Exploring Wireless Channels in Rural Areas: A Comprehensive Measurement Study

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***Abstract*—The study of wireless channel behavior has been an active research topic for many years. However, there exists a noticeable scarcity of studies focusing on wireless channel characteristics in rural areas. With the advancement of smart agriculture practices in rural regions, there has been an increasing demand for affordable, high-capacity, and low-latency wireless networks to support various precision agriculture applications such as plant phenotyping, livestock health monitoring, and agricultural automation. To address this research gap, we conducted a channel measurement study on multiple wireless frequency bands at various crop and livestock farms near Ames, Iowa, based on Iowa State University (ISU)'s ARA Wireless Living lab - one of the NSF PAWR platforms. We specifically investigate the impact of weather conditions, humidity, temperature, and farm buildings on wireless channel behavior. The resulting measurement dataset, which will soon be made publicly accessible, represents a valuable resource for researchers interested in wireless channel prediction and optimization.**

I. INTRODUCTION

In recent years, numerous cutting-edge technologies are being integrated into agricultural practices, revolutionizing precision and automation in the field. These advancements heavily rely on the use of cameras, sensors, and unmanned vehicles to optimize agricultural processes. As the demand for employing such devices in agriculture continues to grow, it has become imperative to address the need for efficient wireless communication. To support these devices effectively, a wireless network is required with characteristics such as large-scale coverage, affordability, high capacity, and low latency.

A reliable wireless connection depends not only on advanced hardware and algorithms but also on a thorough understanding of the wireless channel behaviors. Extensive studies have been conducted over several decades to measure and model the behavior of wireless channels, resulting in numerous research papers on the topic. A comprehensive overview of 5G channel measurements and models, can be found in the survey conducted by Wang et al. in [1].

However, it is worth noting that most agricultural areas are located in rural regions, where the wireless channel characteristics may significantly differ from the existing measurements and models primarily conducted in urban and suburban areas. In recent years, wireless sensor networks have gained significant attention in agriculture, leading to numerous studies focusing on measuring wireless channels in various agricultural scenarios. For instance, Jawad et al. derived empirical path loss models in farm fields using drones [2]. Measurements were conducted in apple orchards [3], [4]. Raheemah et al. generated empirical path loss models for greenhouses [5]. Measurements in cornfields were made by Pan et al. [6], while Zhu et al. conducted measurements in a pig breeding farm [7]. However, it should be noted that these studies primarily focused on Zigbee at 2.4 GHz and their path loss models primarily focus on the impact of distances.

As discussed in previous research [8], [9] and further verified in our previous work [10], weather conditions have a significant impact on wireless channels. In our previous study, we measured the wireless channels of TV White Space (TVWS) in a crop farm and found that channel quality varies considerably between morning and mid-day. Unfortunately, due to hardware limitations, we could not collect accurate weather information to establish the quantitative relationship between channel quality and weather conditions. Now, with ARA wireless living lab [11], we have the ability to collect and analyze wireless channel information alongside accurate and comprehensive weather data.

ARA [11] is part of the NSF Platforms for Advanced Wireless Research (PAWR) program. It is an at-scale platform for advanced wireless research deployed across the Iowa State University (ISU) campus, City of Ames, Iowa, USA, surrounding research and producer farms, and rural communities in central Iowa, spanning a rural area with a diameter of over 60 Km. ARA serves as a wireless living lab for smart and connected rural communities, facilitating the research and development of rural-focused wireless technologies that provide affordable, high-capacity connectivity to rural communities and industries such as agriculture.

Leveraging the ARA wireless living lab, we conducted a measurement study between March and June of 2023 to analyze the TVWS and mid-band wireless channels in various crop and livestock farms. Key contributions of this measurement study are summarized below:

- We performed a comprehensive analysis of multi-band wireless channels using wireless channel measurement data collected by ARA BS and UEs and weather data collected by the weather station and the disdrometer. The weather dataset includes information such as rain rate, raindrop size, humidity, and temperature.
- We gathered and analyzed path loss information from different types of building blockages in various crop and livestock farms, which could be valuable for both radio deployments and algorithm designs in the agricultural domain.
- We will make the dataset publicly available that contains time-stamped wireless channel measurements and weather information, including the channel matrix of a MIMO system, which could be beneficial to data-driven wireless communications research.

The rest of this paper is organized as follows. Section II presents an overview of the entire system. Section III discusses in detail the methodology employed in this measurement study. We present and analyze the measurement results in Section IV. Finally, in Section V, we conclude our study by summarizing the key findings.

II. SYSTEM OVERVIEW

Until now, ARA has deployed 4 outdoor base stations (BS) and 13 user equipment (UE) at fixed locations. In this paper, our research focuses specifically on the base station on the rooftop of ISU Wilson Residence Hall, which is surrounded by essential application facilities for ARA. To the south, there are ISU dairy farm, sheep teaching farm, and Curtiss crop farm. On the west side, a few City of Ames facilities and several farms are located, while agricultural vehicle operations can be found on the east side.

A. Base Station

The rooftop base station at Wilson Hall, located approximately 120 ft above the ground, is equipped with a comprehensive array of wireless equipment. This includes 1 Skylark TVWS BS, 3 Ericsson mid-band BSs, 3 Ericsson mmWave BSs, 3 NI N320 Software-defined radios (SDRs), 1 Keysight RF Sensor, 1 weather station, and 1 disdrometer. It consists of three sectors with azimuths of 60, 180, and 300 degrees, and each sector covers 120 degrees. Fig. 1 shows the antenna layout of the northwest sector (an azimuth of 60 degrees).

The Skylark BS is a commercial off-the-shelf (COTS) device designed to operate in the TVWS bands. It comprises one central unit (CU), one distributed unit (DU), and three radio units (RUs). Each RU is equipped with 14 antennas. Skylark supports massive multiple-input multiple-output (MIMO) technology and is poised to support Open-RAN in the future. As a collaborator of ARA, Skylark provides users with access to a portion of its APIs, enabling control and collection of various types of data, and facilitating comprehensive research on whole-stack mMIMO.

In the mid-band frequency range, there are 3 Ericsson AIR6419 BSs operating in the range of 3450 - 3550 MHz. These BSs also support massive MIMO and can support both CSI-RS and SRS beamformings. Additionally, ARA has deployed 3 NI USRP N320 SDRs at the same band. SDRs are programmable transceivers that offer flexible, reconfigurable, and programmable frameworks for various wireless technologies, eliminating the need for hardware updates. In ARA, SDRs are utilized in conjunction with power amplifiers and low-noise filters to enhance signal strength in outdoor environments. As a tradeoff, the working frequency is limited to 3400 - 3800 MHz by these power amplifiers. The SDRs can run the USRP Hardware Driver (UHD) [12] and GNURadio [13], enabling functions such as spectrum monitoring, signal generation and analysis, as well as running the full-stack LTE and 5G using open-source software like srsRAN [14] and OpenAirInterface [15].

B. User Equipment

In the ARA wireless living lab, two types of user equipment (UE) are utilized: fixed-location UE and portable UE. Fixed-location UEs are strategically placed in crop and livestock farms to facilitate agricultural and animal sciences research, while portable UEs are designed to be mounted on various vehicles such as agricultural vehicles, school buses, and fire commander vehicles. In this measurement study, portable UEs are utilized to assess how wireless links are affected by their surrounding environments, e.g. blockage characteristics of various farm buildings.

As depicted in Fig. 2, each UE is housed within a box that consists of a Skylark Customer Premises Equipment (CPE) operating in the TVWS bands, a Quectel UE to communicate with Ericsson BS in both mid-band and mmWave band, and an NI B210 SDR operating in the mid-band. Additionally, each UE box is equipped with a Cradlepoint IBR600C router, enabling remote access and management of the UE devices through the ARA portal [16].

C. Weather Station and Disdrometer

To collect weather information, ARA also deploys weather stations and high-precision disdrometers at base station sites (Fig. 3). These devices enable continuous collection of weather data such as temperature, humidity, rain rate, and raindrop diameter. By correlating weather data with channel measurement results, we could gain a comprehensive understanding of how the environmental variables impact the wireless channel condition. This knowledge serves as a crucial foundation for uninterrupted ultra-reliable low-latency communication (URLLC) under all-day, all-weather conditions.

III. METHODOLOGY

The measurement study took place between March and June of 2023 and was divided into two parts: fixed-location UE measurements and portable UE measurements, each serving different purposes.

A. Fixed-location UE measurements

The primary goal of the fixed-location UE measurements was to collect data to study the impact of weather conditions. Automated scripts were developed and installed on both BS and UE computers for data collection. These scripts allow for the customization of measurement parameters such as starting time, duration, center frequency, and bandwidth. In this paper, we focus our study on Skylark (TVWS band) and Ericsson/Quectel (Mid-band). At the UE side, the scripts were designed to collect the received signal strength only, while on the BS side, the scripts automatically collected throughput, latency, and SNR. Furthermore, the scripts at the BS side initiated the scripts for the UE side to ensure synchronized data collection at both ends.

In the experiments, we mainly used a fixed-location UE in the Curtiss Farm field and the BS on the rooftop of Wilson Hall. The geographical locations of these nodes are shown in Fig. 4, with a line-of-sight (LOS) path of 0.94 miles between them, enabling a reliable connection throughout the entire duration of the experiments. This allows for long-term automated measurements without interruption. Data in the TVWS bands were collected at 2-second intervals, while for the mid-band, the interval was set to 8 seconds.

Previous studies have demonstrated that wireless communications, particularly in higher frequency bands, are susceptible

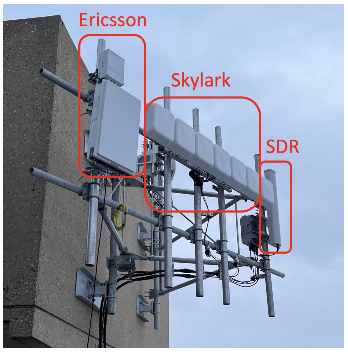

Fig. 1: Antenna layout of the northwest sector.

Fig. 2: An ARA UE box deployed at a fixed location.

Fig. 3: Davis weather station (right) and OTT Parsivel Square disdrometer (left).

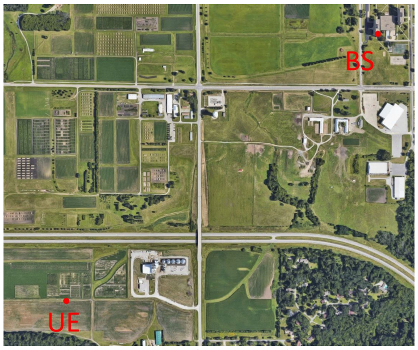

Fig. 4: A line-of-sight path of 0.94 miles between the Wilson Hall BS and a fixed-location UE at the Curtiss Farm field.

Fig. 5: Three farms for portable UE measurements.

to precipitations [9]. In this research, we collected various wireless channel data such as path loss, SNR, throughput, and latency, under different weather conditions and across different frequency bands. Measurements were conducted over several hours to account for varying levels of precipitation. Weather information reported by the weather station and disdrometer was also incorporated to facilitate the study of the impact of different levels of precipitation.

Furthermore, to study the impact of humidity on wireless link quality, as acknowledged in previous studies [10], [17], we also collected data during various time intervals on sunny days. Simultaneously, we recorded humidity data using the weather station.

B. Portable UE measurements

We utilized portable UEs to compare the wireless link performances when UEs are placed at different locations. While there have already been numerous mature channel models available that describe how channel behavior changes with distance, this paper specifically focuses on studying the blockages caused by buildings in farms, which have not been extensively investigated so far. Farm environments consist of different types of buildings with unique structures designed for specific purposes such as crop storage, agricultural machinery storage, and sheep/cattle breeding. These specialized structures cannot be easily modeled using existing models. Therefore, the objective of this section is to fill the gap in knowledge regarding blockages caused by farm buildings.

The portable UE measurement study primarily took place in three farms: Curtiss Farm, Sheep Farm, and Dairy Farm, as shown in Fig. 5. Curtiss Farm is primarily a crop farm cultivating corn and soybeans. Our measurements at Curtiss Farm were divided into three groups, as shown in Fig. 6. Group A involved measuring a barn used for agricultural machinery storage, with a large gate facing north. We conducted measurements at five locations, with an additional reference location, under two conditions: when the gate was open and when it was closed. The five locations consist of one situated to the north of the barn, one positioned to the south of the barn, and three locations inside the barn itself, namely inside-north, inside-middle, and inside-south. The reference location is in the nearby field with a similar distance toward the Wilson Hall BS but a clear LOS path. This is to facilitate the comparison study on the building's impact on wireless links. Group B and Group C focused on measuring the blockage caused by trees and a metal crop storage barn, respectively. Measurements were taken both to the north and south of the trees/barn.

At Sheep Farm, similar to Group A measurements at Curtiss Farm, we placed a portal UE to the north and south of the sheep Farm, as well as three locations inside the building. The fixed-location UE deployed on the rooftop near the north end of the building was used as the reference node.

The measurements at Dairy Farm were also divided into three groups, as depicted in Fig. 7. Group A involved measuring the lactation barn, where cows were bred. Measurements were taken to the north, to the south, and inside the barn. Group B included two hoop houses, one facing west and another facing south. We performed measurements on both hoop houses due to their different orientations. Group C was dedicated to measuring the blockage caused by a large

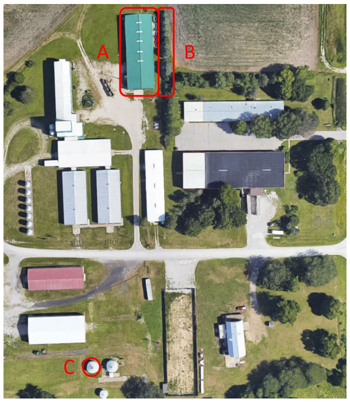

Fig. 6: Three groups of measurements at Curtiss Farm.

hay pile. Although it is not a building, we included this measurement to account for its potential blockage effects, as hay piles are a common source of blockage in farms.

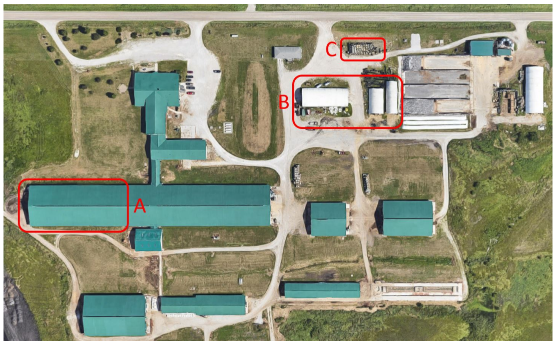

Fig. 7: Three groups of measurements at Diary Farm.

IV. MEASUREMENT RESULTS

In this section, we delve into the analysis of our measurement results. Given the constraints of page length, we have chosen to present a select subset of analyses that highlight the practical value of weather information and the distinctive data regarding the impact of farm buildings. Additional data will be made accessible to the public through the ARA data warehouse.

A. *Impact of Rain*

As mentioned in Section III-A, we utilized a fixed-location UE node at Curtiss Farm to evaluate the impact of various weather conditions, including rain. Among the observed weather events, we focus on analyzing the effects of a single rain event in this paper to isolate the influence of other uncontrollable variables. To gain a better understanding of the impact of rain, we present Fig. 8 and 9 organize the data by dividing the rain rate into five distinct levels. Higher rain rates result in increased path loss. However, even in the presence of the highest rain rate, the received signal strength only experiences a drop of 1.49 dB in the mid-band and 1.09 dB in the TVWS band when compared to no rain.

The ITU-R (International Telecommunication Union - Recommendations) provides a rain attenuation model, P.838-3, in [18], which predicts the attenuation caused by rain based on the rain rate within the frequency range of 1 to 1,000 GHz. The specific attenuation, denoted as γ_R, is determined using a power-law relationship with the rain rate R:

$$\gamma_R = kR^{\alpha}, \tag{1}$$

where coefficients k and α are functions of frequency and can be calculated using equations (2) and (3) provided in [18]. According to this model, the worst-case attenuation caused by rain is estimated to be 0.00226 dB, which is significantly lower than what we have observed from Fig. 8 and 9. One plausible explanation for this substantial attenuation discrepancy is the influence of surface water on the antenna. To gain a deeper understanding of the underlying causes behind this inconsistency, further investigation is warranted. Moreover, there exists potential for the development of a new model designed to account for these variations.

In addition to the rain rate, we also examine the impact of the raindrop size. Fig. 10 shows limited differentiation in both mean and confidence interval for different raindrop diameters, compared to the previous figures. This lack of discrimination could primarily be attributed to the mixing of raindrops with varying diameters in the data. For instance, based on the raw data obtained from the disdrometer, small raindrops (with diameters smaller than 1 mm) are present across all levels of rain rate. Hence, it is not recommended that the raindrop diameter be used as a reliable indicator of the intensity of rain attenuation.

B. *Impact of Humidity*

In our previous study [10], we observed a significant impact of time on path loss, with notable variations between morning and mid-day. While we hypothesized that humidity may be a contributing factor, there was insufficient data to validate this hypothesis. In this study, we collected wireless channel information alongside humidity measurements to investigate further. The results, depicted in Figs. 11 and 12, illustrate the influence of humidity on the TVWS and mid-band signals throughout a clear day. Evidently, humidity exhibits an inverse correlation with received signal strength.

To gain a more profound insight into the impact of humidity, we conducted a thorough analysis, calculating the correlation coefficient. This coefficient serves as a valuable tool for assessing the statistical relationship between these two variables, yielding values that span from -1 to 1. A coefficient of 1 signifies a perfect positive correlation, indicating a direct and proportional relationship between the variables, while -1 denotes a perfect negative or inverse correlation. A correlation coefficient of 0, on the other hand, implies the absence of any linear relationship.

In the measurement results of the rain, the correlation coefficient shows a strong negative correlation (-0.94) between the RSRP and humidity in the mid-band, while the correlation (-0.55) is relatively weaker in TVWS. These observations align with general expectations, as higher frequency bands tend to experience more signal absorption by water vapor when the frequency is lower than 20 GHz.

C. *Impact of Temperature*

Studies, such as [8], [9], believe that temperature is equally important as humidity in affecting wireless channels. In our investigation, we also gathered temperature data to assess its impact. To illustrate our findings, we present the results in Fig. 13 and 14. Both figures demonstrate a positive correlation

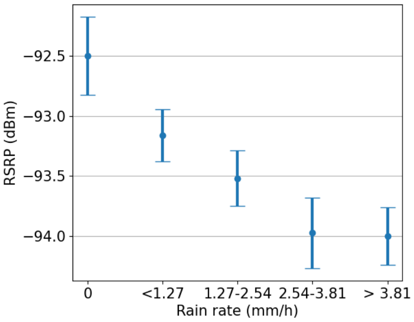

Fig. 8: RSRP vs. rain rate in the mid-band with 95% CI.

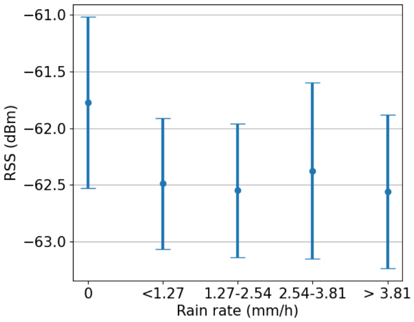

Fig. 9: RSS vs. rain rate in the TVWS band with 95% CI.

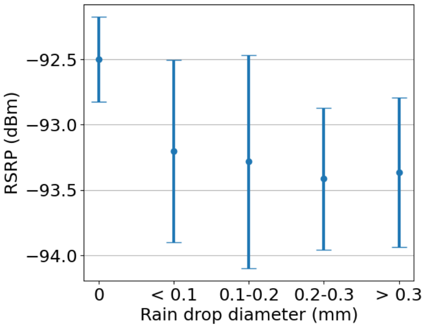

Fig. 10: RSRP vs. raindrop diameter in the mid-band with 95% CI.

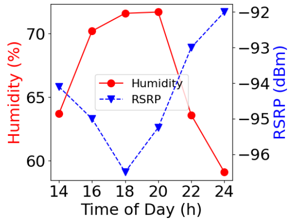

Fig. 11: Humidity and mid-band RSRP over time.

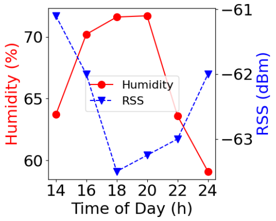

Fig. 12: Humidity and TVWS-band RSS over time.

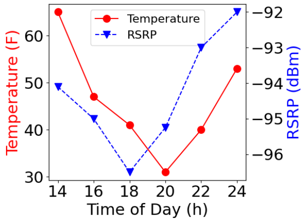

Fig. 13: Temperature and mid-band RSRP over time.

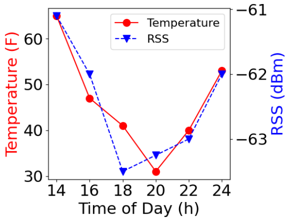

Fig. 14: Temperature and TVWS-band RSS over time.

between temperature and received signal strength. Through correlation coefficient calculations, we found that the TVWS band exhibits a stronger correlation (0.91) with temperature. In contrast, the correlation between temperature and the mid-band is relatively weaker at 0.38. We have not yet found a reasonable explanation for this discrepancy. Considering the insights gained from the humidity analysis in Section IV-B, further investigation is needed to determine whether temperature has a more pronounced impact than humidity in lower frequency bands, while the opposite trend in higher frequency bands.

D. *Impact of Farm Buidlings*

As discussed in Section III-B, all measurement locations are to the south of the Wilson Hall BS. Hence, the signal measurements taken on the north side of the farm buildings were not blocked by any obstacles. In contrast, the signal measurements conducted on the south side of the buildings had to pass through the buildings, resulting in a disparity between the measured signal strengths. This discrepancy can be considered as an additional impact caused by the buildings. Moreover, measurements were conducted inside the buildings to analyze the path loss generated by the walls.

Most of the blockage path loss results are listed in Table I, while Table II specifically presents the results for the agricultural machinery storage building to demonstrate the impact of open and closed gates. To simplify the presentation of the results, the measurements taken on the north side of the buildings were established as the baseline. The tables only display the additional path loss caused by the buildings when compared to the baseline. Moreover, Fig. 15 to 18 includes photos of these buildings, aiding readers in understanding their shapes and structures.

Regarding the findings from Table I, it is observed that hay piles cause significant signal blockage, which is somewhat unexpected. The orientation of the hoop house does not have a substantial impact. However, the orientation of the livestock barn does matter. For effective air circulation, the animal barns should either be transparent in the north-south direction or the east-west direction. The lactation barn, being north-south transparent, exhibits much less blockage compared to the sheep barn, which is east-west transparent.

TABLE I: Additional path loss due to obstruction by various farm buildings.

Blockage Type	**Mid-band**	**TVWS**
Tree	2 dB	2 dB
Metal crop storage barn	7 dB	9 dB
Hoop house (Facing west)	7 dB	6 dB
Hoop house (Facing south)	7 dB	7 dB
Hay pile	12 dB	9 dB
Lactating barn (Outside-north)	0 dB	0 dB
Lactating barn (Inside)	6 dB	10 dB
Lactating barn (Outside-south)	6 dB	> 20 dB
Sheep barn (Outside-north)	0 dB	0 dB
Sheep barn (Inside-north)	9 dB	> 10 dB
Sheep barn (Inside-middle)	18 dB	> 10 dB
Sheep barn (Inside-south)	> 18 dB	> 10 dB
Sheep barn (Outside-south)	> 18 dB	> 10 dB

TABLE II: Additional path loss due to obstruction by the agricultural machinery storage building.

Location	**North gate**	**South gate**	**Mid-band**	**TVWS**
Outside-north	Close	Close	0 dB	0 dB
Outside-north	Open	Close	0 dB	0 dB
Inside-north	Close	Close	19 dB	10 dB
Inside-north	Open	Close	9 dB	5 dB
Inside-middle	Close	Close	18 dB	10 dB
Inside-middle	Open	Close	9 dB	6 dB
Inside-south	Close	Close	24 dB	> 10 dB
Inside-south	Open	Close	17 dB	> 10 dB
Inside-south	Open	Open	16 dB	10 dB
Outside-north	Close	Close	> 24 dB	> 10 dB

Table II presents additional path loss resulting from the obstruction caused by the agricultural machinery storage build-

Fig. 15: Metal crop barn.

Fig. 16: Hoop house.

Fig. 17: Hay pile.

Fig. 18: Storage building.

ing. The table includes measurements conducted with different door configurations, as the building has two large gates facing north and south. Due to the presence of metal plates, the blockage effect is consistently significant, particularly when the north door is closed. However, the data indicates that the openness of the south door can slightly improve the signal quality due to the diffuse reflection of radio waves.

E. Data Set for Future Research

ARA, as a large-scale multi-cell multi-band wireless experimental infrastructure, serves not only as a testbed for rural wireless and applications but also has the potential to play a unique role in providing valuable datasets to support various types of research. For example, one such research area could be AI-related research for channel modeling and channel occupation prediction, where the channel information collected by the MIMO system and RF sensors, along with weather information collected by the weather station and disdrometer, can make significant contributions.

Currently, ARA is in the process of building a data warehouse to store the aforementioned data, and we plan to share it with the public through the ARA portal [16] in the near future. The dataset generated from this measurement study will be included in the data warehouse. It consists of three parts: Skylark TVWS measurements, Ericsson Mid-band measurements, and weather information. All measurements are timestamped, enabling users to seamlessly integrate and analyze the data. Additionally, the data warehouse will also include measurement data that were collected during this measurement study but not yet analyzed and reported in this paper, such as data collected by the Skylark BS with multiple Skylark CPEs under different weather conditions.

V. CONCLUSION

This work investigates the impact of weather conditions and agricultural buildings on TVWS and mid-band wireless channels in rural areas. Our study involved collecting wireless channel data during rainfall and analyzing the impact of rain rate and raindrop size. Our findings revealed that the rain rate has a more significant effect on signal attenuation than the raindrop size. Additionally, we discovered strong correlations between humidity, temperature, and path loss, suggesting a need for further exploration of the relationship between these three factors. Another notable contribution of this paper is the inclusion of path loss data resulting from agricultural buildings, which is an area of research that has only received limited attention so far. Furthermore, all data collected during this measurement study, including weather data, will be publicly accessible through the ARA portal [16]. We anticipate that these datasets of real-world measurement results will prove valuable for estimation, modeling, and algorithm design pertaining to rural wireless channels.

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