A Measurement Study of TVWS Wireless Channels in Crop Farms

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***Abstract*—Operating at lower frequencies than systems such as Wi-Fi, TVWS wireless communication can enable long-range communication in rural communities and can more easily penetrate obstacles (vegetation, terrains). Thus, it is appealing to scenarios where line-of-sight is not always guaranteed. In particular, TVWS communication is a good candidate for supporting precision agriculture such as camera-based plant phenotyping and sensor-based analysis of plant behaviour. Yet there lacks in-depth real-world measurement data on the behavior of TVWS wireless channels in agriculture farms. To fill this gap, we use the field-deployed TVWS network of CyNet to measure TVWS channel behaviour in the Curtiss Research Farm in Ames, Iowa, where the landscape is predominantly composed of soybean and corn fields. We investigate the impact that crop diversity (soybean vs. corn), height and density of corn fields, antennas' placement and variations of temperature and humidity have on the spatiotemporal behaviour of TVWS channels. This study also helps identify path loss models that best reflect radio propagation characteristics of TVWS systems in corn farms for different antenna heights.**

I. Introduction

As wireless technologies are gaining a strong foothold in agriculture, more tasks can be accomplished through connected devices such as cameras, sensors, drones and robots, thus facilitating rapid access to reliable data in decision making which can have significant financial implications. This influx of connected devices available to farmers coupled with ag data analytics form precision agriculture. On average, the farmers spend a lot of their time monitoring crop development and analyzing how the crops respond to their crop management practices. With advanced wireless technologies, farmers can remotely observe the development of their crops without being in the field. Timely periodical reports summarizing data collected from a variety of sensors monitoring the fluctuation of soil moisture, tree foliage, temperature, nitrogen, humidity, pH, CO_2 can be forwarded to a Farm Management System through radio links. While these substantial advances in farming aim at assisting farmers in maintaining good crop growing conditions, they also enable farmers to predict and prevent plant diseases, detect bugs, geolocate the right parcels that will help to optimize yields, decide which fertilizers to use, control irrigation systems, and develop new agricultural practices.

Advanced agricultural practices coupled with IoT-based technology [1], [2] aim at growing crops in controlled environments in order to enhance yields. With the recent advances in genetic improvement via breeding, phenotyping is emerging as a promising crop engineering based technique in agriculture. Phenotyping is the process of analyzing traits to select more productive and less input-demanding genotypes. High-resolution RGB imaging enables the identification of favorable phenotypic traits (e.g., leaf arrangement) and thus more productive genotypes. Implantable plant nanosensors not only enable breeders to identify hybrids requiring less agricultural inputs but also enable farmers to optimize functions such as fertilization and irrigation.

The selection of an appropriate wireless technology depends on agricultural application requirements. For instance, some applications may require low data rate and low energy consumption (e.g., sensor-based measurements) while others will require high data rates and can accommodate more power consumption (e.g., video streaming). For the connectivity between sensors, Zigbee is typically used for short range communications, Bluetooth Low-Energy (BLE) for applications that have low-power requirements, LoRa for applications with low data rates and long range requirements, and narrowband technology (e.g., NB-IoT, SigFox) for applications where a large number of sensors transmit a small amount of data at the same time. For long-range communications between in-field devices (wireless sensors, UAVs, robots) and the Cloud, existing solutions employ LTE or WiFi. LTE does not scale well since it involves a subscription

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fee which can be costly for large farms [3]. As for WiFi, signals operating in the 2.4GHz band may suffer from attenuation, scattering, absorption and diffraction caused by vegetation [4].

IEEE ratified the 802.11af standard also known as TVWS that uses spare channels in the low frequency radio spectrum traditionally allocated to television: 470MHz to 698MHz (UHF and VHF bands). One advantage of the TVWS band is an extended range of 10 to 15 km, or more in good conditions (up to 30 km in flat terrain). Signals at TVWS band can more easily spread over rugged areas, through forests or buildings, where higher-frequency signals experience interference. Thus, TVWS communication is ideal in near-line-of-sight and non-line-of-sight scenarios. Another benefit is that only TV signals are potential interferers. Because TVWS uses lower frequencies that can penetrate obstacles and enable the use of applications with different bandwidth requirements [3], it is an appealing candidate for smart agriculture. However, only a few TVWS measurement campaigns exist and they have only focused on rural [5] and indoor environments [6]. Assessing TVWS performance in harsh agricultural settings has yet to be done.

In this paper, we present a measurement campaign of TVWS wireless channels at Curtiss Farm, a research farm located in Ames, Iowa, USA. We deploy an end-to-end TVWS network between the farm office and the fields, and perform an extensive measurement study of TVWS channels by taking into consideration antennas' placement, variations of temperature and humidity, crop diversity (soybean vs. corn), height and density of corn fields. Some past studies analyzed the impact of crops [7], [8], [9] and the impact of weather [10], [11], [12] on the signal propagation. However, they focused exclusively on IEEE 802.15.4 WSNs. To date, there is no comprehensive study of TVWS in such agricultural settings. This measurement campaign provides unique insight into the spatiotemporal behaviour of TVWS channels in corn fields. Particularly, the contributions from our measurement campaign are as follows:

- We perform a detailed real-world measurement analysis of the spatiotemporal behaviour of TVWS channels subject to a variety of environmental factors such as weather components, antenna heights, crop varieties, crop densities and distance from the TVWS Access Point. We measure Received Signal Strength Indicator (RSSI), Received Signal Strength (RSS), Signal-to-Noise Ratio (SNR), noise and throughput using actual OpenWrt-based TVWS radios from HuWoMobility, and we assess how aforementioned metrics are impacted by environmental factors. Representative key findings of this study are summarized in Table I.
- We investigate which path loss model is most applicable to TVWS in agricultural environments according to the empirical path loss computed for different antenna heights. We find out that, when antennas are close to the ground, the path loss is better modeled by the Okumura-Hata (suburban) path loss model, and, for higher antenna heights, it is better modeled by the Plane Earth path loss model.

Ground antenna height	RSS (dBm)	RSSI (dBm)	SNR (dB)
Time of day Morning vs. Daytime	-5 $\pm$ 0.0392 (-5.04, -4.96)	+1.1 $\pm$ 0.274 (0.826, 1.37)	+7.42 $\pm$ 0.118 (7.3, 7.54)
Crop type Corn vs. Soybean	+1.5 $\pm$ 0.868 (0.632, 2.37)	+0.8 $\pm$ 0 (0.8, 0.8)	+0.36 $\pm$ 0.0392 (0.321, 0.399)
Crop density Sparse vs. Dense	-6 $\pm$ 0.0784 (-6.08, -5.92)	-4.6 $\pm$ 0 (-4.6, -4.6)	-2.2 $\pm$ 0 (-2.2, -2.2)
Tree foliage Sparse vs. Dense	-9 $\pm$ 0.0195 (-9.02, -8.98)	-9.5 $\pm$ 0.118 (-9.62, -9.38)	-9.96 $\pm$ 0.098 (-10.1, -9.86)
Top antenna height	**RSS (dBm)**	**RSSI (dBm)**	**SNR (dB)**
Time of day Morning vs. Daytime	-16.2 $\pm$ 0.195 (-16.4, -16)	-3.7 $\pm$ 0.195 (-3.9, -3.51)	+8.96 $\pm$ 0.137 (8.82, 9.1)
Crop type Corn vs. Soybean	+9 $\pm$ 0.0195 (8.98, 9.02)	+3.5 $\pm$ 0.118 (3.38, 3.62)	+1.5 $\pm$ 0.195 (1.3, 1.7)
Crop density Sparse vs. Dense	-2 $\pm$ 0.0195 (-2.02, -1.98)	-0.2 $\pm$ 0.0195 (-0.22, -0.181)	-1.5 $\pm$ 0.0195 (-1.52, -1.48)
Tree foliage Sparse vs. Dense	-6 $\pm$ 0.0195 (-6.02, -5.98)	-7.1 $\pm$ 0.098 (-7.2, -7)	-8.7 $\pm$ 0 (-8.7, -8.7)
Antenna height variation	**RSS (dBm)**	**RSSI (dBm)**	**SNR (dB)**
Ground to Mid	+4.67 $\pm$ 3.97 (0.7, 8.64)	+4.2 $\pm$ 2.5 (1.7, 6.7)	+3.31 $\pm$ 1.45 (1.86, 4.76)
Ground to Top	+6.67 $\pm$ 2.85 (3.82, 9.52)	+7.23 $\pm$ 0.691 (6.54, 7.92)	+7.5 $\pm$ 1.8 (5.7, 9.3)
Mid to Top	+2 $\pm$ 1.13 (0.87, 3.13)	+3.03 $\pm$ 1.92 (1.11, 4.95)	+4.19 $\pm$ 3.11 (1.08, 7.3)

TABLE I: 95% confidence intervals of the impact of time of day, crop type, crop density and tree foliage on farm wireless channel behavior, when MIMO antennas are placed 20 cm and 214 cm above the ground respectively (i.e., Ground and Top antenna height). The last sub-table shows the impact of antenna height in corn fields (Mid antenna height is $\sim$110 cm). Here is how to read this table: for ground antenna height, the RSS during daytime is 5 dBm lower than that in the morning, the RSS for soybean is 1.5 dBm higher than that for corn, the RSS for dense crop density is 6 dBm lower than that for sparse crop density, the RSS for dense tree foliage is 9 dBm lower than that for sparse tree foliage, etc.

The rest of the paper is organized as follows. In Section II we take a look at the current context and environment in which this measurement campaign was conducted. Then, Section III covers the methodology and tools used for this study. The measurement results are presented and analyzed in Section IV. Finally, we conclude this study by a summary on our key findings in Section V.

II. Preliminaries

CyNet wireless living lab. CyNet [13] is an end-to-end software-defined cyberinfrastructure integrating advanced field-deployed wireless networks for agriculture and transportation research. It is a joint effort between the ISU Department of Electrical and Computer Engineering (ECE), ISU Institute for Transportation (InTrans) and ISU Plant Science Institute (PSI). Due to its wireless resource virtualization through whole-stack slicing [14], it is an ideal platform for prototyping and deploying new PHY and MAC layers in the field, as well as Predictable, Reliable, Real-time, and high-Throughput (PRRT) algorithms for research and education in smart agriculture and smart transportation. CyNet consists of two cellular RANs deployed at the Iowa State University (ISU) Curtiss Research Farm and Research Park in the City of Ames, Iowa, USA. Each RAN targets a specific use case: the former is aimed at smart agriculture while the later is aimed at smart transportation. The Curtiss Research Farm RAN is composed of LTE and TVWS technologies. This study focuses on the TVWS technology.

CyNet agriculture use case. The ISU Plant Science Institute (PSI) is a leader in plant phenotyping, genotyping, and nanosensors. In recent years, Schnable's team and their collaborators have deployed Unmanned Ground Vehicles (UGVs) with high-definition cameras, $\sim$100 implantable nitrate sensors and $\sim$1,000 stationary cameras for phenotype analysis in the ISU Curtiss Research Farm (see Figure 1). Each camera records an image

Fig. 1: Stationary field cameras for phenotype analysis

of an individual row of 6 corn plants every 5 minutes and each sensor records a reading every 10 seconds. In the current solar-powered deployment, the cameras and sensors are controlled by Raspberry Pi single board microcomputers, and the Raspberry Pis are connected to a field-deployed server via WiFi Access Points. The server collects, renames, and stores photos on a local hard drive. The server also displays information about the system's health, to help diagnose any potential problems with the system. As part of the connectivity use cases, interconnecting the in-field PSI server to the farm to access and analyse data anytime, anywhere is crucial.

In-field TVWS Radio Access Network. To establish connectivity between different in-field devices (UAVs, UGVs, cameras) and the farm office, we have secured an FCC experimental license in the TVWS spectrum bands. A 18 m pole has also been installed at Curtiss Farm, and it is equipped with TVWS Access Points, Tower Mounted Boosters (TMBs), directional and omnidirectional antennas in order to provide connectivity from the farm office to the in-field devices. An overview of the in-field TVWS network is presented in Figure 2.

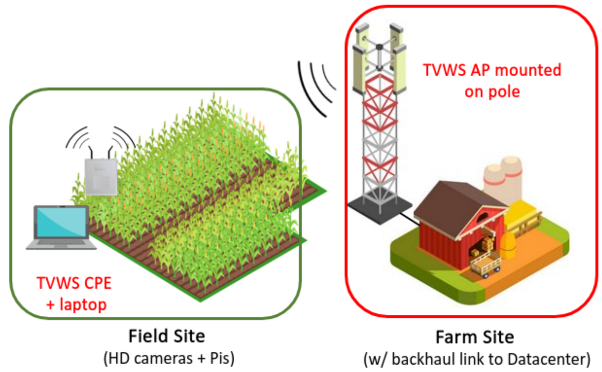


Fig. 2: CyNet TVWS network

The in-field TVWS network considered in this study is composed of two TVWS devices:

- The TVWS AP (Access Point) mounted on the 18 m pole is plugged to directional antennas as depicted in Figure 3. This TVWS AP is connected to a Cisco Catalyst switch in an enclosure inside the farm office. The switch interconnects the farm to the ISU Durham data center through an optical backhaul link.
- The TVWS CPE (Customer Premise Equipment) is used to cover several location points for measurement data collection. It is connected through SMA cables to 2×2 MIMO antennas and through Ethernet to a Dell Laptop that runs an automation script sending probes to the TVWS AP and storing measurements for further analysis.

III. Methodology

In this section we discuss the rationale behind the selection of in-field location points, the devices used during the measurement campaign along with their configurations, the spatial coverage of the TVWS directional antennas and the relevance of the metrics collected to characterize the TVWS channel quality. Finally, we describe the tools and overall process used to conduct all the measurements.

A. *In-field location points*

Figure 4 shows the probed area in Curtiss Farm. The map indicates the location points denoted by LPX. We

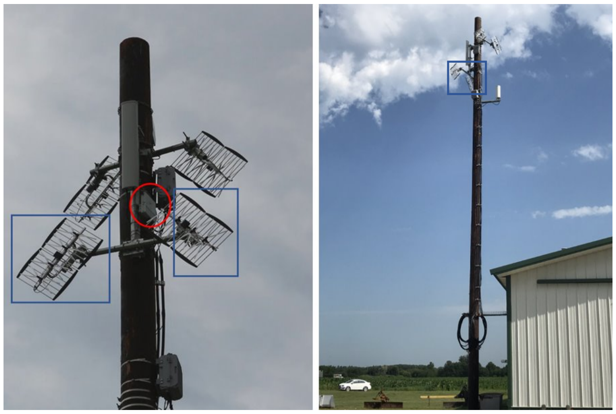


Fig. 3: TVWS AP mounted on pole (red-circled) and TVWS bow-tie antennas (blue-boxed) facing the field

carefully selected the location points that exhibit high diversities such as crop type, crop density, and crop height. To demonstrate the impact of crop types on channel quality, we picked pairs of location points close to each other where one is within a corn field and the other in a soybean field (i.e., LP25-LP26, LP10-LP11). Due to space limitations, this paper focuses only on a representative subset of the location points listed in Table II. Specifically, those location points have been selected for their diverse characteristics such as their distance to the TVWS AP, the crop type, the density and height of the corn plants, and whether or not they are in the line-of-sight of the TVWS AP. One notable exception is the group composed of LP12 and LP13. Those location points are close to the corn field but not inside, instead they are on the roadside obstructed by tree leaves.

B. TVWS system

TVWS devices. We carry out our TVWS measurement campaign with HuWoMobility HL3210 TVWS devices. Those TVWS devices use an integrated Qualcomm Atheros QCA9533 System-On-Chip and their TVWS configuration is shown in Table III. Two TVWS APs have been installed at the Farm Site, each being connected through jumper cables to directional bow-tie antennas. In this study, we use the TVWS AP that is connected to antennas pointing to the farm fields. Since we had CLI access through SSH to the TVWS devices operating under OpenWrt, we create a set of automation scripts that automatically collect metrics with the desired sampling frequencies to be discussed shortly. The transmission power of the AP and CPE is configured at 22dBm.

Corn height/density: Small/Sparse | Medium | High

Location Points		Environmental factors				
Label	**Distance**	**Soybean**	**Corn**	**Line-of-sight**	**Corn density**	**Corn height**
LP4	1086m		✗	YES	H	H
LP5	1074m		✗	YES	S	H
LP10	830m		✗	YES	M	H
LP11	822m	✗		YES		
LP12	563m		✗	NO		
LP13	370m		✗	NO		
LP22	195m		✗	YES	H	M
LP23	214m		✗	YES	M	M
LP25	474m		✗	YES	H	H
LP26	464m	✗		YES		

TABLE II: Selected Location Points in Curtiss Farm

Channel	Bandwidth	Tx Gain	Rx Gain	MCS
578 MHz	24 MHz	22 dB	52 dB	Auto

TABLE III: TVWS parameters

TVWS antennas. The two TVWS antennas used at the AP are bow-tie antennas, mounted on the pole, facing the fields. They have a 14dB gain with a 60° horizontal beamwidth. The omnidirecitonal antennas used at the CPE have a 5dB gain; the distance between the two CPE antennas is $\frac{\lambda_0}{2}$ (i.e., $\frac{1}{2}$ wavelength) where λ_0 is the wavelength obtained by the following formula: $\lambda_0 = \frac{c_0}{f}$ where c_0 is the speed of light in free space (i.e.: 3×10^8m/s) and f the frequency (i.e.: 578MHz). Hence, the separation between the two MIMO antennas is $\sim$26cm.

C. Automation scripts for data collection

In order to minimize in-field time and collect as much data as possible, we implement automation scripts that collect on-the-fly average and per-antenna metrics for each location point. All the metrics are collected when UDP traffic is transmitted/received in the background with the iperf tool. To probe a particular location point, we start the main script from the laptop connected to the TVWS CPE. The main script instructs the TVWS CPE to start recording iperf throughput measurements of the TVWS link with a sampling interval of 100 ms. Then, the main script spawns a remote shell instance on the TVWS AP which collects average link quality statistics such as Noise, RSSI (Received Signal Strength Indicator) and SNR (Signal-to-Noise Ratio) available

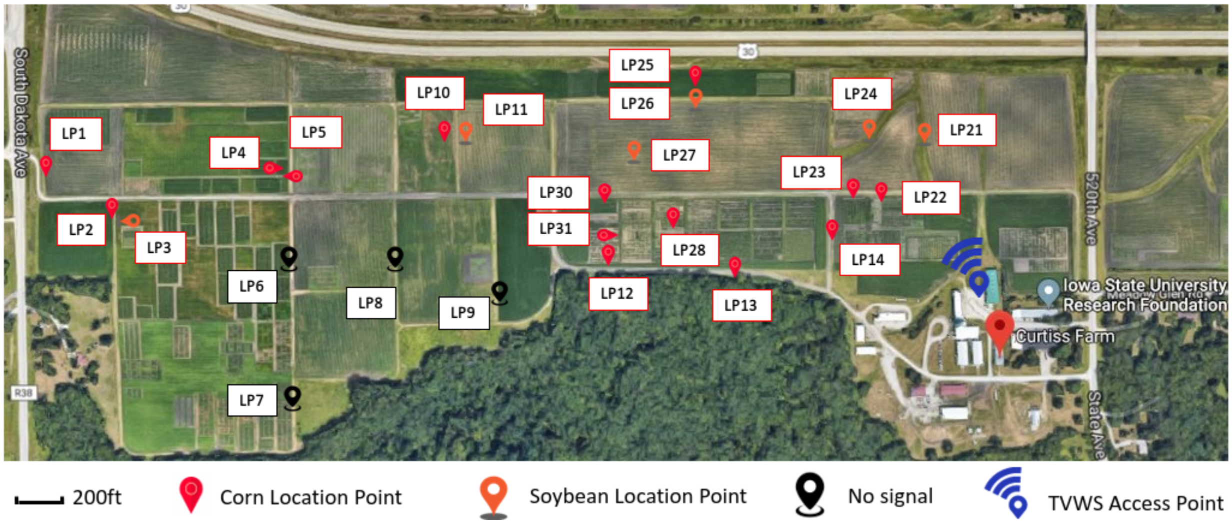


Fig. 4: Location Points in Curtiss Farm fields

from the CLI frontend `iwinfo`. Finally, another shell instance is spawned on the TVWS CPE that collects per-antenna Noise, RSSI and SNR gathered by the Atheros kernel driver (ath9k) debug traces.

Those channel metrics help to characterize spatiotemporal behaviour of the TVVWS channels. The script collects the following channel metrics:

- *Average MIMO SNR and per-antenna SNR:* indicator of link reliability between the AP and CPE;
- *Average MIMO RSSI and per-antenna RSSI:* received signal power at CPE side;
- *Noise power:* quantifies the amount of noise on the channel.

End-to-end performance metrics are also collected. They include downlink throughput and packet loss at the CPE along with delay and jitter of the TVWS link.

D. Data collection process

This measurement campaign has been conducted during the summer of 2019 (July-August period) before the harvest season in September-October. This was the period where most of the plants were tall with a high water content, regardless of the corn variety. Since we had a wet summer in 2019, there was no drought stressed plants. The corn fields and soybean fields were either composed of commercial or experimental hybrid plants. Experimental corn plants were planted much denser than commercial ones.

In order to obtain reliable data that account for diverse factors (e.g., humidity, temperature), we repeated data collection several times at each location point during the early morning, when the humidity was high (∼90%) and the temperature between 11-14°C, and during the early afternoon, when the humidity was ∼60% and the temperature between 28-30°C. Plants contain more water during morning hours than during the afternoon, and the soil moisture does not vary much during daytime. As part of this study, we analyze the effect of changing the MIMO antenna height of the TVWS CPE. Figure 5 shows a 214 cm fiberglass ladder that we used during the measurement campaign. For each location point and time of day, we collected data for different antenna heights: when antennas are located at the bottom (∼20 cm above the ground), in the middle (∼110 cm above the ground) and on top of the ladder (∼214 cm above the ground). Each measurement runs for a duration of 4 minutes. We captured one sample every 100 ms for the throughput and one sample every 20 ms for other metrics. In total, we collected 232 MB of raw data.

Fig. 5: MIMO antennas mounted of top of the ladder

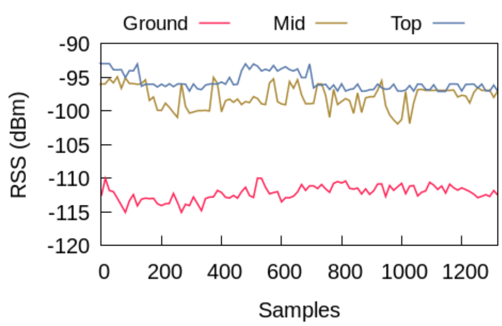
IV. Measurements and Results

A. Impact of weather

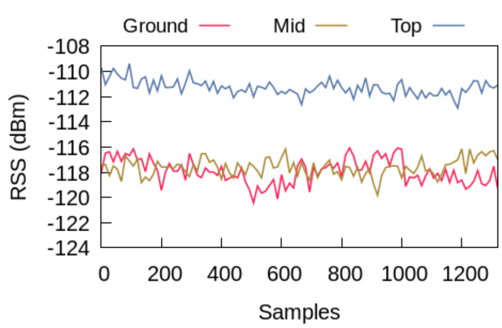
We begin by considering the impact of temperature on the TVWS RSS, SNR and noise. The RSS (Received Signal Strength) is different from the RSSI and is computed as follows: `RSS = RSSI - noise [dBm]`.

For this first set of measurements, we focus on one pair of location points (LP25-LP26), one in the corn field composed of commercial corn and the other one in the soybean field composed of commercial soybeans. The choice of these location points is motivated by the fact that they are in the LOS of the pole antennas, exhibit dense foliage and high density. Thus, we end up collecting data during morning and daytime for different CPE antenna heights in order to assess the impact of weather components (i.e., temperature and humidity) and antenna height variability on link quality. This analysis allows us to determine if temperature and humidity have a significant impact depending on multiple factors.

Here we present the data for the location point LP25 in a dense corn field where corn plants are 2.5 m tall, located 474m away from the TVWS AP. Similar behavior has been observed for LP26 in a dense soybean field composed of 30cm tall commercial soybean plants; details can be found in the technical report [15].

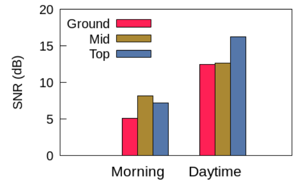


(a) Morning

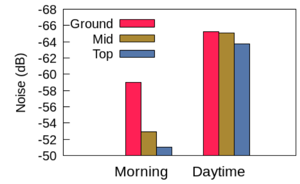


(b) Daytime

Fig. 6: Impact of humidity and temperature on RSS at LP25.



(a) Average SNR at LP25



(b) Average noise at LP25

Fig. 7: Average SNR and Noise at LP25: SNR decreases with humidity while noise increases with humidity.

Figure 6a and Figure 6b show the temporal behaviour of the RSS in the early morning when the temperature is around 12°C and the humidity slightly above 90% and in the afternoon (i.e., Daytime) when the temperature is around 29°C and the humidity below 60%. In the early morning, the mean RSS is -94.8 dBm when MIMO antennas are on top of the ladder, -97.6 dBm when antennas are located at mid height of the ladder and -113 dBm when antennas are located just 20 cm above the ground. Consequently, the RSS increases when the antenna height increases. In the early afternoon, the RSS is negatively impacted by the rise in temperature. This negative correlation between RSS and temperature was also observed for IEEE 802.15.4 links in the ISM bands [11] and for indoor sensors using sub-GHz bands [12]. In both cases (morning and daytime), we notice that the RSS increases with the antenna height but not proportionally to the relative height. This can be explained by the fact that the signal suffers from a greater attenuation at Ground and Mid antenna heights due to the presence of corn biomass surrounding the antennas.

Conversely, while the RSS dropped for all antenna heights in the afternoon, Figure 7a shows that the SNR increases when the temperature increases for all antenna heights. This is because the noise decreases when temperature increases as depicted in Figure 7b. We observe this trend at other location points as well, independently of the crop type.

Figure 8 clearly shows that temperature and humidity have a stronger impact than antenna height variability on TVWS RSS. Moreover, in the morning, the density plot width is reduced especially outside the interquartile range. Interestingly, the RSS measured during daytime exhibits similar distribution shapes for all antenna heights, with RSS values being concentrated around the lower and upper adjacent values (i.e., first and third quartile). In the morning, the major RSS gap between Ground and Mid antenna height is due to the high humidity that induces a higher corn leaf water content. Therefore, the high concentration of water molecules on

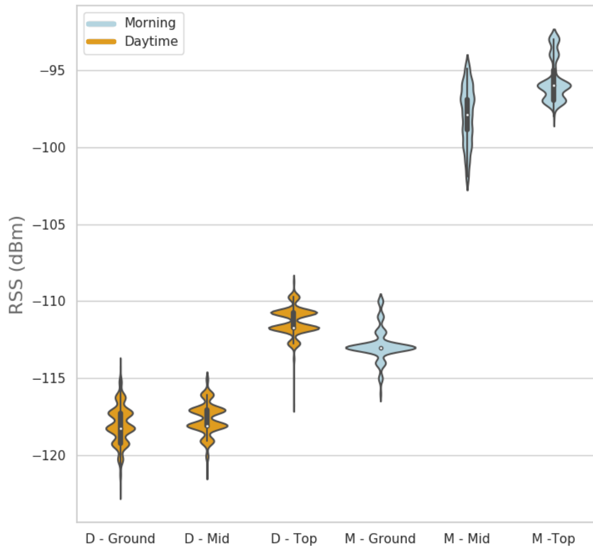
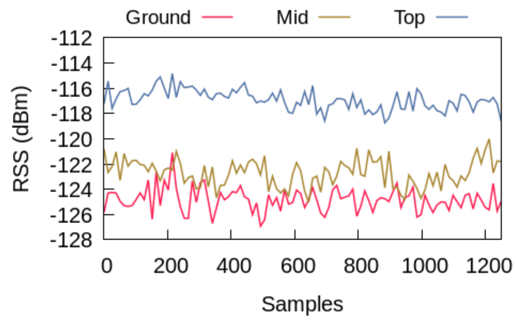
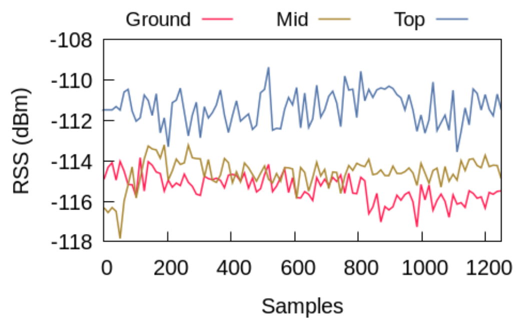


Fig. 8: RSS distribution and probability density for LP25.



(a) LP12



(b) LP13

Fig. 9: Impact of tree foliage on RSS at LP12-LP13.

leaves surrounding antennas close to the ground tends to attenuate the signal.

B. *Impact of tree foliage*

The south of Curtiss Farm is bordered by a forest composed of trees with dense foliage. Due to the height of those trees, we will be able to see how performance are impacted in NLOS scenarios for different antenna heights.

Roadside location points (LP12-LP13). The pair of location points LP12-LP13 along the roadside are located 563 m and 370 m from the TVWS AP, respectively. They are in NLOS due to the heavy tree foliage along the roadside. At LP12, a dense foliage obstructs the line-of-sight while at LP13 the foliage is less dense but the ladder is close to the tree.

We investigate the temporal behaviour of the RSS in Figure 9a and Figure 9b. For the sake of readability the curves have been smoothed out, but the fluctuations can be seen in Figure 10 that shows a side-by-side comparison of LP12-LP13 RSS distribution.

From Figure 9b, we observe that for LP13, the RSS margin between Ground and Top antenna height is relatively small (i.e.: 4 dBm). LP13 exhibits an average RSS of -111 dBm, -114 dBm, -115 dBm at Top, Mid and Ground antenna height, respectively. Since the foliage is equally dense from Ground to Top but present small gaps at Top antenna height, there is no significant gains from placing the antennas on top of the ladder. While the signal is stronger at Top antenna height, it fluctuates a lot

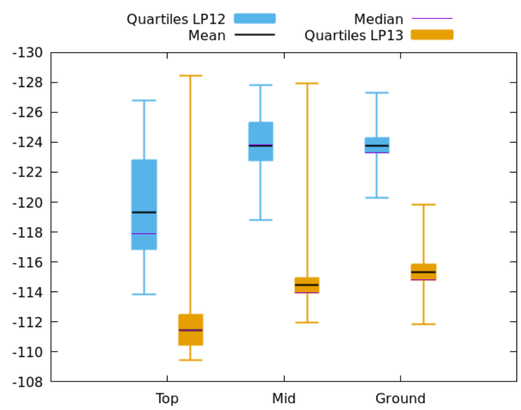


Fig. 10: RSS distribution at LP12-LP13: LP13's RSS oscillates between -128 and -109 dBm due to the presence of dense foliage at Top antenna height.

as shown by the wide interquartile range in Figure 10. At LP12, a section of the tree is directly obstructing the line-of-sight at Ground and Mid antenna height. This clearly impacts the received signal: the average RSS for Top antenna height is -117dBm while for Mid and Ground antenna height it ranges between -123 dBm and -124 dBm, which is a 7 dBm RSS margin. Figure 11 shows the average SNR at LP12 and LP13. The SNR at LP12 for Ground and Mid antennas is poor (i.e.: below 5dB). The SNR doubles when antennas are located on top of the ladder. As for LP13, the average SNR is comprised between 14 dB and 18 dB which indicates that a decent link quality can be expected even under tree foliage obstruction.

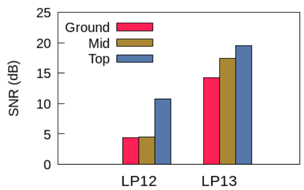


Fig. 11: Average SNR at LP12-LP13.

Throughput fluctuations in Figure 12 confirms the previous observations. At LP12, the average throughput is of 18.1 Mbps for Top antenna height and of 0.19 Mbps and 0.79 Mbps for Ground and Mid antenna height, respectively. At LP13, the stable RSS and decent average SNR of Mid antenna height translate to a stable temporal behaviour of the throughput and an average throughput of 14.6 Mbps. At Top antenna height, the average throughput is 21 Mbps. Due to the close proximity of antennas and tree foliage, the throughput exhibits rapid fluctuations over time. Finally, at Ground antenna height the throughput remains stable around 2.31 Mbps.

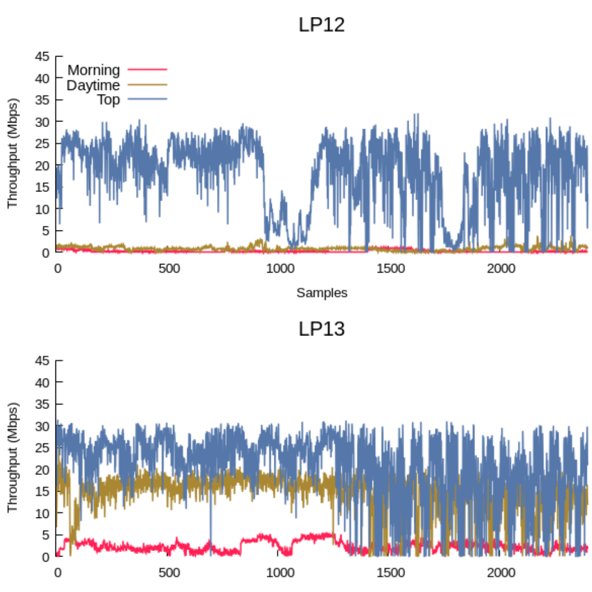


Fig. 12: Downlink throughput at LP12 and LP13.

C. *Impact of crop type*

In order to capture the TVWS channel behaviour for different crop types (corn, soybean), we collect measurements for the pair of location points LP10-LP11 which are located more than 800 m from the TVWS AP.

LP10 is located in a moderately dense corn field with tall corn plants, and LP11 is located in a dense soybean field. They are located at 830 m and 822 m from the TVWS AP, respectively. Figure 13 presents the RSSI of MIMO antennas. As we can notice for Antenna 1, the RSSI gap between Mid and Ground antenna height is of 10 dBm at LP10, much more that the gap between Mid and Ground antenna height at LP11. We also notice for Ground antenna height that the RSSI at LP10 is 10 dBm weaker than the one at LP11. We can infer that the thickness of corn has a negative influence on the radio signal, the attenuation is less important for soybean plants even though they tend to be much more concentrated as the distance along row and the distance between rows is much smaller than that of corn plants. Interestingly, we observe different trends between antennas: Antenna 0 exhibits more fluctuations and a weaker RSSI regardless of the antenna height which highlights the importance of antenna placement. In Table IV we can notice that the RSSI standard deviation is higher at Ground antenna height and that the RSSI standard deviation decreases with antenna height for both LP10 and LP11.

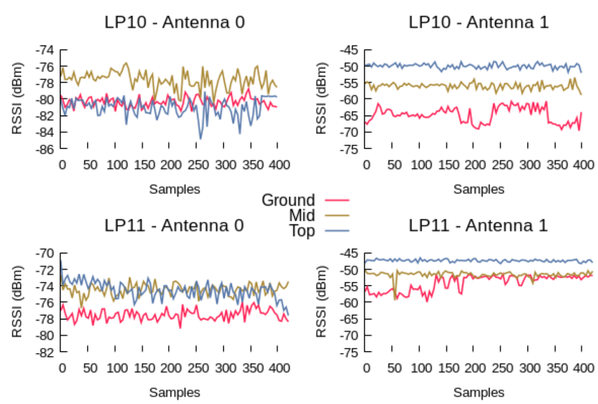


Fig. 13: RSSI of MIMO antennas at LP10 and LP11.

	Antenna 0		Antenna 1	
Antenna height	LP10	LP11	LP10	LP11
Top	1.46	1.94	0.824	0.723
Mid	1.26	2.41	1.13	1.6
Ground	1.48	3.78	2.81	5.81

TABLE IV: Per-antenna RSSI standard deviation at LP10 and LP11.

In Figure 15, it is worth mentioning that the throughput for the corn field at LP10 shows more fluctuations over time than the throughput for the soybean field at LP11. Especially at Top antenna height, we can notice a strong deviation from the mean throughput over time.

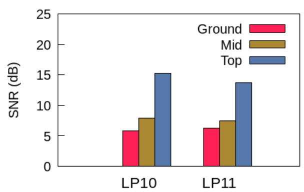


Fig. 14: Average SNR at LP10 and LP11.

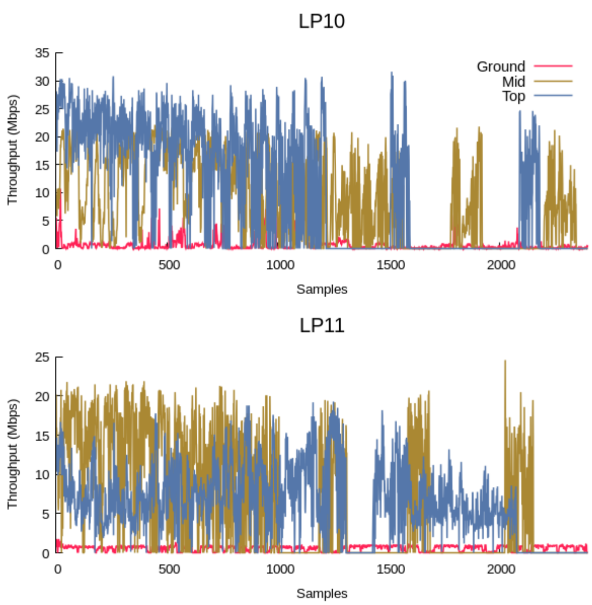


Fig. 15: Downlink throughput at LP10 and LP11.

D. Impact of crop density

Dense vs Sparse corn field (LP4-LP5). To show the impact of corn density on TVWS performance, we select the pair of location points LP4-LP5. They are located at 1.086 km and 1.074 km from the TVWS AP, respectively. LP4 is located inside the field where the density is high. On the other hand LP5 is located in a path in-between two rows of corn plants (i.e.: low density).

Figure 16 shows the per-antenna RSSI of both location points. Even though TVWS has superior penetration characteristics than WiFi, the penetration loss is exacerbated when the signal has to penetrate through the trunks and kernels of mature corn plants. Therefore, due to the high corn density at LP4, the signal was lost when antennas were located close to the ground. At LP4, we notice an important gap of 10 dBm between Ground and Top antenna height for Antenna 1. There is also a 10 dBm difference between LP4 (i.e.:-76 dBm) and LP5 (i.e.:-66 dBm) RSSI at Mid antenna height. The RSSI gap is reduced at Top antenna height where LP4 exhibits an RSSI of -66 dBm and LP5 of -60 dBm. Similarly to LP10-LP11, we witness lower RSSI values for Antenna 0 and a less significant gap between antenna heights.

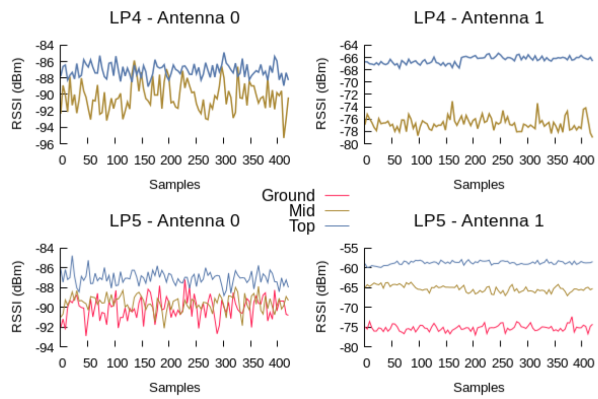


Fig. 16: RSSI of MIMO antennas at LP4 and LP5.

Table V shows once again that the RSSI standard deviation is stronger in the presence of dense vegetation and that it decreases with antenna height.

	Antenna 0		Antenna 1	
Antenna height	LP4	LP5	LP4	LP5
Top	1.48	1.39	0.811	0.681
Mid	2	1.5	1.35	0.978
Ground	N/A	1.55	N/A	1.75

TABLE V: Per-antenna RSSI standard deviation at LP4 and LP5.

SNR results are shown in Figure 17. At top antenna height, LP5 SNR is 2.07 dB higher that the SNR at LP4, and at Mid antenna height it is 3.21 dB higher than the SNR at LP4, confirming the link quality degradation due to high corn density.

	Throughput		Delay		Jitter delay		Packet Loss	
Antenna height	LP4	LP5	LP4	LP5	LP4	LP5	LP4	LP5
Top	12.2 Mbps	20.7 Mbps	1.81 ms	2.10 ms	1.763 ms	0.631 ms	2.7%	7.7%
Mid	0.55 Mbps	13.5 Mbps	16.35 ms	5.63 ms	134.526 ms	11.33 ms	95%	2%
Ground	N/A	0.33 Mbps	N/A	11.57 ms	N/A	105.036 ms	N/A	76%

TABLE VI: LP4-LP5 performance metrics.

The performance metrics collected in Table VI for LP4 and LP5 also reflect the SNR discrepancies. Propagation at LP4 is dominated by scattering, thus the signal amplitude decreases with crop density. Performance measured

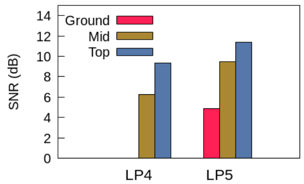


Fig. 17: Average SNR at LP4 and LP5.

at LP4 are on average 41% worse than LP5 due to corn plant penetration. Still, LP4 exhibits a throughput that is sufficient to accommodate video streaming at Top antenna height. The throughput for LP4 and LP5 is shown in Figure 18. At LP4 for Top antenna height, even though the throughput reaches 20 Mbps, it oscillates frequently between 3 Mbps and 20 Mbps. At LP5 on the other hand, the throughput is more stable toward the mean value of 20.7 Mbps.

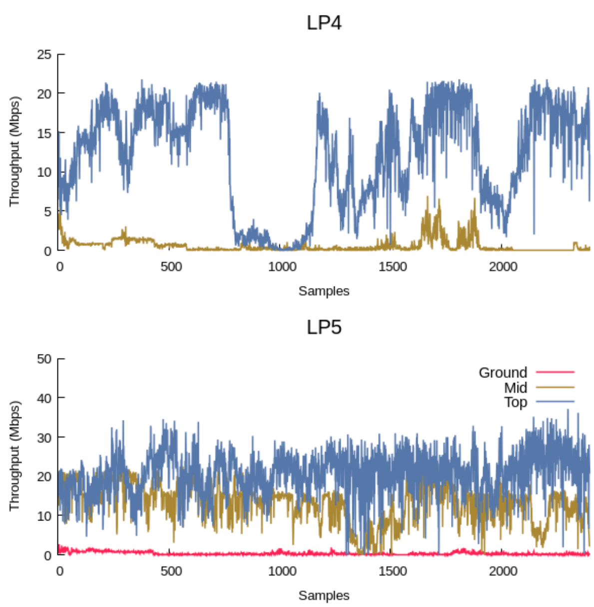


Fig. 18: Downlink throughput at LP4 and LP5. The signal is lost at Ground antenna height for LP4.

Results collected for the pair LP22-LP23 can be found in the technical report [15].

We summarize collected measurements (RSS, RSSI and SNR) in Table VII for each antenna height. The table also includes measurements for distant location points LP2 (corn) and LP3 (soybean).

E. TVWS empirical path loss

Since path loss depends on antenna height, distance, and frequency, we compare the empirical TVWS path

Antenna height: G = Ground, M = Mid, T = Top

	RSS (dBm)			RSSI (dBm)			SNR (dB)		
	G	M	T	G	M	T	G	M	T
LP2	N/A	N/A	-118	N/A	N/A	-52.9	N/A	N/A	11.8
LP3	N/A	-120	-113	N/A	-59.2	-52.8	N/A	1.5	7.33
LP4	N/A	-124	-119	N/A	-58.9	-54.9	N/A	6.27	9.33
LP5	-124	-119	-117	-59.7	-54.7	-52.6	4.84	9.48	11.4
LP10	-118	-117	-114	-56	-54.3	-49.3	5.86	7.95	15.2
LP11	-117	-110	-105	-55.2	-51.2	-45.8	6.22	7.51	13.7
LP12	-124	-123	-117	-60	-59.3	-53.1	4.34	4.55	10.8
LP13	-115	-114	-111	-50.5	-48.6	-46	14.3	17.4	19.5
LP22	-119	-111	-110	-52.8	-46.9	-44.9	13.9	17.1	20.5
LP23	-113	-113	-108	-48.2	-48.4	-44.7	16.1	16.6	19
LP25	-118	-118	-111	-52.8	-52.5	-47.5	12.5	12.6	16.2
LP26	-122	-119	-113	-55.4	-52.4	-45.9	11.1	14.3	21.1

TABLE VII: Average RSS, RSSI and SNR measurements of location points for each antenna height.

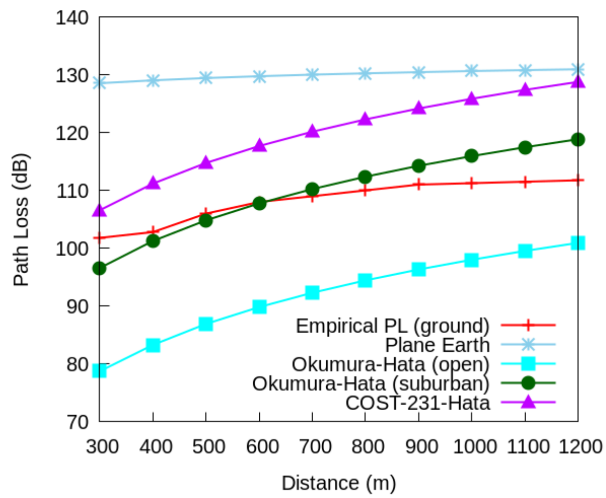


Fig. 19: Empirical path loss (Ground antenna height).

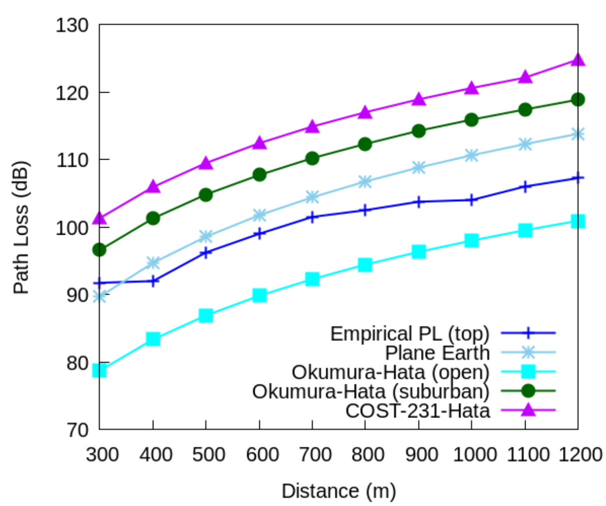


Fig. 20: Empirical path loss (Top antenna height).

loss measured at Curtiss Farm with existing path loss models to see which existing model best predicts the loss of TVWS systems in agricultural settings. We select well-known path loss models typically used in wireless mobile communications such as Plane Earth, Okumura-Hata for open and suburban environments and COST-231-Hata. Compared to the free-space path loss model, the plane earth model includes the effect of ground reflection. Okumura-Hata is a widely used propagation model and its correction factor for suburban environments targets terrains with trees and houses. The COST-231-Hata model is an extension of the Okumura-Hata model and is aimed at urban environments with CPE antenna heights up to 10 m and AP antenna heights between 30 m and 200 m. Figure 19 shows the empirical path loss for Ground antenna height. Since the loss at Ground antenna height is mainly due to ground reflection and vegetation (trunks, kernels, stems) the Okumura-Hata model for suburban environments approximately models the TVWS empirical path loss measured at Curtiss Farm. On the other hand, at Top antenna height (Figure 20), the empirical path loss is better modeled by the Plane Earth model.

V. Conclusion

This paper explored the impact of farm crops on the spatiotemporal behaviour of TVWS channels. We observed that while the SNR is negatively correlated with humidity, noise and RSS are positively correlated with humidity. While humidity can be beneficial to the RSS for long distances beyond 1 km, it can be detrimental to the TVWS performance at short distances if either the TVWS CPE Rx gain or the TVWS AP transmit power are not controlled. Moreover, the per-antenna RSSI standard deviation decreases with antenna height which indicates that the link suffers less from RSSI fluctuations when MIMO antennas are distant from the ground. Notably, crop diversity tends to influence the signal propagation. The thickness of trunks/stems played only a minor role in signal attenuation. However, factors such as crop density and tree foliage depth have a stronger negative impact on TVWS performance than crop trunk thickness.

This measurement campaign also highlights that the antenna height has a positive influence on TVWS performance if the TVWS system lies in a steady-state regime where the received signal is not too strong. Even though fading and scattering affect the TVWS performance, throughput beyond 30 Mbps can be achieved intermittently in harsh agricultural conditions.

Finally, we show that, when MIMO antennas are placed close to the ground, the Okumura-Hata model for suburban environments can be utilize to predict the pass loss of TVWS systems in crop farms, while for 7-feet antenna height the plane earth model is the best candidate to predict the path loss.

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