Rethinking Sustainable Sensing in Agricultural Internet of Things: From Power Supply Perspective

Ye Liu, Dong Li, Bangsong Du, Lei Shu, and Guangjie Han

***Abstract*—Agricultural Internet of Things (IoT) is expected to address several challenges facing the current agriculture industry, including food production, food safety, ecological environment protection, and food waste. However, before achieving this blueprint, a fundamental problem that should be addressed is the sustainability. Unfortunately, solar energy harvesting, which is today's common approach for sustainable agricultural IoT, has many limitations and can barely support future development. This article bridges this gap by proposing a versatile power supply paradigm, called *PowerEdge*, that organically integrates ambient energy harvesting, distributed energy storage, wireless power transfer, and intelligent reflecting surface techniques to achieve sustainable smart agricultural operations. A proof of concept with commercially available products is also presented, along with extensive experimental studies in five scenarios. Several interesting novel observations are found. Finally, four technical challenges and four open research issues associated with the proposed solution are discussed.**

I. Introduction

The Internet of Things (IoT) is reshaping various industries, including manufacturing, transportation, energy, retail, and healthcare. It is also viewed as an opportunity to fundamentally transform the current agriculture industry [1]. Until now, researchers from academia and industry have explored several key IoT applications for the agricultural domain, such as precision farming, livestock monitoring, smart greenhouses, predictive analytics, and crop management optimization. Related survey works have been summarized in [2], which are helpful to guide readers for more information. These efforts are promoting Agriculture 4.0 - the coming agricultural revolution. By that time, a smart agriculture industry is expected, where the agricultural production process will be intelligent, production pattern will be sustainable, and the agri-food supply chain will be efficient. Thus, the problems facing the current agriculture industry, such as food security, food safety, and food waste, will be resolved.

A. Trends and Challenges

Sensing is the first step in IoT operation processes. It is responsible for digitalizing the physical world by using various types of sensors to measure the environmental properties and convert them into electronic signals that can be distinguished by embedded systems. In agricultural contexts, popular sensing devices used in precision farming applications are field microclimate weather stations, smart cameras, multispectral sensors, electrochemical sensors, and so forth. They enable real-time remote monitoring of crop fields in terms of weather conditions, soil nutrient status, and the health of crop plants. For smart livestock management, the physiological status of animals and their movement trajectories can be remotely monitored on time with the help of sensing devices such as biosensors, microphones, and global navigation satellite systems. At present, sensing in agricultural IoT shows the following four trends:

1) From Simple Environment Monitoring to High-Throughput Plant Phenotyping: Environmental conditions such as pH levels, soil nutrients, and ambient temperatures are the main monitoring objects in traditional smart agriculture studies. In recent years, IoT-based plant phenotyping [3] has been paid significant attention, which aims at accurately expressing the interaction between plant growth, genetic background, and the environment quantitatively using emerging information and communication technologies. Therefore, an agricultural IoT system is expected to fully support high-throughput sensing.

2) From Laboratory Research to Field Experiment: Majority of the agricultural production activities occur outdoors (e.g., farmland and lake). To facilitate the research process, agricultural IoT systems are frequently placed in laboratory environments or deployed temporarily in the field. Today, long-term realistic sensing of plants and animals is desired for an in-depth investigation and practical applications.

3) From Small-Scale Sparse Observation to Large-Scale Precision Measurement: Constrained by the hardware size and maintenance cost, wireless sensor nodes are typically sparsely deployed on a limited scale and they can only monitor a subset of plants, animals, or environmental conditions. In the near future, precision management for each element will not be a dream as the size and cost of IoT devices are drastically reduced.

4) From Coarse-Grained Sampling to Fine-Grained Recording: As environmental conditions in agriculture are relatively stable, a large sampling interval (e.g., one sample per hour) could ensure the quality of service in previous agricultural IoT applications. However, such infrequent data collections can barely satisfy the requirements of plant phenotyping, smart livestock management, and digital twins in agriculture. Hence, there is a need for sensing in a fine-grained manner.

The above trends pose challenges to agricultural IoT. On the one hand, power-hungry sensors [4] will be used frequently to perform phenotyping and livestock monitoring tasks. Fine-

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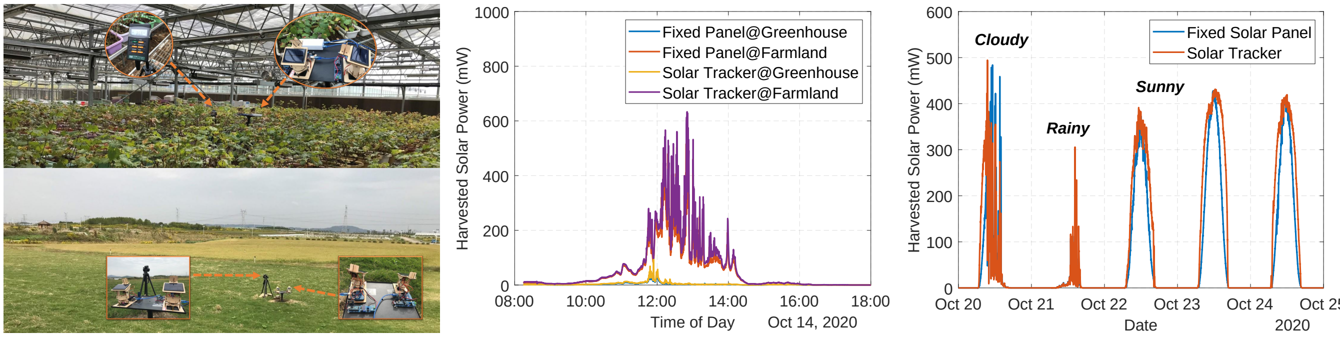


(a) (b) (c)

Fig. 1. Case study of solar energy harvesting in agriculture. The TES-1333R data logging solar power meters were used to measure solar irradiance as a reference. The size of mini solar panels are 80×55 mm. The converted current and voltage were measured using Adafruit INA219 breakout boards. Light tracers were used to demonstrate that the maximum energy can be harvested. (a) Two typical agricultural scenarios: greenhouse and farmland; (b) Corresponding results of harvested solar power; (c) Results at an open field in five days.

grained recording with a high duty cycle will further exacerbate the energy consumption of sensor nodes. On the other hand, when thousands of battery-power sensor nodes are placed in the field for long-term realistic sensing, the maintenance overhead and electronic waste would be outrageous. For these reasons, sustainable sensing is even more vital in agricultural IoT.

B. Today's Approach and Limitations

Over the past decade, ambient energy harvesting has emerged as the most prominent direction toward autonomous sustainable sensing because it can convert external energy from environmental sources (e.g., light, wind, radio waves, and thermoelectrics) into electrical energy, which is then exploited to recharge the sensor nodes. In agricultural IoT, the most widely used sustainable sensing solution is solar energy harvesting. However, several negative lessons are also learned from past practical experience. Along with the case study presented in Fig. 1, we discuss five learned lessons as follows:

1) Intermittency: First, although solar is a renewable energy source, it cannot be harvested at night. Even during the daytime, solar irradiance varies depending on the time of the day, weather, and seasons. Harvested solar power in a cloudy day at the studied scenarios (see Fig. 1(a)) is shown in Fig. 1(b), and the result in five days of this case study can be seen in Fig. 1(c), which includes one cloudy day, one rainy day, and three sunny days.

2) Limited Application Scenarios: Second, because solar irradiance is also location-dependent. The collected energy is less productive in non-line-of-sight (NLOS) environments, not to mention underground and underwater. In this case study, solar irradiance in a greenhouse is naturally much less than that in a farmland due to windows and curtains. This situation becomes worse when indoor solar energy harvesting meets the smart greenhouse curtain system. When the weather got better at noon, the curtain was automatically closed to adjust light exposure reaching the greenhouse. As a result, the harvested power in the greenhouse rapidly decreased to almost zero even though solar irradiance increased.

3) Low Utilization Efficiency: Third, solar power density sometimes is very high, but energy cannot be fully harvested because of limited battery capacity. As a result, the sensor nodes have to either put their best effort into sensing, computing, and data communication or lose the ambient energy. This issue is more serious since small battery-free sensor nodes are typically equipped with MEMS (Micro-Electro-Mechanical System) supercapacitors. In this case study, the cumulative solar energy could be more than 2300 mWh. A large storage capacity is helpful to avoid energy overflow and store energy for later use. However, it implies the need for large supercapacitors and batteries. Therefore, it is challenging to harvest ambient energy as much as possible while minimizing the system size.

4) Tracking or Fixed: The harvested power with and without solar tracking are shown in Fig. 1(b) and Fig. 1(c). Light tracing can help collect more solar energy, especially on sunny days. However, the benefit is low when the original solar irradiance is less, such as on nighttime and rainy days. By taking into account the energy consumption of the light tracing system, the situation would become more evident. Therefore, a context-aware self-adapting algorithm should be implemented. In addition, the threshold for turning round should be set carefully to avoid frequent movements of solar panels or insensitivity.

5) Centralized Power Supply Paradigm: Finally, solar energy harvesting can be considered as a centralized power supply paradigm as the sun is the only energy source. Therefore, it inherits both advantages and disadvantages of a centralized system.

C. Bridging the Gaps in Agricultural IoT

This article aims to overcome the above limitations to bridge the gaps between sensing trends and sustainability issue in agricultural IoT. Unlike previous contributions on this topic that focus on energy harvesting techniques [5], on-demand sensing [6], or battery-free smart objects [7], we consider this problem from the perspective of the power supply paradigm. We propose PowerEdge, a versatile power supply paradigm, which organically integrates emerging techniques such as multi-source energy harvesting, wireless power transfer, and intelligent reflecting surface. It enables many capabilities, including *(i) steady energy supply:* sensor nodes could be active at any time according to application requirements; *(ii) whole scenarios coverage:* it could decouple sensor nodes deployment from renewable energy sources to enlarge the scope of potential agricultural applications; *(iii) high utilization efficiency:* ambient energy could be stored as much as possible, and be consumed on demand without redundant actions.

In the rest of this article, we first present the proposed solution. Following that, we demonstrate a proof-of-concept prototype using commercial off-the-shelf (COTS) products, and evaluate its performance experimentally. Then, a discussion on limitations, technical challenges, and open research issues of the PowerEdge solution is provided. Lastly, concluding remarks are drawn.

II. PowerEdge: A Versatile Power Supply Paradigm

This section first presents the ideological origin of PowerEdge. Then, a detailed description of this power supply paradigm and its advantages are given, respectively.

A. From Cloud Computing to Edge Computing

Cloud computing, from a macroscopic view, is a centralized computing service paradigm that delivers IT (Information Technology) resources to users over the Internet. This is a significant shift from traditional on-premise computing in which infrastructures, platforms, and software applications are hosted locally. Cloud computing brings many benefits in terms of cost savings, elasticity, and productivity. For example, an enterprise does not need to purchase all sorts of hardware, software, and hire staff to maintain these IT resources. Moreover, the capacity of computing power, storage, and bandwidth can be flexibly scaled up and down as required. In addition, the product development cycle could be significantly shortened as a complete development environment is provided.

However, cloud computing comes with limitations when it meets IoT. First, an unprecedented volume of data are generated by massive IoT devices. Transmitting the entire data to the cloud for analysis and storage consumes considerable amount of energy and network bandwidth. Second, the response time is long because the cloud is far away from end IoT devices, which makes it unsuitable for latency-sensitive applications. Third, security and privacy are other great concerns as data are stored in third-party cloud service providers.

To address these issues, edge computing is proposed [8], which is a decentralized computing paradigm deployed between IoT devices and cloud servers. In this context, as edge nodes are also capable of data processing, analysis, and storage, only a part of the data is eventually transported to the cloud. Therefore, electrical energy and network bandwidth are significantly saved. Since edge nodes are close to the IoT devices, the response time can be reduced to milliseconds. Lastly, security and privacy issues are also relieved because the sensitive data can be analyzed and protected at the edge layer locally.

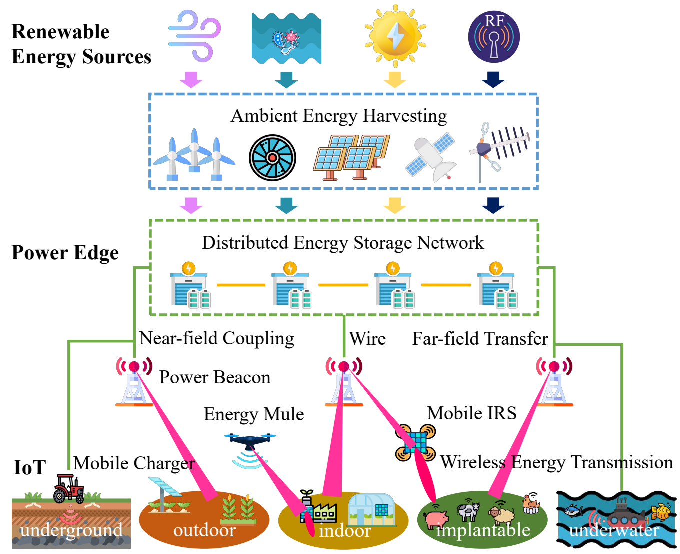


Fig. 2. Vision of edge powering for sustainable IoT in agriculture.

B. From "Cloud" Powering to Edge Powering

The roadmap of data flow is from an on-premise computing, cloud computing, to edge computing. Interestingly, the energy flow is developing along a similar route as the data flow. The traditional battery-powered IoT could be considered as an on-premise powering since the energy is stored on site, and the energy harvesting IoT could be thought of as cloud powering, where energy sources, such as the sun, are the central energy providers. The above observation motivates us to think about two questions: "*Is the next generation of power supply paradigm edge powering, and if so, how does it look*"? We attempt to answer them in this section by presenting our vision and enabling technologies to realize edge powering.

1) Vision: The proposed solution is named PowerEdge. Fig. 2 demonstrates its power supply paradigm consisting of three layers. The first layer is renewable energy sources, which can provide clean and unlimited energy. Solar and wind energy are the most popular renewable energy sources in the air, whereas hydro and tidal energy comes from water flow. In addition, manganese-oxidizing microorganism is another renewable energy source in natural waters. Nowadays, our lives are filled with radio frequency (RF) signals coming from digital TVs, radio broadcasting, and cellular base stations. Therefore, an RF signal is an attractive energy source, especially when the 6G era is imminent. The second layer is the power edge, which should be capable of harvesting renewable energy, storing it to its best capacity, and transferring it to sensing devices via wired or wireless links. The third layer is IoT in agriculture. Here sensing devices could be either equipped with rechargeable batteries or capacitors in a battery-free manner. Moreover, energy transfer should support a variety of agricultural scenarios as these sensing devices are frequently placed underground, in water, or implanted into animals' bodies. Next, we explain the details of our vision of edge powering and show how emerging technologies can support such a power supply paradigm.

2) Ambient Energy Harvesting: The interface connecting the renewable energy sources layer and the power edge layer is ambient energy harvesting techniques through photovoltaic panels, turbines, antennas, and other types of energy harvesters. Unlike existing energy harvesting IoT systems that equip each sensor node with a microenergy harvester, larger ones can be deployed at appropriate positions in the PowerEdge to utmost capture the ambient energy.

3) Distributed Energy Storage: Then, distributed energy storage networks are responsible for storing the captured energy and balancing the remaining capacity globally to ensure continuity, as well as serve as a power supplies for power beacons through wireline connections or wireless links.

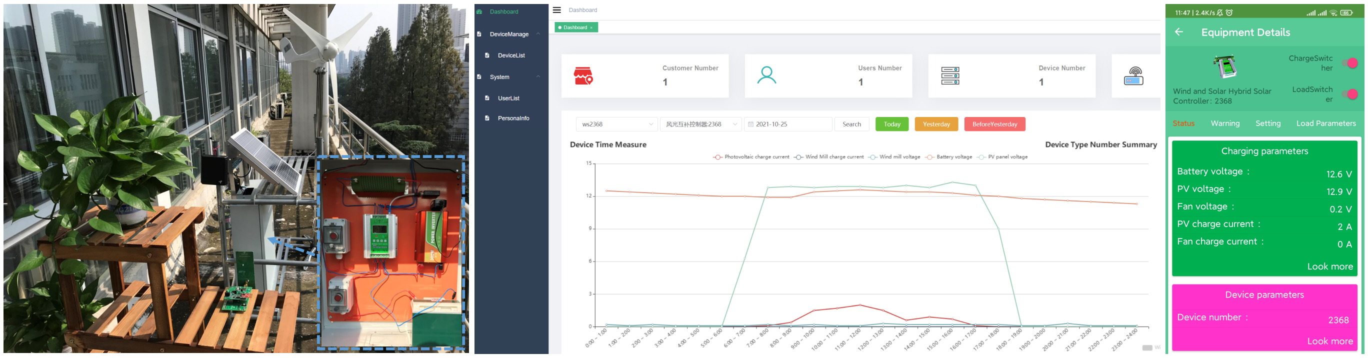
4) Wireless Power Transfer: Power beacons play the role of wireless energy providers for sensing devices and actuators in the IoT layer. Besides the fixed power beacons, unmanned vehicles and robots can serve as energy mules to wirelessly recharge smart devices on demand. Currently, there are different kinds of feasible wireless power transfer technologies. Inductive coupling and magnetic resonant coupling are near-field approaches, which have high power transfer efficiencies greater than 90%, but the charging distance is typically within several centimeters. They are suitable for energy transfer from an energy storage network to power beacons, and from mobile chargers to IoT nodes in the PowerEdge paradigm. Conversely, electromagnetic radiation approaches through RF wave and laser are far-field technologies for long-range wireless power transmission. They are suitable for charging IoT nodes from fixed power beacons in the PowerEdge paradigm. A comprehensive survey on wireless power transfer technologies is presented in [9], which provides an in-depth discussion on the development history, working principles, and leading international standards. In addition, the network applications reviewed in it are valuable to the deployment of PowerEdge.

5) Intelligent Reflecting Surfaces (IRS): The IRS, also called reconfigurable intelligent surfaces (RIS), is considered an enabler for 6G systems. With the help of an array of inexpensive radiating elements, such as patch antennas with tunable switches, the IRS/RIS can actively control the propagation of wireless signals by adjusting the quantized phase shift [10] in a programmable manner, thereby unfavorable signal reflection, refraction, and absorption can be avoided. This emerging technology would also be a key element for edge powering to enhance the capability of far-field wireless power transfer in PowerEdge in terms of charging efficiency and coverage area. By taking an example of outdoor livestock management where these intelligent surfaces are placed on a farm. The position information of animals on the farm is reported to power beacons as needed. Then, simultaneous wireless information and power transfer are performed between the power beacons and the IRS/RIS controllers, which can then perform beamforming with a higher charging power in the exact direction of the animals. In addition, the energy coverage area can be enlarged by attaching the intelligent surfaces on unmanned vehicles, as these mobile IRS/RISs could relay energy at suitable places. More information about IRS/RIS can be found in [11], which provides a discussion on its principles, potential applications, and research directions.

C. The Advantages of Edge Powering

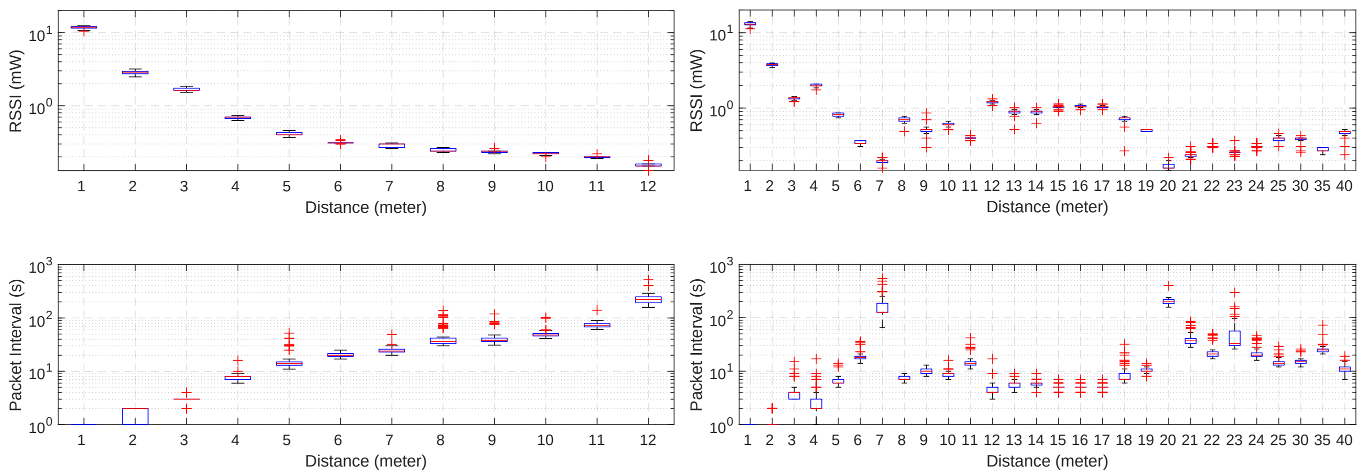
Similar to edge computing in a data flow, the proposed edge powering in energy flow will bring many benefits for a sustainable IoT. We discuss them from the following aspects:

- *Multi-Source Energy Harvesting:* Current energy harvesting IoT systems are typically equipped with single or two energy harvesters based on the target application scenarios. Unfortunately, relying on a single ambient energy source frequently results in intermittency, which causes sensor nodes in IoT networks to break off. Edge powering decouples the ambient energy sources and application scenarios, so smart devices can rely on various renewable energy sources.
- *Steady Energy Supply:* Edge powering also decouples energy harvesters and energy storage from IoT end devices. Hence, the deployment of energy harvesters and their size are adaptable. In addition, the issue of limited battery capacity in current energy harvesting IoT systems could be solved, because distributed energy storage networks can maximize the harvested energy for later use.
- *On-demand Energy Utilization:* In this power supply paradigm, the use of energy is actively dominated by application requirements rather than passively adjusting work tasks according to the available ambient energy. The charging action of power beacons could be either triggered by users at the cloud or end sensor nodes and actuators in a request-then-charge mode.
- *Diversified Scenarios Support:* Indoor energy harvesting will not be a problem in edge powering as power beacons could be elaborately deployed at suitable locations. Energy coverage outdoors can be improved with the help of energy mules, mobile chargers, and IRS/RISs. Owing to good transmission medium adaptability and developed wireless power transfer technologies, edge powering is also feasible in the underground, underwater, and implantable application scenarios, such as soil nutrient analysis, smart fisheries management, and livestock health monitoring.
- *Backscatter Communication:* Ambient backscatter [12] is a low-power wireless communication primitive enabling IoT devices to transmit data leveraging ambient RF signals as carriers rather than actively generating carrier signals, by working on the frequency-shift based semi-passive mode or hybrid active and passive mode [13]. The wireless energy waves in edge powering can be exploited as ambient backscatter sources to reduce the energy consumption.
- *Ubiquitous Wireless Sensing:* Finally, wireless sensing is a promising direction to achieve contactless and sensorless monitoring [14]. Many such systems have been developed for event detection, human activity recognition, and indoor localization. Recently, researchers have been exploring the application of wireless sensing technologies in agriculture. For instance, it has been reported that WiFi and RFID systems can measure soil moisture. Therefore, edge powering is conducive to the development of ubiquitous wireless sensing in agriculture.



(a) (b) (c)

Fig. 3. Demonstration of minimal PowerEdge system. (a) Proof of concept with COTS products; (b) Snapshot of PC client; (c) Snapshot of mobile APP.



(a) (b)

Fig. 4. Evaluation of wireless power transfer using COTS Powercast system in line-of-sight scenarios. (a) Results in an open field; (b) Results in a hallway. RSSI is the abbreviation of received signal strength indicator.

III. Proof of Concept

This section presents a minimal system of PowerEdge and its quality of service by experimental studies.

A. Building Minimal System

As shown in Fig. 3(a), the components of the demonstrated PowerEdge system include the following: a 12V30W solar panel (\$16), a 12V100W wind turbine (\$73), a wind solar hybrid controller (\$94), a 12V-to-220V power inverter (\$40), a 12V20AH battery (\$31), two switches (\$8), a remote monitoring module (\$19), and a Powercast TX91501B power transmitter (\$280).

First, renewable solar and wind power are captured by the solar panel and wind turbine, respectively. The energy is then stored in a battery through a wind-solar hybrid controller. After that, the power inverter is responsible for converting the 12 V direct current (DC) voltage into 220 V alternating current (AC) voltage to power the TX91501B transmitter. It generates 915 MHz radio waves to wirelessly transfer energy to a battery-free sensor node that is equipped with a patch antenna and Powercast P2110 evaluation board. Lastly, when the sensor node is activated, it senses environmental conditions and transmits the data to an access point. Meanwhile, the WiFi-based remote monitoring module periodically reports system status information to the cloud. Users can check it on PC client and mobile APP, as shown in Fig. 3(b) and Fig. 3(c). The battery voltage only decreased from 12.5 V to 11.3 V, which is higher than the minimum operating voltage (10.5 V) of the power inverter, even though the power transmitter worked continuously for 24 hours.

B. Performance Evaluation

The above demonstration proves the feasibility of PowerEdge for sustainable sensing. However, we still do not know its performance in a real agricultural environment. The two fundamental questions are: *(i) How far can the Powercast system support wireless power transfer? (ii) Can the report cycle meet the application requirements?* To answer them, the following experiments were conducted.

a) Line-of-Sight: We first evaluated its performance in an open field to understand the maximum distance within which it can function. As shown in Fig. 4, a packet was received approximately every four minutes from battery-free sensor node when the TX91501B power transmitter was placed 12

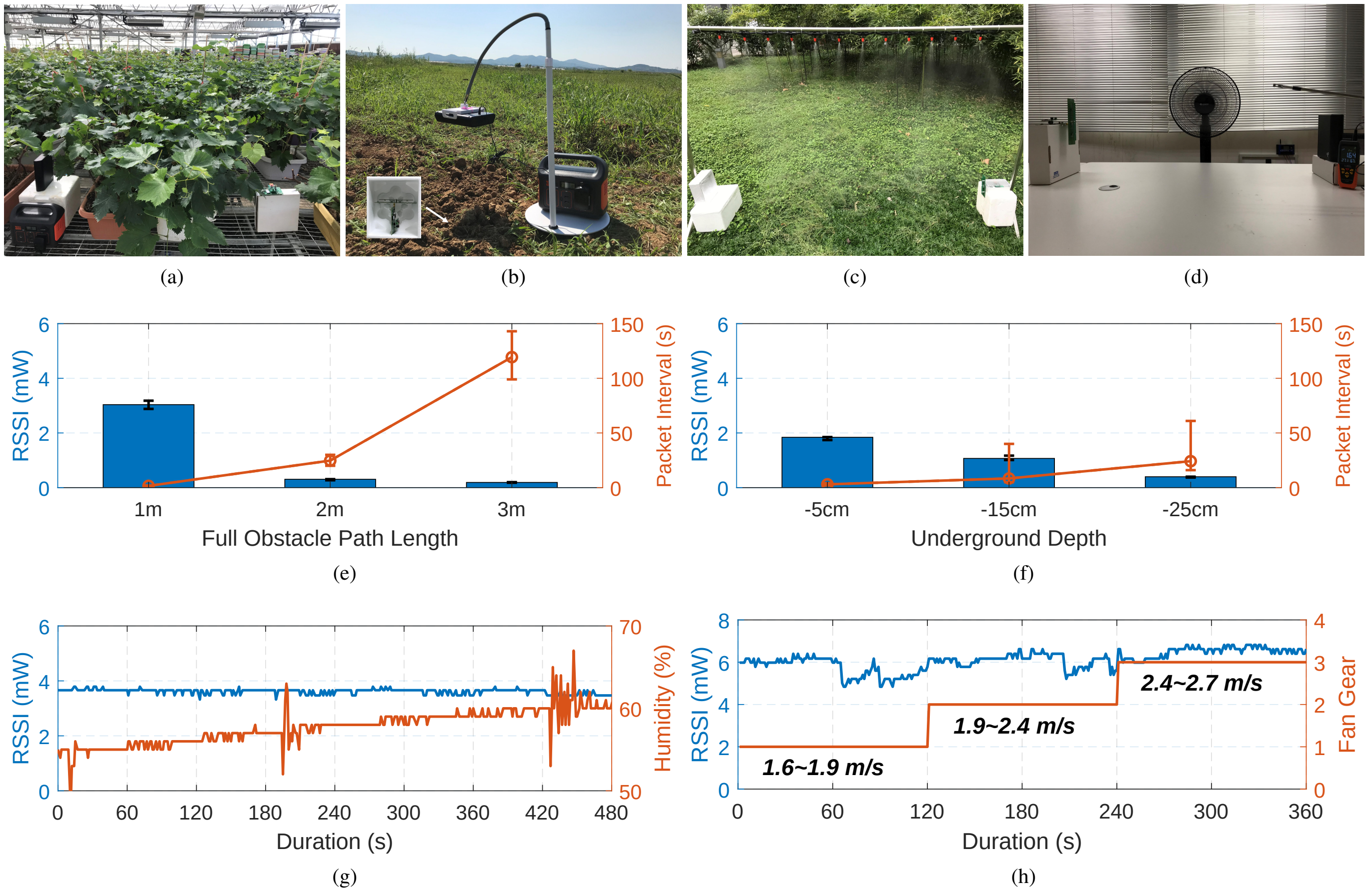


Fig. 5. Evaluation of wireless power transfer using COTS Powercast system under different environmental conditions. (a) Plants are the obstacles between the TX91501B power transmitter and battery-free sensor node with a patch antenna; (b) Underground scenario, where the soil is the medium of wireless power transfer; (c) Irrigation affecting the microclimate; (d) Fan operation affecting the microclimate; (e)-(h) The corresponding experimental results.

meters away. The results match with the official documentation and previous research studies. Generally, the multipath effect affects wireless communications, and we speculate that it will also impact wireless power transfer. Therefore, we additionally conducted the test in a hallway, where power waves were reflected by the wall. Surprisingly, the battery-free sensor node could function even when it was 40 meters away from the power transmitter, and the packet interval was approximately 11 seconds. As the total length of the hallway is 41 meters, we did not conduct more tests, but we believe the maximum distance the system can achieve would be far more than 40 meters in this scenario. To the best of our knowledge, these observations are novel.

b) Non-Line-of-Sight: In an agricultural environment, plants are common obstacles that limit the ability of wireless power transfer. Hence, we evaluated its performance in an extreme NLOS circumstance, where the power transfer path was filled with plants, as shown in Fig. 5(a). The results in Fig. 5(e) show that the system could work at three meters, and the corresponding average packet interval was 119 seconds. This can satisfy many agricultural scenarios. For example, the inner height of a greenhouse is frequently less than four meters.

c) Underground: We conducted tests to understand if the proposed PowerEdge paradigm is feasible in an underground situation. To protect the sensor node, it was packed in a foam box, as shown in Fig. 5(b). The results in Fig. 5(f) demonstrate that the system can work underground, and the packet intervals in all tests (-5 cm, -15 cm, and -25 cm) were significantly less than 100 seconds. We also conducted experiments at the -30 cm underground condition, but no packet was received. Thus, the available power transfer distance should be between -25 cm and -30 cm.

d) Microclimate: A typical agricultural IoT application is automatic irrigation, where a microclimate with higher humidity is typically formed in the target area. In addition, the operation of facilities in an agricultural factory, such as fans, also changes the weather. Therefore, we conducted tests, as presented in Fig. 5(c) and Fig. 5(d), to investigate the impact of microclimates on wireless power transfer. The results in Fig. 5(g) and Fig. 5(h) show that there was no significant fluctuation on RSSI when the relative humidity and wind speed increased.

e) Weather Conditions: Finally, it is crucial to investigate the effectiveness of wireless power transfer in different weather conditions because several agricultural production activities occur outdoors. During the 74-hour outdoor deployment, which included sunny, light rain, and cloudy conditions, a total of 82,367 packets were received. The results in Fig. 6 demonstrate that PowerEdge is robust to weather changes.

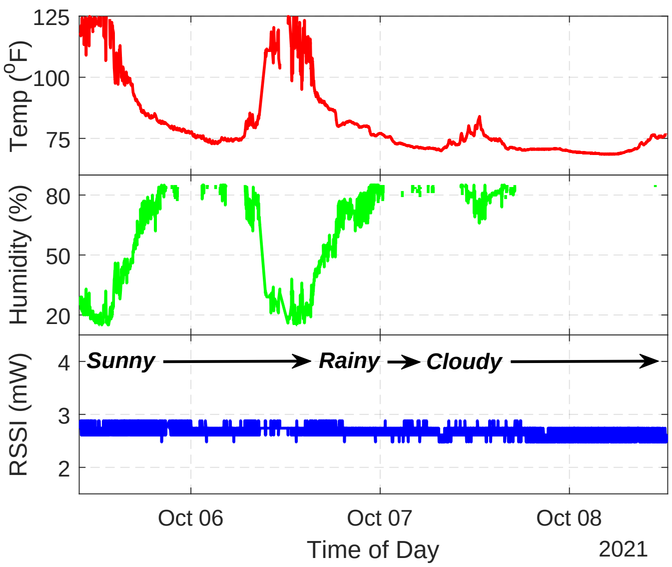


Fig. 6. Evaluation of weather impact on wireless power transfer in a 74-hour outdoor deployment. The available measurement range of the used temperature sensor is between 25 ^{o}F and 125 ^{o}F, and the humidity sensor is between 15% and 85%.

IV. Discussion

A. Limitations and Technical Challenges

We discuss the limitations and technical challenges of the proposed PowerEdge solution from the following aspects:

1) Energy Efficiency: The efficiency of PowerEdge depends on the energy harvesting efficiency and power transfer efficiency. However, they are not yet satisfactory. At present, the solar panel efficiency is still below 25% and wind turbines should be less than 59% efficient. The RF-to-DC conversion efficiency of a leading commercial chip is approximately 52%. Therefore, the technical challenge behind this limitation is to explore novel materials and circuit design for high efficiency of ambient energy harvesting and wireless power transfer.

2) Charging Distance: A fundamental research issue of wireless power transfer is to increase the charging distance. As demonstrated in the performance evaluation, the leading TX91501B power transmitter can only reach a charging distance of 12 meters in an open field, which is far less from practical applications in large outdoor farms. One of the corresponding technical challenges is to improve the sensitivity of the ultra-low-power DC-DC boost charger module.

3) Antenna Size: Patch and dipole antennas are commonly used for wireless power transfer. However, they are relatively large and hinder the miniaturization of RF-powered IoT devices. Therefore, reducing the size of the antenna is vital for practical applications of PowerEdge.

4) Cost Implication: Compared with separate ambient energy harvesting IoT, the proposed edge powering solution brings more deployment costs, especially large energy harvesters and wireless power transmitters. Fortunately, existing infrastructure, such as solar farms and 5G micro-stations, could be exploited to capture ambient green energy and transfer it over the air.

B. Open Research Issues

Although we have shown the effectiveness of the PowerEdge solution, comprehensive studies are required in the deployment of PowerEdge for sustainable agricultural IoT. Four open research issues are highlighted as follows:

1) Plant and Livestock Growth with Electromagnetic Exposure: Although the international standard for safety guide concerning human exposure to electromagnetic fields (e.g., IEEE C95.1-2019) has been established, the impacts of wireless power transfer on the growth of plants and livestock are still incompletely understood. Therefore, it must be thoroughly studied.

2) Energy Interference in Multi-Charger Dense Sensor Networks: As IoT-based plant phenotyping features dense sensor networks, another open issue is to investigate how constructive and destructive interference affect wireless power transfer in both multi-charger simultaneous power transfer and multi-receiver situations.

3) Application-Dependent System Modeling and Networking: Indoor arrangements of greenhouses and plant factories are different, leading to different spatial energy distributions due to the multipath effect and signal attenuation. Therefore, system modeling is application-dependent and thus affects the deployment of power transmitters and sensing devices, charging scheduling strategies, as well as medium access control and routing protocols.

4) IRS/RIS-Aided Wireless Power Transfer: Most recent works on IRS/RIS focus on IRS/RIS-aided 6G wireless communications, it is also promising to enhance wireless transfer for the proposed edge powering solution in terms of energy efficiency and charging distance. Channel modeling and design of low-cost high precision intelligent surface [15] are two research directions to be studied.

V. Conclusion

In this article, four trends in agricultural IoT regarding high-throughput plant phenotyping, desire for a field study, large-scale precision measurement, and fine-grained recording are first presented. As they would exacerbate the issue of sustainable sensing in agricultural IoT, five limitations of solar energy harvesting technique are discussed in terms of intermittency, limited application scenarios, low utilization efficiency, solar tracking, and centralized power supply paradigm. To bridge this gap between future sensing requirements and sustainability, the concept of edge powering is proposed, along with detailed explanation of how emerging technologies support this concept. In addition, the advantages that edge powering can provide are discussed.

To prove its feasibility, a minimal system of the proposed edge powering solution is developed using COTS components. Furthermore, performance evaluations are conducted experimentally to investigate the impact of environmental conditions, namely, multipath, obstacle, underground, microclimate, and weather, on the received signal strength and packet interval. Finally, the limitations and technical challenges of the proposed edge powering solution are highlighted from the perspectives of energy efficiency, charging distance, antenna size, and cost implication, opening new doors for future research.

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REFERENCES

[1] J. Ruan, H. Jiang, C. Zhu, X. Hu, Y. Shi, T. Liu, W. Rao, and F. T. S. Chan, "Agriculture IoT: Emerging trends, cooperation networks, and outlook," *IEEE Wireless Communications*, vol. 26, no. 6, pp. 56–63, 2019.

[2] Y. Liu, X. Ma, L. Shu, G. P. Hancke, and A. M. Abu-Mahfouz, "From industry 4.0 to agriculture 4.0: Current status, enabling technologies, and research challenges," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 6, pp. 4322–4334, 2021.

[3] P. Neveu, A. Tireau, N. Hilgert, V. Nègre, J. Mineau-Cesari, N. Brichet, R. Chapuis, I. Sanchez, C. Pommier, B. Charnomordic, F. Tardieu, and L. Cabrera-Bosquet, "Dealing with multi-source and multi-scale information in plant phenomics: the ontology-driven phenotyping hybrid information system," *New Phytologist*, vol. 221, no. 1, pp. 588–601, 2019.

[4] T. Roitsch, L. Cabrera-Bosquet, A. Fournier, K. Ghamkhar, J. Jiménez-Berni, F. Pinto, and E. S. Ober, "Review: New sensors and data-driven approaches—a path to next generation phenomics," *Plant Science*, vol. 282, pp. 2–10, 2019.

[5] J. Huang, Y. Zhou, Z. Ning, and H. Gharavi, "Wireless power transfer and energy harvesting: Current status and future prospects," *IEEE Wireless Communications*, vol. 26, no. 4, pp. 163–169, 2019.

[6] Y. Liu, Q. Chen, G. Liu, H. Liu, and Q. Yang, "Ecosense: A hardware approach to on-demand sensing in the Internet of Things," *IEEE Communications Magazine*, vol. 54, no. 12, pp. 37–43, 2016.

[7] G. Maselli, M. Pietrogiacomi, M. Piva, and J. A. Stankovic, "Battery-free smart objects based on RFID backscattering," *IEEE Internet of Things Magazine*, vol. 2, no. 3, pp. 32–36, 2019.

[8] L. U. Khan, I. Yaqoob, N. H. Tran, S. M. A. Kazmi, T. N. Dang, and C. S. Hong, "Edge-computing-enabled smart cities: A comprehensive survey," *IEEE Internet of Things Journal*, vol. 7, no. 10, pp. 10 200–10 232, 2020.

[9] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless charging technologies: Fundamentals, standards, and network applications," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1413–1452, 2016.

[10] D. Li, "Ergodic capacity of intelligent reflecting surface-assisted communication systems with phase errors," *IEEE Communications Letters*, vol. 24, no. 8, pp. 1646–1650, 2020.

[11] C. Pan, H. Ren, K. Wang, J. F. Kolb, M. Elkashlan, M. Chen, M. Di Renzo, Y. Hao, J. Wang, A. L. Swindlehurst, X. You, and L. Hanzo, "Reconfigurable intelligent surfaces for 6G systems: Principles, applications, and research directions," *IEEE Communications Magazine*, vol. 59, no. 6, pp. 14–20, 2021.

[12] N. Van Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, "Ambient backscatter communications: A contemporary survey," *IEEE Communications Survey & Tutorials*, vol. 20, no. 4, pp. 2889–2922, 2018.

[13] D. Li, "Two birds with one stone: Exploiting decode-and-forward relaying for opportunistic ambient backscattering," *IEEE Transactions on Communications*, vol. 68, no. 3, pp. 1405–1416, 2020.

[14] C. Li, Z. Cao, and Y. Liu, "Deep AI enabled ubiquitous wireless sensing: A survey," *ACM Comput. Surv.*, vol. 54, no. 2, Mar. 2021.

[15] O. L. A. López, H. Alves, R. D. Souza, S. Montejo-Sánchez, E. M. G. Fernández, and M. Latva-Aho, "Massive wireless energy transfer: Enabling sustainable IoT toward 6G era," *IEEE Internet of Things Journal*, vol. 8, no. 11, pp. 8816–8835, 2021.

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