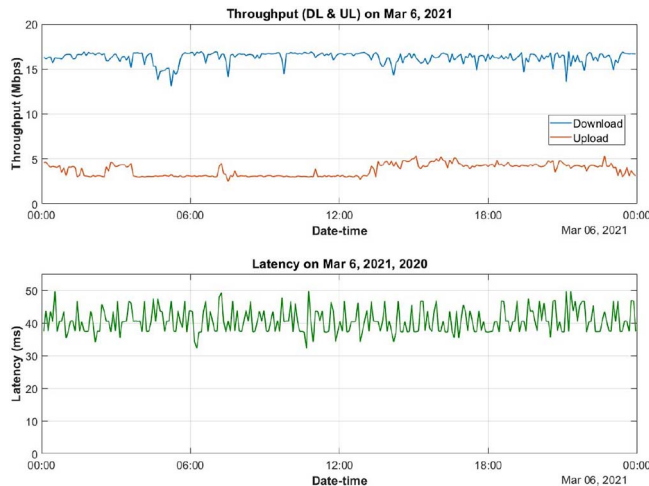


FIGURE 18. Live plot of throughput and latency data vs. time for a day at client site at Tillman County.

or

$$P_{L(dB)} = -K_{dB} + \gamma \left( \frac{d}{d_0} \right)_{dB} \quad (3)$$

which shows linear variation of path loss with slope  $\gamma$  as logarithmic distance changes.

Among the 18 locations, where received TVWS signal data were collected in outdoor testing at Stillwater, 5 locations were in the line of sight of the base antenna at different distances. The received signal data at those points were used to model the path loss. The transmitted power was considered to be the maximum conducted power of the base radio which was 600 mW (28 dBm) [41]. The path loss data were plotted in Fig. 19, where the measured data (blue dots) looked linear as expected in (3). Curve fitting was performed using MATLAB (shown by the magenta line in Fig. 19) and the modeled equation became  $P_{L(dB)} = 49.189 + 2.735 \left( \frac{d}{d_0} \right)$ . Comparing this equation with (3), we get  $K_{dB} = -49.189$  and  $\gamma = 2.735$ .

The experimental findings were also compared to typical or ideal theoretical values. Using a center frequency of 602 MHz for TVWS channels 35-36, equation (2) yielded the ideal value of  $K_{dB} = -72.916$  dB. It indicates that in our case, the path loss is 23.73 dB lower because of the combined effects of higher directionality and lower efficiency of the base and client antennas in comparison to ideal omnidirectional antennas. The modeled  $\gamma$  value was higher than that of free-space propagation and falls in the typical range

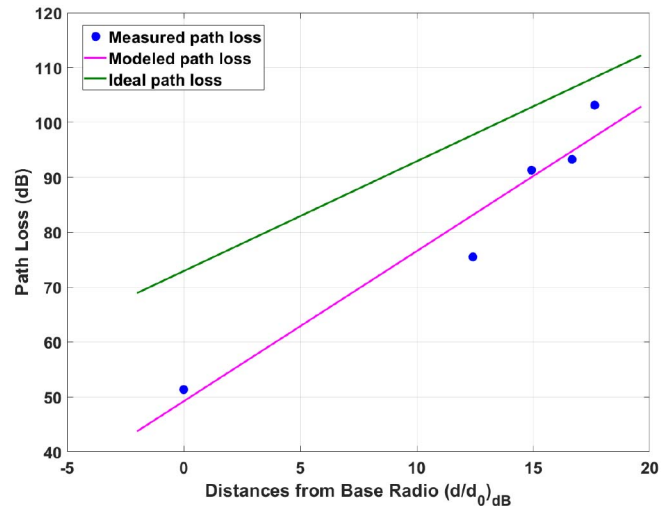


FIGURE 19. TVWS path loss model showing linear relationship between path loss and distance in logarithmic domain.

of path loss exponent values in urban cellular network (2.7 to 3.5) [52], [53]. This could be due to the shadowing effect by large trees in the test area that was not included in the path loss model. The ideal path loss with omnidirectional antenna in the free space using  $K_{dB} = -72.916$  and  $\gamma = 2$  is plotted in Fig. 19 (green line) which clearly shows that the combined effect of shadowing and antenna directionality is lowering the path loss of the TVWS system within the test distance.

### B. THROUGHPUT ANALYSIS

The maximum throughput possible with Adaptrum TVWS radios were 13 Mbps for single channel (6 MHz bandwidth) and 24 Mbps for dual channel (10 MHz bandwidth) [41], [42]. Throughputs achieved in various tests in our TVWS trial as a percentage of this limit are summarized in Table 5. In lab test, Adaptrum radios used 64 Quadrature Amplitude Modulation (QAM) as seen in Fig. 4. Users did not have any control over the modulation order chosen by Adaptrum radios during signal transmission. If the radios had chosen higher order modulation (256QAM instead of 64QAM), the throughput would have been closer to the maximum values. The results found in outdoor test and live system were quite satisfactory at the outdoor environment with all the path loss, noise, multipath and lower order modulation. The lower upload throughput (5.3508 Mbps or 22.3% of the maximum possible value) in the live system



**TABLE 5.** Maximum achieved throughputs as percentages of maximum achievable throughput.

Test	Throughput (DL)
Lab test (single channel)	82.3%
Lab test (Dual channel)	77.5%
Outdoor test	70.8%
Live test	70.6%

is attributed to the lower upload SNR (11 dB as seen in Fig. 17) than the download SNR (25.8 dB) present in the channel at the time of data collection.

## VII. CONCLUSION AND FUTURE DIRECTIONS

In conclusion, broadband Internet connectivity was feasible using TVWS which was demonstrated by the testing conducted at Stillwater and the Internet connection provided to Collin's Cattle at Tillman County, Oklahoma. The performance analysis showed satisfactory results for a trial including good throughput and latency for the rural communities. The download throughput of the live service was found to be maximum 16.94 Mbps and an average of 16.27 Mbps using 10 MHz channel width at a distance of 6.32 km from the base station. The outdoor test results were compared with theory and typical values and the system was found to be performing within the realm of expectation. The path loss was found to be lower, hence better than the free space path loss with omnidirectional antenna within the test distance. The system performance could be further enhanced by using more improved WSDs in future efforts. Sometimes, the noise floor of the selected TV channel changed over time, but the WSDs used in this project did not have an automated solution to switch channels based on lower noise floor. In future, Adaptrum's new ACRS2.0 B1000 radio, or even newer model B2000 radios, can be used for similar trials to achieve even higher throughput, because these new WSDs will have the capability to combine more than two channels to increase the channel width and throughput.

It has been known from Adaptrum that their base radio is capable of connecting up to 8 client radios simultaneously, but it will divide the overall throughput among them. Under fully loaded condition, the division ratio will depend on the channel SNR and the modulation rate used. Therefore, the network can be expanded in future by using multiple client radios served by single base radio. Multiple base radios can also be installed to increase the coverage area and the throughput achieved by each client radio in future. Also, more complex terrain could be considered in future trials to evaluate the effects of different terrains on the network performance.

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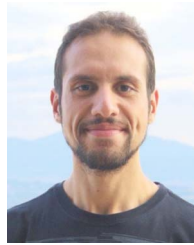


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