Understanding the Impact of Environmental Conditions on Zero-Power Internet of Things: An Experimental Evaluation

Ye Liu, Dong Li, Haipeng Dai, Chunguo Li, and Rui Zhang

***Abstract*—The booming Internet of Things is transforming all industries, making them more productive and efficient. Unfortunately, with its widespread use, a series of challenges are posed by sustainable sensing, harsh working environments, laboursome battery replacement, and the requirement for an ultra-small form factor. The concept of zero-power Internet of Things has recently been proposed to overcome these challenges by integrating far-field wireless power transfer, ambient energy harvesting, and backscatter wireless communications into networked embedded systems. However, the development of far-field wireless power transfer is still in its infancy, and how environmental conditions affect its performance in the real world remains unclear. This article fills this gap and provides an extensive experimental study to quantify the impact of environmental conditions, namely, line-of-sight propagation, multipath interference, building materials, and non-air mediums on far-field wireless power transfer. Inspired by this study, we further shed light on some future research directions.**

I. INTRODUCTION

The rapidly evolving Internet of Things (IoT) ecosystem presents several trends. First, the quantity of IoT devices worldwide will dramatically increase from millions to billions. Second, its working environment is from general conditions to complex situations. These devices not only are deployed in favorable scenarios, but also will be more exposed to harsh environments when applying IoT to transportation, marine, or agriculture fields. Third, the device dimension is from size tolerance to specific dimensional requirements since they are desired to be embedded in bodies, plants, and other goods.

The above trends pose a series of challenges. Sustainable sensing is the most significant one, as the explosion of IoT devices will lead to massive energy consumption. In addition, harsh working environments result in battery performance instability due to its physical and chemical characteristics. Moreover, frequent battery replacement for the massive IoT devices causes an unimaginable maintenance burden, not to mention that in hazardous and hard-to-reach situations. Last, it is challenging when IoT meets emerging applications that need ultra-small form factor smart devices.

To overcome these challenges, the concept of zero-power Internet of Things (ZP-IoT) has drawn much attention in recent days. For example, Ericsson and MIT teamed up to investigate the 6G network with zero-energy devices. Orange S.A. demonstrated their crowd-detectable zero-energy device. OPPO released a white paper on zero-power communication. All of these efforts raise hope for a future where IoT devices can operate in a battery-free manner through harvesting energy from surroundings and exploring ambient radio-frequency waves for ultra-low power backscatter communication.

Far-field wireless power transfer (WPT) [1] is considered a key technology for the realization of ZP-IoT as it can offer many advantages. First, it is feasible to achieve a sustainable energy supply for the massive IoT devices in the edge powering paradigm [2]. Second, benefiting from contact-free power recharging, the maintenance of IoT systems could be significantly simplified. Third, dedicated wireless power signals could provide additional mediums for backscatter communication [3] and wireless sensing. Research on far-field WPT is surging at present. Moreover, a few commercial products have emerged, like Powercast Transmitters, Ossia Cota, Dialog WattUp, and Mi Air Charge.

Although it is known that environmental conditions have impacts on far-field WPT, far too little attention has been paid to experimental evaluation in contrast to extensive theoretical contributions. To date, the extent to which environmental conditions affect the performance of far-field WPT has not been investigated in detail yet. The lack of quantitative research with real systems might render the assumptions made in theoretical analysis deviating from real-world behaviors and therefore cause the incompetence of proposed solutions for node deployment, charging schedule, and network protocol.

This article aims to bridge the gap by making the following specific contributions:

- To the best of our knowledge, this is the first comprehensive experimental study to investigate far-field WPT under different environmental conditions, including line-of-sight (LOS) propagation, multipath interferences, construction materials, and non-air media.
- Our study, for the first time, provides quantitative answers to the following key questions: (i) what is the maximum distance the leading commercial Powercast wireless powering system can work in LOS scenario; (ii) how does multipath propagation affect the received power and packet interval of battery-free IoT devices; (iii) how does far-field WPT interact with typical materials (wooden furniture, concrete wall, and glass window) in an indoor environment; and (iv) how well can far-field WPT support applications via media such as soil or water.

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TABLE I
A SUMMARY AND COMPARISON OF THE STATE-OF-THE-ART EXPERIMENTAL EVALUATIONS ON FAR-FIELD WIRELESS POWER TRANSFER.

Research Focus	Reference	Year	Power Transmitter	Receiving Antenna	Evaluation Board
Energy-neutral network	Dedi et al. [4]	2018	Tektronix TSG-4104A + LabVIEW + Yagi antenna	Patch antenna	Powercast P1110-EVB + Zolertia Z1
	Kae et al. [5]	2018	USRP + LabVIEW + Dipole antennas	Patch antenna	Powercast P1110-EVB + Zolertia Z1
Long-range wireless charging	Kae et al. [6]	2019	Large-scale phased antenna array + FPGA	Patch antenna	Powercast P1110-EVB + Zolertia Z1
SWIPT	Kisong et al. [7]	2019	CC1200 Development Kit	Cable	Powercast P2110-EVB + CC1200 transceiver
Waveform design	Mustafa et al. [8]	2020	NI PXIe-1082	Coaxial cable	Powercast P2110-EVB + WSN-Eval-01
	Nachiket et al. [9]	2021	USRP-2900 + GNU Radio + Whip antenna	Whip antenna	Powercast P2110-EVB + Arduino Nano
Applications	Morteza et al. [10]	2021	Powercast TX91501B	Patch antenna	Powercast P2110-EVB + WSN-Eval-01
	Ye et al. [2]	2022	Powercast TX91501B	Patch antenna	Powercast P2110-EVB + WSN-Eval-01
Environmental conditions	This article	2022	Powercast TX91501B Powercast TX91503	Patch antenna Dipole antenna	Powercast P2110-EVB Powercast P21XXCSR-EVB + WSN-Eval-01

- Although the impact of environmental conditions on wireless communication has been well established theoretically and experimentally, the corresponding investigation for far-field WPT is still in its infancy. Our study intends to contribute to a deeper understanding of far-field WPT and provide essential inputs to the system design of ZP-IoT. Moreover, it is believed that the presented extensive experiments can be very beneficial to readers, especially the new researchers and engineers in this area.

The remainder of this article is structured as follows. We first overview the state-of-the-art and highlight this work's new findings. Then, the details of the testbed, experimental setup, and observations are presented, along with theoretical explanations. After that, some insights inspired by the experiments are highlighted. Conclusion remarks are given at last.

II. STATE-OF-THE-ART

This section first conducts a literature review on the current research works focusing on experimental evaluation for far-field WPT, summarized in Table I. Then, the new findings of our study are discussed.

1) Energy-Neutral Network: It is a fundamental question on how to minimize the energy consumption of dedicated wireless power transmitters while keeping IoT devices alive. To the above question, Dedi et al. [4] built a system model and conducted experiments investigating: (i) the relationship between transmission power and its resultant efficiency; (ii) the current-voltage characteristic curve of a leading WPT module; as well as (iii) storage leakage and energy consumption of sensor node in different modes. Afterward, the authors extended the above study to the multi-node multi-antenna scenario [5], where multiple antennas were equipped for a wireless power transmitter to charge numerous nodes. The results showed that beam-splitting charging outperforms the time-sharing one.

2) Long-Range Wireless Charging: The operational distance of WPT at the current stage is relatively short. This hinders the deployment of ZP-IoT. Although some theoretical and conceptual contributions have been achieved for long-range wireless charging, the implementation of such systems is still needed to verify their practicality. To fill this gap, Kae et al. [6] implemented a wireless power system that can make possible IoT devices working at 50 meters. Furthermore, two lessons learned are: (i) the Gaussian beam is an ideal shape, and (ii) the analog approach is practical on cost and transfer efficiency when implementing a large-size antenna array.

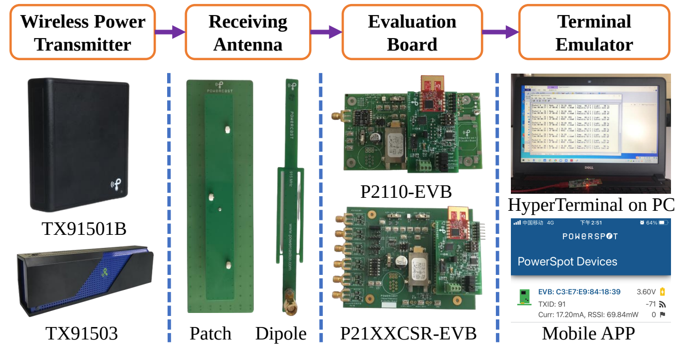
3) Simultaneous Wireless Information and Power Transfer: It is promising to harvest energy from existing wireless signals without disrupting data transmission. However, the essential difference between existing wireless signals and dedicated wireless power transmitters lies in the continuity of RF energy, as the air is not continuously occupied by wireless communications. One of the early experimental studies on SWIPT was presented in [7]. The authors investigated how network factors affect energy harvesting. A key finding is that a lower data rate helps harvest more energy, which would bring a tradeoff between the power transfer efficiency and the data rate. Besides, some insights for practical system design were given in terms of network topology, channel utilization requirement, and capacitor design. In addition, several SWIPT prototypes have been developed, which are summarized in [11].

4) Waveform Design: Considerable modulation schemes have been designed for wireless communication. An interesting question is whether the shape of electromagnetic waves has an impact on WPT and which is the best candidate for ZP-IoT. Therefore, exploring the relationship between the waveform and the conversion efficiency is essential. An experimental study [8] was conducted to evaluate charging time with different modulation techniques. The results demonstrated that the 4-amplitude shift keying (ASK) has the fastest charging speed. Another work in this research direction can be found in [9], where the experimental results demonstrated that the phase shift keying (PSK) and the quadrature amplitude modulation (QAM) outperformed the multisine waveforms.

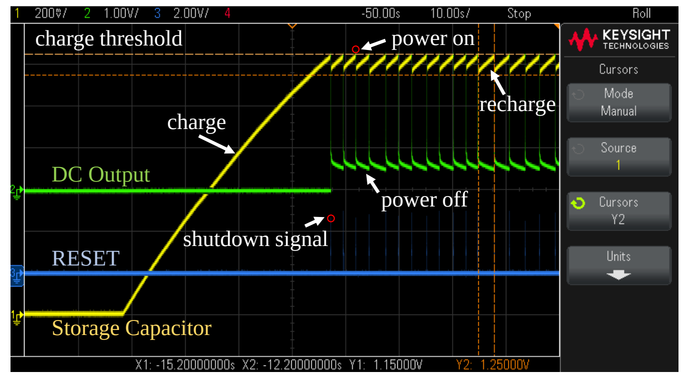
5) Applications: Besides the above fundamental experimental studies, practical evaluation of WPT in target application scenarios is equally essential. The reliability and safety of aircraft are most crucial as human lives are priceless. With the advantages of cableless and battery-free operation, ZP-IoT is an emerging solution to provide real-time monitoring for protecting passengers and aircraft. A system design and measurements were presented in [10], which demonstrated the power distribution inside an Airbus A330 cabin with the leading Powercast system. The result also indicated that shadowing and small-scale fading effects would cause variations in the received power from the theoretical values. Our previous study [2] explored the feasibility of WPT in the agricultural sector. In addition, the experimental measurements have shown that microclimate and weather conditions are not the dominant factors affecting the variation of wireless powering, which motivated us to conduct the current investigation.

6) New Findings: This article differs from the state-of-the-art in two aspects. First, leading commercial off-the-shelf (COTS) development kits and evaluation boards are chosen for experimental evaluation. It helps to reproduce the work by other researchers without a complex experimental setup in a cost-effective manner. In addition, the results can be used as ground truth guiding future applications and research with COTS systems. Second, this experimental study is conducted with quantitative analysis from an environmental conditions perspective. Some new findings are summarized as follows:

- Under normal conditions, the leading COTS Powercast system enables up to 16 meters of line-of-sight wireless powering in our case when equipping the new P21XXCSR-EVB and the patch antenna.
- The new PowerSpot TX91503 RF wireless power transmitter has a lower power density than the classic TX91501B power transmitter. This is because the new system is designed for simultaneous multi-charging in a home scenario, and its beam pattern obeys the horizontal polarization with a larger width and height than the TX91501B version.
- The constructive interference during rich multipath propagation can significantly enhance the operation range from several meters to more than 40 meters in both patch and dipole antenna conditions. However, there are several energy holes over the domain when using a dipole antenna as a front-end harvester or the TX91503 as a power source.
- The results of wireless powering measurement across wooden furniture, concrete wall, and glass window demonstrated that a 915 MHz wireless signal could hardly penetrate the tested glass window to charge ZP-IoT devices while it does going through the other two materials. But an exciting thing observed is that the ZP-IoT device behind a power transmitter could be activated even at 5 meters away, benefiting from reflected signals.
- Potting soil is an environment-friendly media for RF-based WPT. Moreover, although there is severe attenuation in the water, the Powercast system is capable of providing 10-20 centimeters charging range.



(a)



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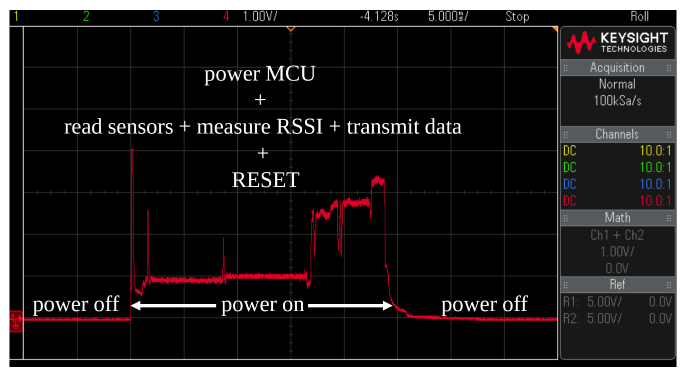


(c)

Fig. 1. The testbed and its operating principles. a) hardware components; b) voltages of the storage capacitor (yellow line), DC output voltage (green line), and RESET pin (blue line) captured by a Keysight DSOX1204A oscilloscope; c) current variation of the WSN-EVAL-01 wireless sensor board in a duty cycle witnessed through a current sensing resistor.

III. Testbed

The findings mentioned above are produced using the leading Powercast wireless power development kits. Therefore, this section describes the hardware components and illustrates its working principle. They are shown in Fig. 1.

1) RF Wireless Power Transmitters: The TX91501B is the most popular wireless power transmitter in research studies. Its power signal operates in the 915 MHz ISM band with direct sequence spread spectrum (DSSS) modulation. In addition, it has a gain of 8 dBi with 60° vertical beam pattern, which provides a maximal 3 W effective isotropic radiated power (EIRP). The latest model, PowerSpot TX91503, is also tested. Its output power is 3 W EIRP too, but the beam pattern is different, presenting a horizontal polarization with 70° widths. Moreover, it can adaptively stop power transmission when the paired devices are not around. In addition, the TX91503 has a smaller form factor and can be controlled by a mobile APP.

2) Receiving Antennas: The PA-915-01 patch antenna from Powercast has been widely adopted as a front-end RF energy harvester in previous experimental studies. This directional antenna has a 122° horizontal and 68° vertical energy pattern with a peak gain of 6.8 dBi. Our study also evaluates the Powercast's DA-915-01 dipole antenna for an in-depth understanding. Although it has a much lower gain with 1 dBi, this dipole antenna has an omnidirectional energy pattern.

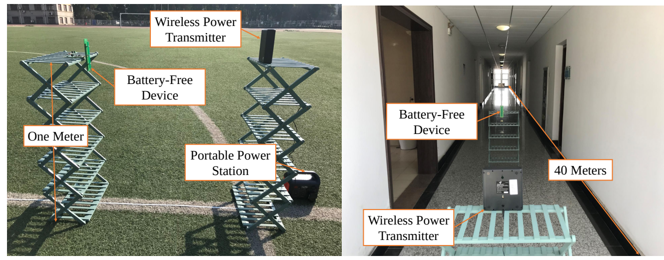
3) Evaluation Boards: The Powercast P2110-EVB mainly includes an SMA (SubMiniature version A) connector, a 915 MHz energy harvesting module, and storage capacitors. First, the SMA connector is used for energy input from receiving antenna or test equipment. Then, the energy harvesting module is responsible for converting the RF energy to direct current (DC) power and storing it in a capacitor (1000 μF, 50 mF, or user-installed value). The regulated output voltage could be adjusted from 2 V to 5.5 V. Finally, there is a connector to join the evaluation board and add-on battery-free IoT device. The WSN-EVAL-01 wireless sensor board is chosen in our case. The second evaluation board we choose is the Powercast P21XXCSR-EVB, a newly designed one with greater sensitivity and six operation frequency bands.

4) Terminal Emulators: Last, the sensed data from the WSN-EVAL-01 node is transmitted to an access point (WSN-AP-01), which is connected to a laptop using a USB cable. The HyperTerminal program display the received signal strength indicator (RSSI), the time differential between received packets (dT), sensor values, etc. Besides the PC terminal, a mobile APP called PowerSpot is available for download from the Apple and Google Play APP stores. It could schedule the TX91503 power transmitter and monitor charging status in terms of the battery voltage, charging current, and RSSI.

5) Working Principle: The captured varying signal voltages and current in Fig. 1(b) and Fig. 1(c) display the detailed work process. When the power transmitter starts to work, the voltage of the storage capacitor ($50mF$) in the evaluation board gradually rises. If it reaches the activation threshold ($1.25V$), the DC output voltage jumps to the operation voltage ($3.3V$) of a battery-free IoT device, which is immediately powered on to measure the environment and reports it to the access point by an 802.15.4-compliant radio. When the task is finished, the RESET function is triggered to power off the IoT device rather than consume the whole energy to reduce the recharging time.

IV. Experimental Evaluation

This section presents the experimental setup, observation results, and theoretical explanations. The two critical metrics evaluated are RSSI and packet interval. The RSSI indicates the received signal strength at the receiving antenna, while the latter metric means the time differential between two transmission cycles, that is, the recharging duration. Each value is averaged by 20 measurements in most cases except for the very long recharging duration situations.



(a) (b)

Fig. 2. Measurement scenarios of line-of-sight propagation. a) football ground; b) corridor for generating multiple paths.

A. Line-of-Sight Propagation

1) Experimental Setup: The first experiment is carried out at a football ground to examine the maximum power transfer distance of the leading COTS system with LOS propagation. The measurement scenario is shown in the left side of Fig. 2, where the power transmitter and battery-free device are placed on two separate shelves, whose heights are equal to one meter. We fix the power transmitter on the right side and vary the location of the battery-free device from one meter to the position until it cannot send any packet in 30 minutes.

2) Observation Results: Fig. 3(a) and Fig. 3(b) show the performance when using the TX91501B and TX91503 as the power source, respectively. It is clearly seen that the RSSIs decay exponentially with the distance in all system settings as expected, while the corresponding packet intervals have an opposite trend. Even so, the leading Powercast system can enable a maximum charging distance of 6 meters with a dipole antenna and 16 meters with a patch antenna and P21XXCSR-EVB components. Although the packet interval would be up to 25 minutes, most data could be sent within 200 seconds. The P2110-EVB has a better conversion efficiency, but the maximum operating range is slightly shorter than the new P21XXCSR-EVB board. In addition, the classic TX91501B power transmitter is much better for face-to-face charging than the new TX91503. An interesting outcome is that the measured results with the TX91503 are not smoother than that with the TX91501B, especially when the receiver is moved from the source three meters away. This result is likely to be related to beam pattern and ground reflection.

3) Theoretical Explanation: The Friis transmission equation can explain some of the observations. First, there is an inverse exponential relationship between the received power and the propagation distance. Second, a higher antenna gain can improve the signal strength. Moreover, the beam pattern affects both power density and coverage area. A narrow beam is good at direct wireless powering, while a wide one is more suitable for simultaneous multi-charging. Furthermore, the greater sensitivity of the RF-to-DC converter in the P21XXCSR-EVB board helps increase the operational range.

B. Multipath Propagation

1) Experimental Setup: The second experiment further investigates the WPT in the LOS scenario but in the context of the multipath propagation. As shown in the right side of Fig. 2,

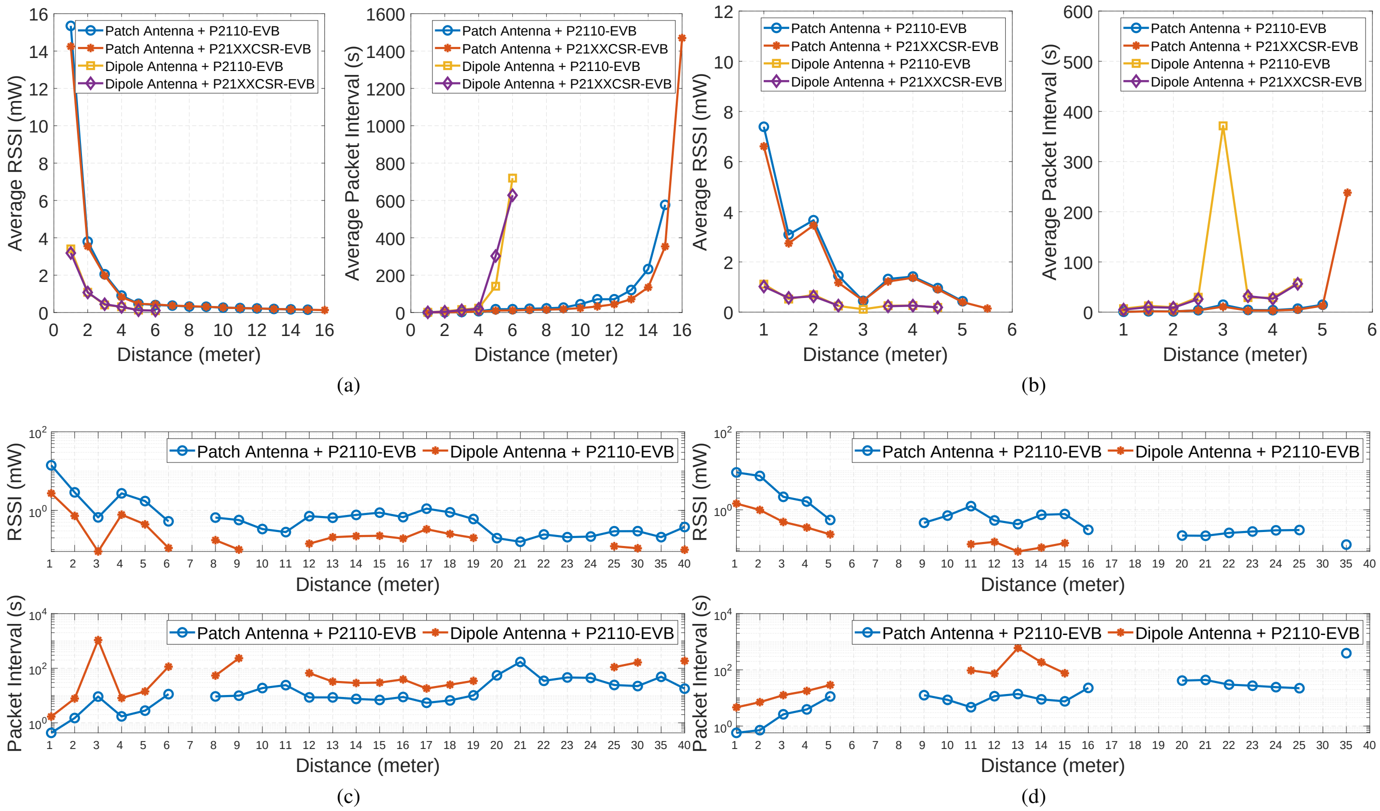


Fig. 3. Measurement results of received signal strength indicator (RSSI) and packet interval with different power transmitters. a) line-of-sight propagation with TX91501B; b) line-of-sight propagation with TX91503; c) multipath propagation with TX91501B; d) multipath propagation with TX91503.

the system is placed in a corridor to generate the multipath effect. Our previous study [2] preliminarily demonstrated the feasibility of performance improvement relying on the multi-path effect. Here, we conduct a more comprehensive analysis using different receiving antennas and power transmitters. Interestingly, some new facts emerge. We choose the P2110-EVB as the evaluation board since it has similar performance to the P21XXCSR-EVB and has been popularly used in existing experimental studies so that a fast reproduction of this measurement is available.

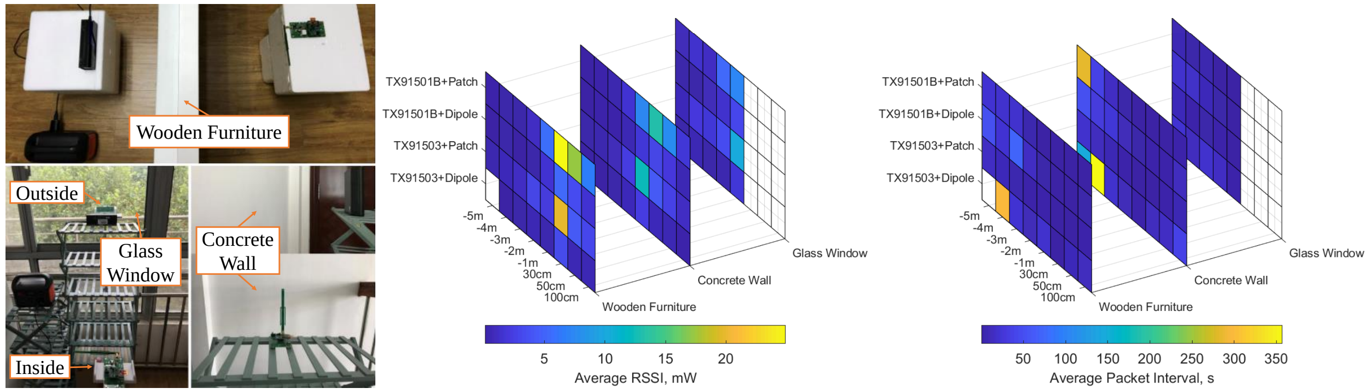
2) Observation Results: Fig. 3(c) and Fig. 3(d) show the average RSSI and packet interval achieved by TX91501B and TX91503 power transmitters in the corridor scenario. It can be seen that the maximum operational distance is significantly improved. Taking advantage of multipath propagation, a dipole antenna can even receive enough energy to trigger a battery-free device at 40 meters and 15 meters away from the TX91501B and TX91503 transmitters, respectively. However, such improvement is unstable because power density fluctuates, and there are even many energy holes in the region.

3) Theoretical Explanation: The multipath interference theory could explain this phenomenon. The wireless power signal is reflected from the corridor's sidewall, roof, and ground surface, causing multipath propagation. Therefore, the total power strength is the addition of the primary wave and many reflection waves. When the waves arrived approximately in phase, a constructive interference occurred, which could increase the received power strength. This is the reason why charging distance can be significantly improved. On the contrary, if these waves come out of the phase, the received power strength becomes weak due to destructive interference. As a result, energy holes are generated when the induced voltage is below the cold start threshold of the Powercast energy harvesting module.

C. Penetration and Reflection Characteristics

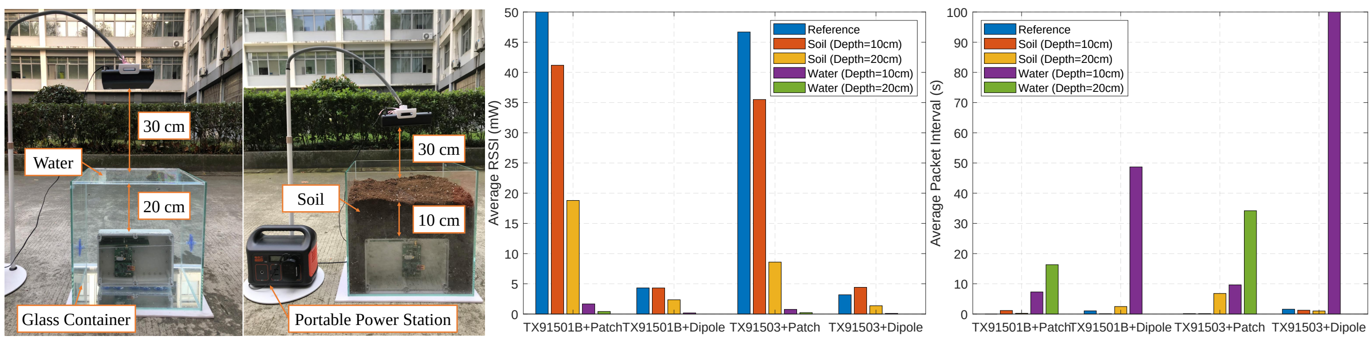
1) Experimental Setup: Indoor environment is a typical scenario for WPT. Unfortunately, there are often obstructions between the power transmitters and receivers since ZP-IoT devices may be placed everywhere, within the furniture or in other rooms. Thus, it is necessary to investigate the performance when facing common building materials. This experiment has chosen wooden furniture, concrete wall, and glass window to measure, as demonstrated in Fig. 4(a).

2) Observation Results: Our original plan is to conduct only penetration testing. Fig. 4(b) and Fig. 4(c) show the results when the distances between the three obstruction surfaces and the receiver are 30, 50, and 100 centimeters. The results indicate that all four system settings can provide satisfactory services when penetrating wooden furniture and concrete wall. However, a negative observation (the blank grids in the rightmost piece) shows that the device outside the window cannot be activated, which means the 915 MHz power signal could hardly penetrate the tested glass window. Surprisingly, the access point receives packets from another node on the desk. This indicates that the glass window is able



(a) (b) (c)

Fig. 4. Investigation of penetration and reflection characteristics with various materials. a) measurement scenarios: wooden furniture, glass window, and concrete wall; b) RSSI results; c) packet interval results.



(a) (b) (c)

Fig. 5. Investigation of wireless powering over non-air mediums. a) measurement scenarios: potting soil and water; b) RSSI results; c) packet interval results.

to reflect most of the power signal back to the room. Thus, we additionally conduct reflection measurements for all materials ranging from one to five meters. From the heatmaps, we can see that all of the tested materials reflect a part of the signal enabling a "back charging" even at five meters away.

3) Theoretical Explanation: Different propagation mechanisms will occur when an RF signal strikes an object, such as penetration, reflection, scattering, and diffraction. The reaction depends on an object's atom size, radio wavelength, power strength, and the distance between a power transmitter and the thing. The larger the wavelength of a radio wave has, the easier it passes through a surface. In this case, the wavelength of a 915 MHz radio wave is about 33 centimeters making it possible for non-line-of-sight wireless powering and back charging, with the help of penetration and reflection. It is worth mentioning that a directional antenna is not always beneficial, especially in scenarios with rich reflection, since the energy signal could be from all directions. This finding is also a likely explanation for the highly long packet interval in the top left corner of the second piece in Fig. 4(c).

D. Wireless Powering over Non-Air Mediums

1) Experimental Setup: The purpose of the last experiment is to investigate wireless powering over soil and water to understand better its capability in applications, such as plant phenotyping and water quality sensing. First, as shown in Fig. 5(a), we put an encapsulated battery-free device equipped with the patch or dipole antenna into a glass container. After that, the device is filled with potting soil and water, respectively. Then, we measure the performance using TX91501B and TX91503 power transmitters. The depths of the mediums are respectively set to 10 and 20 centimeters, while the power transmitter is placed 30 centimeters above the medium's surface. In addition, a reference measurement is conducted, in which nothing is filled in the glass container, and the total charging distance is 50 centimeters.

2) Observation Results: From Fig. 5(b) and Fig. 5(c), we can see that the corresponding RSSI and packet interval results over the soil medium are close to the reference values, demonstrating that potting soil is friendly with WPT. Although there is a sharp drop in the case of water medium, the node with a patch antenna can still transmit packets on average every 17 seconds and 34 seconds, triggered by the TX91501B and TX91503 power transmitters when the water depth is 20 centimeters. But a disappointing outcome is that the node can not work at this water depth when equipped with a dipole antenna, so the green bars are missing in the figures.

3) Theoretical Explanation: The performance of wireless powering over the soil is mainly affected by different types of soil, saturation, and operating frequency of the power transmitter. Theoretical models and experimental results on electromagnetic attenuation over clay and gravel soils can be found in [12]. In our study, the slight power loss over potting soil is mainly because it is drier and has less density than clay. Besides, although it is common sense that there is electromagnetic signal attenuation by water, so far, much less is known about its microscopic processes, not to mention a definite answer. For this reason, it is an important research direction in the physical science area.

V. Insights from the Experimentation

Inspired by the above experimental evaluation, we point out some insights for future research in this section.

1) Electric Field Polarization Control for Long-Range Wireless Powering and Sensing: To protect against adverse health effects of electromagnetic fields exposure on humans, the output power of energy sources is limited by government regulations. The experimental results demonstrate that even the leading commercial system can only achieve a maximum direct charging distance of 16 meters. Moreover, joint WPT and wireless sensing is a trend, but the transmitted signal in an indoor environment is complex, which may cause a trade-off between wireless powering and sensing. Fortunately, recent investigation [13], [14] has shed light on a promising research direction, namely cross-polarization control. It can both improve the reading range of zero-power IoT devices and mitigate electromagnetic clutter. Thus, the impact of field polarization on far-field WPT will be studied and explored.

2) Dealing with Energy Holes by Intelligent Reflecting Surface: Under the influence of environmental conditions as demonstrated, the transmitted energy density is not always present in an ideal exponential distribution. Instead, it would fluctuate with many energy holes, bringing challenges for peer-to-peer connections and wireless mesh networks since it is difficult to accurately predict the energy status of IoT devices. More seriously, some critical nodes would die due to energy holes. The emergence of the intelligent reflecting surface (IRS) technique can be exploited to address this problem by precisely adjusting power signals in a programmable manner [15].

3) Understanding Concurrent Far-Field Wireless Power Transfer: In the current study, we investigate the most basic scenario: one charger and one battery-free node. Concurrent far-field WPT will be a more general situation that includes multiple nodes and chargers. When conducting this work, we discover by accident that both neighbor nodes and chargers could cause energy interference, which will spark a flurry of research activities in the future. For example, it is interesting to investigate power models, device placement, and scheduling for concurrent far-field WPT.

VI. Conclusion

The goal of this study is to investigate the effects of environmental conditions on far-field WPT, one of the critical enabling technology for ZP-IoT. Our experiments demonstrate that the maximum wireless charging distance provided by the leading commercial system is 16 meters in a LOS scenario. The performance could be opportunistically improved to more than 40 meters with the help of multipath propagation through wall reflections, in other words, naive reflecting surfaces. In addition, it is shown that wireless RF power systems, benefiting from the RF signal penetration and reflection characteristics, could enable cross-room and "back" charging with common building materials. Moreover, this experimental study has identified potting soil can be well compatible with WPT, and an operating range of 20 centimeters is available over water charging. Since our work is an initial attempt to unveil the practicability of far-field WPT for ZP-IoT, further experimental investigation and theoretical modeling are still needed for a comprehensive understanding. Among them, field polarization control, IRS-aided energy transfer, and concurrent wireless charging are pointed out.

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