

Ambient IoT: Communications Enabling Precision Agriculture

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Abstract—One of the most intriguing 6G vertical markets is precision agriculture, where communications, sensing, control, and robotics technologies are used to improve agricultural outputs and decrease environmental impact. Ambient IoT (A-IoT), which uses a network of devices that harvest ambient energy to enable communications, is expected to play an important role in agricultural use cases due to its low costs, simplicity, and battery-free (or battery-assisted) operation. In this paper, we review the use cases of precision agriculture and discuss the challenges. We discuss how A-IoT can be used for precision agriculture and compare it with other ambient energy source technologies. We also discuss research directions related to both A-IoT and precision agriculture.

Index Terms—Ambient IoT, backscatter communication, precision agriculture, 3GPP, RFID.

I. INTRODUCTION

In recent decades, agriculture has undergone a paradigm shift driven by technological advancements to meet the demands of a growing population. This evolution has given rise to precision agriculture, an innovation that leverages cutting-edge technologies to optimize resource utilization, enhance crop yields, and mitigate environmental impacts. Precision agriculture aims to integrate data-driven decision-making, automation, and advanced sensor technologies to create a more efficient and sustainable agricultural system.

Concurrently, many economic sectors have been significantly changed by the rapid growth of Internet of Things (IoT) devices which offer simplification and lower costs in a wide range of applications. This growth is expected to continue, with potential deployments in agriculture, healthcare and manufacturing markets [1]. In agriculture, the advent of IoT has enabled improved systems for sensing data, communicating, inferring information and making decisions. Currently, standards such as Narrowband IoT (NB-IoT) and enhanced machine-type communication (eMTC), which are based on the 3rd Generation Partnership Project (3GPP), as well as

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LoRaWAN, facilitate communication for IoT devices. However, supporting a high density of IoT devices in rural areas remains challenging with the current wireless infrastructure [2]. Precision agriculture relies on sensor data, GPS-guided machinery, and variable rate technology for optimal crop management. This approach enhances productivity, reduces resource waste, and supports sustainable farming through data-driven decisions. However, achieving this promise requires sensor deployment at high densities and commonly available communications, such as Wi-Fi, are inadequate for vast farm areas. Instead, energy-harvesting devices using ambient sources for power and communication are needed to meet these requirements. Devices that harvest energy from ambient sources such as electromagnetic, solar, and thermal to power and communicate and operate within the 3GPP network are known as Ambient IoT (A-IoT) devices. A-IoT devices can operate with or without a battery and do not require a constant power supply, relying on backscattering to communicate.

Backscatter communications have been around for decades and are used in technologies such as Radio Frequency Identification (RFID) [3] and Wi-Fi backscatter [4]. However, there is little prior work on dense deployments and operations within the existing cellular architecture. Recently, 3GPP has started discussion on A-IoT devices with potential use cases, relevant communication scenarios and topologies of operation for such devices. While there is research looking at the performance of A-IoT devices in conventional use cases, there is very little literature on the application of A-IoT devices in the domain on precision agriculture. We review the feasibility of A-IoT devices for precision agriculture with a link-budget analysis and compare A-IoT to RFID devices. Also, we look at the challenges and potential research directions for A-IoT devices. In this work, we aim to answer several fundamental questions relating precision agriculture and A-IoT:

- What are different use cases of A-IoT in precision agriculture?
- What is backscattering and how does A-IoT interface with existing 3GPP architecture?
- What are the challenges and potential research directions for A-IoT in precision agriculture?

II. PRECISION AGRICULTURE WITH AMBIENT IOT

Precision agriculture uses sensors, GPS, drones, and other technologies to optimize crop management to enhance efficiency, increase yields, and minimize environmental impact. Fig. 1 illustrates a landscape of use cases where precision agriculture benefits significantly from A-IoT devices.

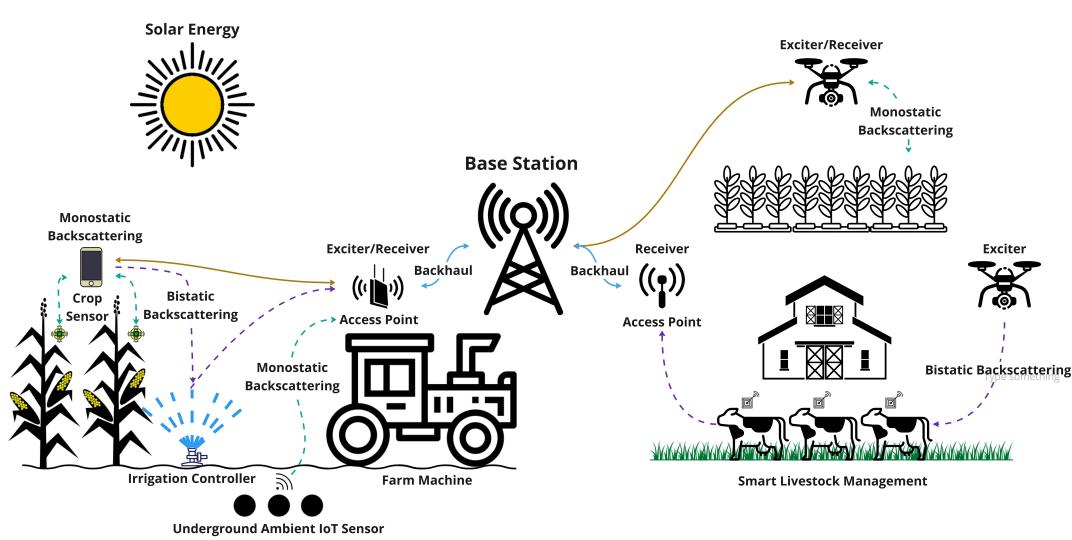


Figure 1. Landscape of A-IoT devices used in Precision Agriculture.

A. Sensing in Precision Agriculture

A-IoT devices can be used in precision agriculture to monitor environmental conditions in farms and greenhouses. These devices can measure parameters such as air temperature, humidity, CO₂ concentration, light, soil temperature, and pH. By monitoring these parameters, predictions can be made about soil health, crop yield, pest management etc. A-IoT devices are ideal for this purpose because they do not require an external power source and are compact. This allows farmers to deploy a large number of sensors in fields to monitor both crops and soil efficiently. Sensors can be placed in open fields, greenhouses with A-IoT devices connected to the network through various discussed topologies.

B. Actuation and Controllers in Precision Agriculture

In agricultural production, various factors such as soil, climate, and water significantly affect crop growth and yield. Agricultural equipment, like pesticide sprayers, fertilizer spreaders and irrigation systems, can be actuated or controlled periodically based on sensor data to ensure optimal yield, and effective crop management. Providing a continuous power supply for these controllers in outdoor farms is a challenge. A-IoT enables seamless communication for these control and actuation devices by harvesting ambient energy and triggering the controllers. This ensures reliable data transmission and remote control capabilities, even in areas with limited infrastructure. Since the controllers operate periodically, the A-IoT precision agricultural controllers can be activated periodically by the farm management system. This integration of A-IoT with the cellular architecture enhances the responsiveness and efficiency of agricultural operations.

C. Underground Soil Sensing in Precision Agriculture

Existing sensors used in precision agriculture are mostly above ground or have antennas above ground. To accurately measure nitrogen levels, soil moisture, and other important metrics, sensors need to be placed underground. Given the

need for dense sensor deployment, it is essential to use devices that are small, low-cost, power-efficient, and biodegradable. A-IoT devices are ideal for this use case due to these characteristics. Communication from A-IoT devices to the network can be facilitated using a mobile relay node on farm machinery such as tractors, sprayers and harvesters. As these machines move across the field, the A-IoT devices become active and send data to the node mounted on the machine.

In corn fields, there is a notable distinction between surface soil moisture and the moisture content deeper underground. Corn plants develop deep roots to access water, emphasizing the need for soil moisture monitoring at multiple depths. Unlike conventional sensors that require periodic removal for data retrieval, underground A-IoT devices offer the advantage of data collection without physical intervention, which is particularly beneficial for crops like corn.

D. Smart Livestock Management

Smart livestock farming employs innovative production systems to enhance sustainability and reduce food waste and crises. Body temperature is a vital health indicator for livestock and is crucial for farmers to identify and act on potential diseases early. Changes in body temperature signify illness, making it a precision health indicator. Importantly, acquiring body temperature data is not latency-intensive, and the increasing herd size necessitates the use of cost-effective ear tags over high-power IoT devices. A-IoT devices are ideal for this application due to their low cost, small form factor and battery-free operation. Cattle and pigs can be equipped with small ear tags that monitor their body temperature and transmit data to the farm.

E. Food Supply Chain

Innovative solutions are essential to tackle food waste and ensure food safety. A controlled environment is crucial for fresh foods, such as vegetables and meat, to maintain their safety and shelf life. An efficient method is needed to monitor every stage of the food supply chain to reduce food waste.

The increasing demand for organically sourced food items also requires a reliable way to guarantee production and processing methods in the food supply chain. Equipping the food supply chain with A-IoT devices in each transport item can address these needs. These devices update relevant information at each stage, from the seed stage to harvesting and packaging facilities. The end user can verify the produce by accessing the data from the A-IoT device. Similarly, suppliers can use these devices to track real-time demand and stock accordingly, reducing food waste. This principle applies at each stage of the food supply chain, decreasing overstocking and waste.

III. BACKSCATTER COMMUNICATIONS

A-IoT devices use backscatter communication, a wireless technique where devices reflect and modulate an incoming radio frequency (RF) signal to transmit data [5]. This method is particularly useful for devices with limited or zero internal power, as it does not require the generation of new RF signals. There are two types of backscatter communication: monostatic and bistatic as seen in Fig. 1.

In a monostatic system, the energy exciter and signal receiver are the same device, whereas in a bistatic system, they are separate devices. At the heart of backscatter communication lies impedance mismatching. Varying the load impedance of an A-IoT device changes its reflection coefficient, affecting the amplitude and phase of the reflected wave. This allows the A-IoT device to perform various modulation techniques, such as amplitude-shift keying (ASK), amplitude modulation (AM), phase-shift keying (PSK), phase modulation (PM), and their combinations via load modulation [5]. The modulation order is proportional to the number of load impedance states in the A-IoT device.

Backscatter communication is widely used in technologies such as RFID, Wi-Fi backscatter, and Bluetooth Low Energy (BLE) backscatter. In RFID, a dedicated RF transceiver emits RF energy towards RFID tags, which reflect the RF signal back to the transceiver, modulated with data. This approach is efficient for inventory management, asset tracking, and access control. While RFID systems are useful, they require dedicated transceivers to enable backscattering for the RFID tags. Further, the reader has to be in close proximity to RFID tags for backscattering, which is a key limitation of RFID technology. In contrast, A-IoT leverages existing ambient RF (cellular or TV) signals for operation, distinguishing it from traditional RFID systems. This adaptability positions A-IoT as an exciting research area that aligns well with established communication infrastructures.

IV. AMBIENT IOT

Ambient IoT devices include both active devices with energy harvesting and passive devices with backscattering. These devices can be used in both monostatic and bistatic configurations depending on the requirements of the use cases.

A. Comparison with existing IoT architectures

A-IoT devices are characterized by ultra-low complexity, compact size, limited capabilities, and an extended lifespan

of approximately a decade. The distinctive features of A-IoT devices further enhance their appeal for various applications. These characteristics sharply contrast with existing low power wide area network (LPWAN) technologies like LoRaWAN, NB-IoT, and eMTC, as seen in Table I. In essence, A-IoT leverages backscattering ambient energy sources, targeting a different class of devices compared to existing IoT devices.

Table I
COMPARISON OF IOT NETWORK ARCHITECTURES

Network Architecture	Max Power	Coverage	Data Rates
LoRaWAN	25mW	10-15km (rural)	0.3-5.5 kbps
NB-IoT	200mW	5-15km (rural)	250 kbps
Active A-IoT	10mW	500 m	5 kbps
Battery-free A-IoT	10 μ W	500 m	5 kbps

B. A-IoT with 3GPP

3GPP has recently started discussions about A-IoT devices and has included them in technical reports (TRs) 38.848 [6] and 22.840 [7]. The specifications of A-IoT in Rel-19 study item are summarized in [8].

The three types of A-IoT devices are battery-less (BL), battery-assisted (BA), and battery and signal-assisted (BSA) devices. BL devices have no energy source and no independent signal generation/amplification, relying solely on backscatter communication. BA devices have an energy source for amplifying the backscattered signal but no independent signal generation. BSA devices have an energy source and independent signal generation, using active RF components for transmission. The major specifications of these devices are listed in Table II.

A-IoT devices are designed to support indoor environments with coverage ranging from 10 to 50 meters and outdoor environments from 50 to 500 meters. The data rate for uplink and downlink transmissions ranges from 0.1 kbps to 5 kbps. Each device can handle message sizes up to 1000 bits for reception and transmission. A-IoT devices support up to 150 devices per 100 square meters indoors and up to 20 devices per 100 square meters outdoors.

3GPP has defined the following network topologies for A-IoT devices to connect to the network via base stations (BSs) and user equipments (UEs). In these topologies, the links may be unidirectional or bidirectional. The following main topologies are considered in recent 3GPP discussions:

- 1) BS \leftrightarrow A-IoT device: Direct, bidirectional communication.
- 2) BS \leftrightarrow intermediate node \leftrightarrow A-IoT device: Bidirectional communication between A-IoT device and the intermediate node (e.g., relay, integrated access and backhaul (IAB) node, UE, repeater).

V. FEASIBILITY STUDY - UNDERGROUND BACKSCATTERING

In this section, we explore the use of backscattering technology for underground soil sensing in precision agriculture. This feasibility study examines the potential of backscattering communication for underground sensing, primarily focusing

Table II
PROPOSED SPECIFICATIONS FOR A-IoT DEVICES

Device Type	Description	Power Consumption	Complexity
Battery-less (BL)	No energy source. Only backscatter communication.	$\leq 10\mu\text{W}$	Comparable to UHF RFID ISO18000-6C (EPC C1G2)
Battery-assisted (BA)	Energy source for amplifying the backscattered signal. No independent signal generation.	Between BL and BSA devices	Between BL and BSA devices
Battery and signal-assisted (BSA)	Has an energy source. Can independently generate signal.	$\leq 10\text{mW}$	Much lower than NB-IoT devices



Figure 2. RFID tags the size of corn seeds planted in the field with a conventional seed planter.

on A-IoT devices, by leveraging UHF RFID field trials. Given the similar device complexities between BL A-IoT and UHF RFID devices, we conducted underground field trials using RFID devices due to their commercial availability. Although our primary focus is on BL A-IoT devices, the comparable technology in RFID allows us to draw relevant insights. We also perform a link budget analysis to compare the underground read ranges of BL A-IoT and RFID technologies.

A. Field Trials - Backscatter Communication for Underground Sensing

To assess the feasibility of A-IoT devices for underground sensing, a high-density deployment of sensors is necessary. Deploying a large number of sensors in agricultural settings presents several challenges. Currently, sensors are manually buried underground, a method that is labor-intensive and time-consuming, especially for large farms. Additionally, the deployment process must minimize disruption to existing crops. The high density required for effective monitoring necessitates innovative deployment practices to reduce labor and time.

In our field trials at Purdue University, we deployed RFID tags underground using a conventional seed planter, as shown in Fig. 2. Using RFID tags comparable in size to corn seeds, we ensured compatibility with existing seed planters without modifications. This automated deployment method significantly reduces labor and time compared to manual deployment, offering benefits to farmers without adding overhead for sensor installation. We planted 288 RFID tags in 12 rows of corn at a depth of 2.5 cm underground and the number of tags were distributed based on the soil moisture levels.

The next challenge after deployment of these sensors is reading the data from these sensors. Unlike traditional sensors that can automatically transmit and receive data, backscattering devices need excitation to activate these sensors for communication. Currently, RFID devices are excited manually for devices deployed in a large area using RFID readers. This is an arduous process to implement for a large farm to read the sensor data. Unlike the wireless channel across air, the wireless channel across soil is harsh. Apart from distance-based loss, there are losses from soil moisture, refraction etc. Thus, reading RFID tags planted underground is much more difficult compared to terrestrial use cases.

In our field trials, we automated the reading process using OATSMobile, a communications platform enabling *connected farms*. OATSMobile, a customized agricultural sprayer (Fig. 3), has six RFID antennas mounted on the machine and an RFID reader (Zebra FX9600) in its cabinet. The antennas were strategically placed to optimize tag detection, with two antennas directed towards each row of corn where the RFID tags were planted. As OATSMobile moves through the farm, it positions the antennas between the rows of corn. In a single pass, it covers four rows, reducing obstruction between antennas and plants. The experiment was conducted at different corn growth stages to observe seasonal effects. Out of 288 planted RFID tags, 152 unique tags were successfully read, resulting in a 53.9% reception success rate. The success rate was influenced by factors such as soil moisture, corn canopy growth, and tag depth. The link-budget analysis in the following section corroborates the impact of soil moisture on the read range of the backscattering devices.

B. Underground Backscattering Link Budget Analysis

We conduct a link budget analysis for both excitation (downlink) and backscattered (uplink) connections of A-IoT and RFID devices placed underground to understand our field trials. This evaluation allows us to compare the read ranges of A-IoT devices with RFID devices. In our analysis, we considered the transmitter and reader above the ground, and the tag, which is either underground.

For tags placed underground, the analysis is complex due to soil channel characteristics. The downlink is an aboveground-to-underground (AG2UG) link and the uplink is an underground-to-aboveground (UG2AG) link. The received tag power is $P_{rx,tag} = P_T G_T G_{tag} L_{AG-UG}(d_1)$ where P_T is the transmitter power, G_T is the transmit antenna gain, G_{tag} is the tag antenna gain, $L_{AG-UG}(d)$ is the AG2UG



Figure 3. OATSMobile - communications platform enabling connected farms. OATSMobile is equipped with an RFID reader and six antennas to read RFID tags placed underground alongside corn plants in a field.

path loss and d_1 is the distance between the transmitter and the tag [9]. Similarly, the backscattered power received in the reader is $P_{rx,read} = P_{rx,tag}G_{tag}G_RMLUG-AG(d_2)$ where G_R is the reader antenna gain, M is the backscatter modulation factor, and $L_{UG-AG}(d)$ is the UG2AG path loss. Both $L_{AG-UG}(d)$ and $L_{UG-AG}(d)$ include aboveground path loss, underground path loss, and refractive loss components [10]. The underground path loss depends on factors such as volumetric water content and soil clay fraction, which alter soil permittivity.

In monostatic cases, $d_1 = d_2$ and $G_T = G_R$ as the exciter and the reader are the same device. In bistatic cases, $d_1 \neq d_2$, and $G_T = G_R$ if the transmitter and reader use the same antenna gain, otherwise $G_T \neq G_R$. For successful communication, the following conditions must be met:

- Received tag power $P_{rx,tag}$ should be exceed the tag activation threshold P_{thr} . Only if this condition is met, the tag wakes up. The distance d_{act} at which $P_{rx,tag} = P_{thr}$ is called the DL distance or activation distance.
- Received backscattered power $P_{rx,read}$ should exceed the reader sensitivity S . The distance d_{read} at which $P_{rx,read} = S$ is named the UL distance or read distance.

The link budget analysis parameters for RFID and A-IoT systems are as follows: the transmitted power (P_T) is 30 dBm for RFID and 24 dBm for A-IoT. The tag threshold power (P_{thr}) is -10 dBm for RFID and -25 dBm for A-IoT, with receiver sensitivities (S) of -75 dBm and -100 dBm, respectively. The modulation factors (M) are 0.33 for OOK in RFID and 0.25 for A-IoT. Both systems share a path loss exponent (γ) of 3, and antenna gains ($G_T = G_R$) of 6 dBi, with a tag gain (G_{tag}) of -1 dB. The transmitter is placed 0.3 meters aboveground, and the volumetric water content (VWC) ranges from 5% to 25%. Based on these parameters, we calculated activation and read distances for both A-IoT and RFID devices and are illustrated in Fig. 4.

Our results demonstrate the superior read range capabilities of A-IoT devices compared to RFID for tags placed underground in monostatic and bistatic configurations. A-IoT tags

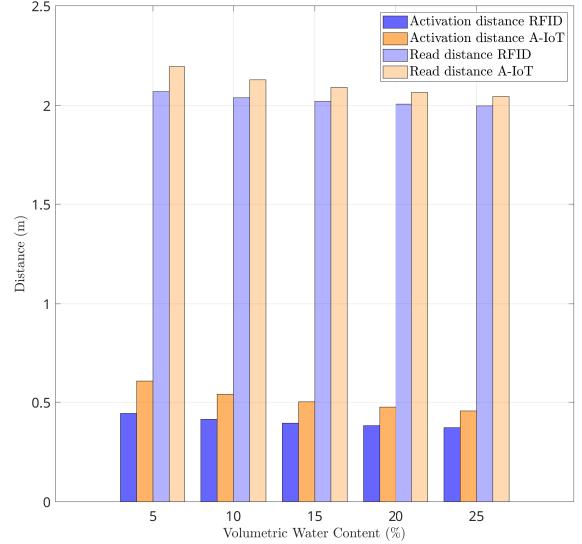


Figure 4. Activation distance and read distance of A-IoT and RFID devices placed underground in both monostatic and bististic configurations. In a monostatic configuration, $d_{act} = d_{read}$ while in a bististic configuration, $d_{act} \neq d_{read}$.

exhibit a higher activation and reading distance than RFID tags, although the activation distance for underground tags is reduced due to higher soil path loss. Additionally, the data shows a decrease in d_{act} and d_{read} with increasing volumetric water content (VWC), indicating higher path loss in wetter soil. These findings suggest that A-IoT technology, with its lower activation threshold and higher sensitivity, is better suited for robust and reliable subterranean soil sensing applications, enhancing underground communication and precision agriculture techniques.

VI. CHALLENGES AND RESEARCH DIRECTIONS

A. Challenges

Ambient IoT faces challenges due to lack of coordination between transmitter and receiver, making it difficult to know the channel state information (CSI). The ambient RF signal can interfere with the receiver, complicating the detection process. While advanced machine learning techniques can improve detection and estimation, the simplicity and battery-free nature of A-IoT devices mean that existing wireless algorithms cannot be applied directly. Therefore, new techniques are needed to overcome these challenges.

1) *Energy Harvesting*: Despite the simplicity, backscattering has many challenges in providing reliable communication for A-IoT devices. Some of the key research problems in backscattering comprise energy efficiency, communication range, network responsiveness etc. The battery-free and ultra-low power operation of backscattering makes it a good technique for A-IoT devices. The ambient RF signals are used for backscattering and typically RF harvesting efficiency is as low as 18.2% [5]. Research could be directed on improving the energy efficiency of backscattering systems for RF signals.

2) Backscatter Signal Detection/Estimation: Unlike traditional communication systems, in a backscatter scheme, transmitting bits ‘1’ and ‘0’ correspond to whether the device is backscattering or not. Since A-IoT devices merely backscatter existing RF signals, it becomes challenging for the reader to detect and estimate the data as it cannot estimate the CSI without pilot symbols [11]. Implementing machine learning (ML)-based techniques is also challenging because the acceptable error rates for detection are much lower than those in traditional ML applications [12]. Therefore, further research is needed in the detection and estimation of ambient backscattering signals, given the lack of coordination between the device and the reader.

3) Security: Security is one of the major aspects in any network. In A-IoT systems, the devices are limited in complexity and therefore cannot employ the complex techniques used in 5G-NR. Also, security in A-IoT systems should be focused in physical layer as devices have minimal upper layer components unlike traditional systems. These devices are very easy to eavesdrop on as they are very similar to RFID systems. We need to ensure authentication and confidentiality over physical layer security. There is a need to develop new security designs and protocols that work in low-complexity devices such as A-IoT devices.

4) Access for Stateless Devices: The challenge lies in communicating with devices that have low or no stored energy and cannot always respond to network paging signals. Current cellular protocols rely on paging mechanisms with Radio Resource Control (RRC) states, assuming devices are always reachable and can initiate paging. However, A-IoT devices lack defined RRC states, making these assumptions invalid and necessitating new access mechanisms.

B. Research Directions

A-IoT presents unique challenges, including lack of coordination between devices and the reader. This section explores potential avenues to improve connectivity and energy efficiency of A-IoT devices.

1) MIMO Backscatter Communications: Multiple-input multiple-output (MIMO) has been a key technology, improving the capacity and reliability of wireless networks. However, its use in backscatter communications has been limited, despite its potential to enhance range, capacity, and reliability. Multi-antenna readers can increase the read range through transmit and receive beamforming, which requires estimating the MIMO backscatter channel. Employing multiple antennas on tags is challenging due to their passive nature.

Several open research problems must be addressed to facilitate MIMO techniques such as beamforming. First, backscatter channel estimation is critical. While acquiring CSI has been widely studied in prior MIMO work, backscatter channel estimation remains unexplored due to its unique cascaded structure with forward and backward channels, complicating the signal model. Initial work for the monostatic scenario exists [13], but bistatic/ambient scenarios remain unexplored. Next, space-time codes can be promising for multi-antenna tag precoding. Passive tags cannot adapt to the channel due to

their nature, but space-time codes (e.g. Alamouti) can achieve diversity gain without explicit CSI. A novel space-time code proposed in [14] outperforms the Alamouti code for multi-antenna tags.

2) Multiple Access / Random Access: A-IoT devices have ultra-low complexity and a large device density. In order to support the large A-IoT device density concurrently, we need state-of-the-art multiple access techniques. Since A-IoT devices have high device density, random access techniques are employed to support high device density. For UHF RFID devices, schemes such as slotted ALOHA, Q-protocol are used for random access. Since BL is of the same complexity as UHF RFID, A-IoT devices could use similar random access techniques. There are research opportunities in finding better multiple access techniques for all devices types in A-IoT.

3) Advanced Modulation Techniques: In backscattering communication, the load impedance of the A-IoT device is varied to modulate the reflected signal to the reader. Currently, simpler modulation schemes such as ASK, PSK are used in backscattering. For larger data rates, we need larger number of load impedance states in order to support higher order modulation schemes with low complexity.

4) Security: A-IoT security should guarantee authentication and confidentiality for every device in the network. Unlike traditional wireless systems, A-IoT devices have lower complexity. Hence, we should focus on physical layer security and algorithms beyond 5G-NR [15]. This is achievable via lightweight authentication protocols such as hash functions etc.

5) Positioning: Positioning A-IoT devices is crucial for various precision agriculture applications, enabling the tracking of farm assets, livestock, and machinery. However, passive A-IoT devices pose challenges since they cannot process received signals, making downlink-based positioning difficult. Instead, localization should be done by the reader, though large inter-site distances in rural networks can hinder positioning due to low signal strength. Moving nodes like tractors and drones can read backscattered signals and locate A-IoT devices in a bistatic/multi-static manner, with location data reported to Location Management Function (LMF). Additionally, A-IoT devices can serve as anchors to help localize other 3GPP nodes, enhancing positioning through triangulation without constructing new Positioning Reference Units (PRUs). This approach is particularly beneficial in rural areas with low 3GPP node density.

VII. CONCLUSION

This work provides an overview of Ambient IoT, a simple, low-cost and battery-free technology with significant potential for precision agriculture. This article explored various use cases of A-IoT in this field, highlighting its advantages over RFID, particularly for underground sensing. Despite promising prospects, several challenges need to be addressed for A-IoT to become a reality. These include the need for multiple access, positioning and efficient multiple access. By exploring these research directions, we can harness the full potential of A-IoT in precision agriculture. This article serves as a comprehensive summary of A-IoT and its promising applications in advancing agricultural practices.

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