Understanding Concurrent Radiative Wireless Power Transfer in the IoT: Out of Myth, into Reality

Ye Liu, Dong Li, Haipeng Dai, Xiaoyuan Ma, and Carlo Alberto Boano

***Abstract*—Radiative wireless power transfer plays a vital role in addressing the challenges facing today's Internet of Things, such as frequent battery replacement, unimaginable electronic waste, and autonomous operation at hard-to-reach places. Concurrent charging is a fundamental pattern in radiative wireless power transfer, where multiple chargers transmit energy waves concurrently, or the signals are received by multiple nodes simultaneously. However, its system model has yet to be understood, and many widespread assumptions ("myths") are too ideal, e.g., the constant power density in the time domain, neglected antenna type, and non-interference between neighbor devices. This article aims to uncover realities that bust these myths experimentally. Firstly, extensive results indicate that instantaneous received power in the time domain fluctuates heavily due to imperfect matches between multiple transmitters. Secondly, the extent to which antenna type affects concurrent charging is investigated. Thirdly, energy interference among neighbor devices is identified, and its interference pattern is explored for the first time. Inspired by the new findings, some insights are pointed out from the above three perspectives at last.**

I. INTRODUCTION

The Internet of Things (IoT) is becoming a new fundamental infrastructure worldwide. Over the past decade, a plenty of IoT systems have been deployed for smart cities, Industry 4.0, and Agriculture 4.0. They not only help in productivity enhancement and cost reduction, but also improve the quality of life and create new opportunities. However, one key lesson learned from these experiences is that power supply will become a bottleneck for IoT's future development. First, batteries are the primary power supply for IoT systems at the current stage. A limited capacity causes frequent battery replacement, which is an unimaginable burden with the pervasiveness of IoT devices. In addition, electronic waste due to battery disposal will be outrageous in the next decade, as we expect 500 billion IoT devices being deployed, according to Cisco. Furthermore, IoT systems in the future will often be deployed at hard-to-reach places. Such applications are expected to achieve long-duration or even potentially perpetual monitoring with minimum maintenance.

As a promising technology to fill the above gap, radiative wireless power transfer (WPT) [1] has recently been paid great attention by academia and industry. It can provide contactless and remote energy delivery for low-power IoT devices through radiofrequency electromagnetic radiation, thus making power supply convenient, especially for implantable embedded systems and those operated in hazardous environments. Moreover, the transmitted wireless energy is repeatedly stored in supercapacitors. Benefitting from the battery-free operation, WPT can prevent the enormous disposal of batteries.

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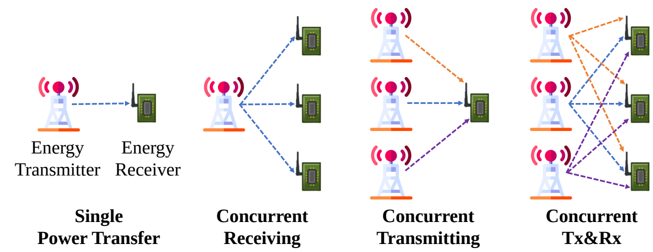


Fig. 1. The four relationships between the energy transmitter and energy receiver in radiative wireless power transfer.

There are four relationships between the energy transmitter and energy receiver in radiative WPT: one-to-one, one-to-many, many-to-one, and many-to-many wireless charging. As demonstrated in Fig. 1, the one-to-one relationship means one wireless charger is deployed to power one IoT device, while one-to-many indicates that multiple IoT devices are in the operation range of the wireless charger. Practical applications usually need many wireless chargers to work together for power and coverage enhancement, thus forming the many-to-one and many-to-many charging situations, which are called concurrent radiative WPT since multiple wireless chargers transmit energy waves simultaneously. In fact, the one-to-many situation could be also considered as a kind of concurrent radiative WPT because of the simultaneous energy harvesting from the perspective of the receiver side.

Existing research on concurrent radiative WPT holds three widespread myths (or assumptions) about the system model. First, the received power at any point is steady in all time [2]–[4], and its value can be calculated by wave interference theory. In other words, the distribution of wireless power intensity in a charging network is static from the time domain. However, this assumption has recently been challenged by experimental WPT research studies [5]–[7] that demonstrate the dynamic nature of received power caused by unsynchronized frequency, time, and phase among multiple energy transmitters. For example, one pioneer study, IVN [5], capitalizes on this phenomenon to opportunistically charge implantable IoT devices. Second, the antenna type of energy receiver is not specified, implying an omnidirectional antenna is equipped. Few theoretical research has paid attention to the directional antenna problem, in which the received energy outside a sector area is assumed to be zero [8]. Third, there has been very little discussion about the relative positions of neighbor nodes [9], [10] since it is a common belief that they have no influence on each other.

In this article, we seek to further uncover realities that bust these three widespread model assumptions through experimental study. Specifically, we first investigate the distribution of received power at a point during single and concurrent radiative WPT. Second, we evaluate the effect of directional antenna on concurrent radiative WPT. Third, we demonstrate energy interference among neighbor nodes. The leading commercial WPT development kits from Powercast are chosen to collect data for this research. Our experimental results reveal discrepancies between the abovementioned myths and realities. It is hoped that these observations will provide a significant opportunity to advance the understanding of concurrent radiative WPT. The main contributions of this article are summarized as follows:

- We present comprehensive experimental study to investigate concurrent radiative WPT from the perspectives of concurrent wireless power transmitting and concurrent wireless power receiving.
- Our study validates that instantaneous received power during concurrent wireless power transmitting in the time domain is not constant, and its distribution spreads widely due to the mismatch between energy transmitters. In addition, packet interval is more stable than that does in a single power transfer.
- The impact of antenna type on concurrent radiative WPT is experimentally evaluated, which offers fresh insights, such as that the peak instantaneous received power could boost greatly via concurrent transmission. More importantly, directional antenna affects the distribution of instantaneous received power.
- This study identifies, for the first time, the pattern of energy interference in concurrent wireless power receiving. It is similar to a combination of signal penetration, Fresnel Zone, and wave interference. We name this new interference pattern "*Octopus Zone*" because the demonstrated heatmap looks like an octopus.

The remainder of this article is structured as follows. We first review research directions on concurrent radiative WPT. Then, the experimental study is presented in detail. Following that, we discuss insights from the observation and shed light on future research directions. Finally, the conclusions are drawn.

II. Research Directions in Concurrent Radiative Wireless Power Transfer

A considerable amount of research on concurrent radiative WPT has been conducted in past years. This section gives a systematic literature review on related works, which are classified into the following five research directions.

1) Experimental Study: Concurrent radiative WPT in the IoT was first experimentally investigated in [9], which demonstrated the constructive and destructive interference of harvested power when two energy transmitters simultaneously charge a sensor node. Some findings obtained are that (i) the interference intensity from the spatial domain is affected by charging path length and the distance difference between the transmitters, and (ii) this interference is more severe near the sensor node. Moreover, the authors explored the feasibility of concurrent WPT at multiple frequencies. Such an idea was realized afterward in [11]. The authors presented a prototype and evaluated the performance of single power transfer, concurrent power transfer, and the enhanced design with carrier shift diversity. Unlike these efforts, which have investigated concurrent powering from the spatial domain perspective, we conduct this study from the time domain perspective.

2) Theoretical Model: Along with experimental studies, the establishment of theoretical models has been ongoing. For example, the first analytical expression focusing on concurrent energy transmission in two-dimensional (2D) and three-dimensional (3D) placement was formulated in [2]. The 2D energy model considers omnidirectional dipole antennas, synchronous initial signal phases, and the same transmission power. Thus, the total energy is an ideal superposition at energy receivers. Meanwhile, the 3D energy model additionally took into account geometrical parameters to calculate phase shift. Based on this seminal study, a more realistic model was elaborated [8], in which vector models are introduced to explain constructive and destructive interference.

3) Medium Access Control (MAC) Protocol: The power intensity with concurrent radiative WPT is quite diverse over the network, which becomes more complex as the number of chargers increases. Therefore, designing efficient MAC protocol for wireless-powered IoT networks is challenging due to the energy imbalance and topology dynamicity. A growing body of MAC protocols has been proposed to overcome this issue [12]. Among them, RF-MAC [13] is one classical protocol considering energy interference and cancellation from multiple wireless chargers. Most recently, a new MAC protocol called RF-DiPaQ [14] was proposed for batteryless energy-harvesting networks. It uses a promising channel sensing technique for medium access during concurrent transmission.

4) Charging Scheduling: It is a fundamental research problem to optimize the schedule of static and mobile energy transmitters in one-to-one wireless-powered networks so to improve charging efficiency. This is especially true in concurrent radiative WPT since energy interference significantly affects network performance. Concurrent charging scheduling was proved to be an NP-hard problem in [3], where two greedy algorithms were proposed to minimize charging time. The nonlinear superposition charging effect due to concurrent energy transfer was also investigated in [4], and a fast charging approach was designed. On the other hand, optimizing the charging schedule to avoid concurrent charging under many-to-many wireless-powered networks has been carried out [10] to cope with energy cancellation and electromagnetic exposure issues due to destructive and constructive energy interference.

5) Precision Energy Transfer: One promising feature of concurrent radiative WPT is that the energy density distribution across the charging area could be controlled. For instance, the establishment of the Energy-Ball [6] system is the first step towards synchronizing energy transmitters. Energy-Ball enables the concentration of a majority of the energy onto the target device. The Energy-Ball system is also capable of

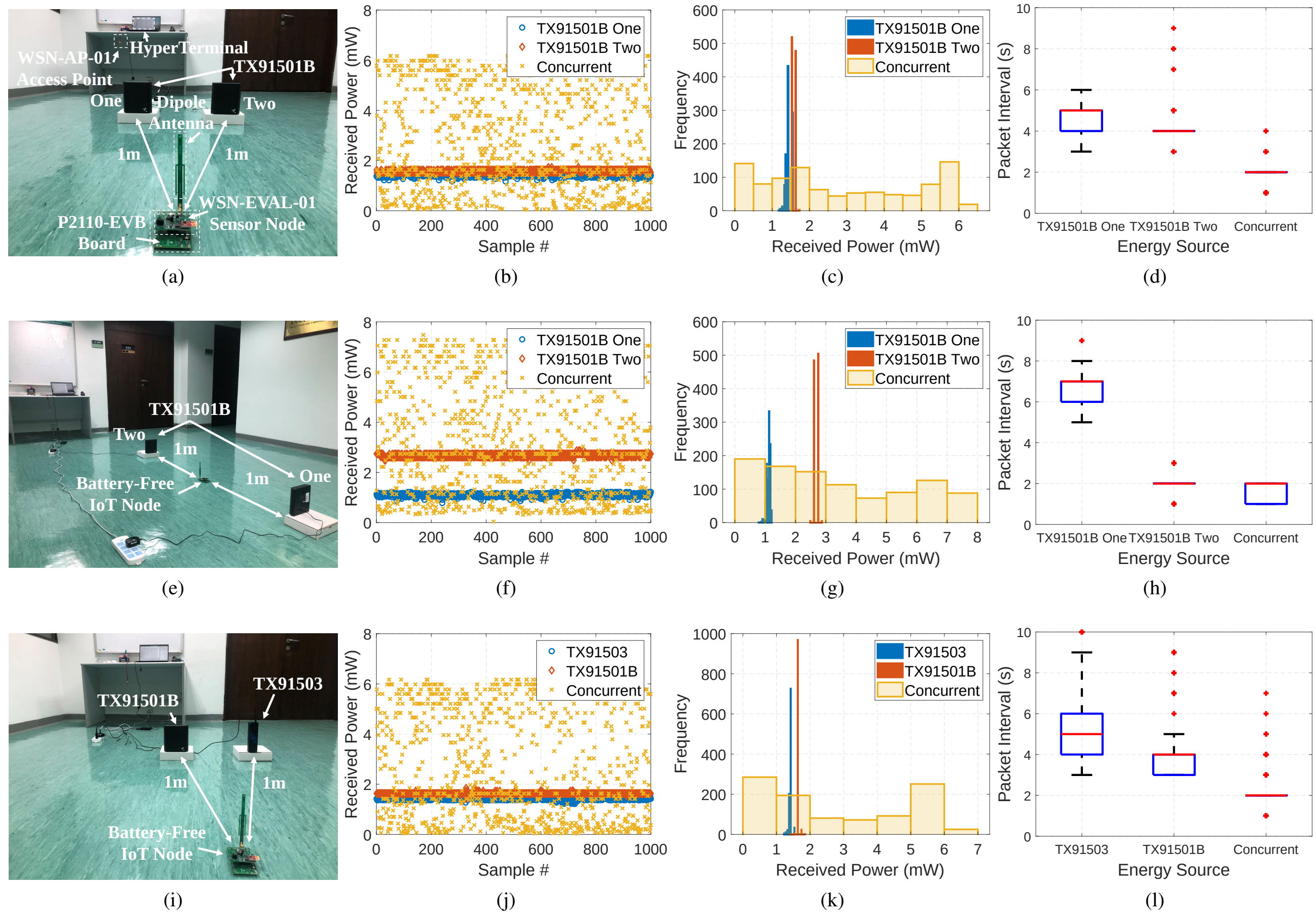


Fig. 2. Measurement scenarios and results of concurrent wireless power transmitting to a receiver with an omnidirectional antenna.

tracking moving devices by swiftly adjusting its phase. The In-N-Out system [7] incorporates a coherent beamforming algorithm that facilitates stable power reception through a heuristic transmitters synchronization process. Another effort can be found in [15], where the simulation and implementation of a closed-loop multi-antenna power transfer is provided. These works have focused on a master-slave mode, while we conduct our study from a different perspective, namely, concurrent radiative WPT in a distributed random network.

Overall, these studies significantly promote the development of concurrent radiative WPT from different aspects. Our work aims to further contribute to this growing area of research by challenging widespread assumptions and experimentally demonstrating the realities with extensive evaluation. Our work helps establishing more practical network models and designing more efficient protocols, charging schedules, and precision energy transfer systems.

III. Myth Versus Reality

In this section, we first present the testbed. Then, the experimental setups and observation results are given in detail.

A. Testbed

1) Energy Transmitter: Two types of wireless power transmitters are chosen for the experiment. As depicted in Fig. 2(a), the first transmitter is the Powercast TX91501B, renowned for its extensive utilization in academic research. It operates at a center frequency of 915 MHz and delivers a power output of 3 watts EIRP (Equivalent Isotropic Radiated Power). Furthermore, the Powercast TX91501B features a beam pattern with a width and height of 60 degrees, employing vertical polarization. The power modulation technique employed by this transmitter is Direct Sequence Spread Spectrum (DSSS).

The second wireless power transmitter employed is the Powercast TX91503, as illustrated in Fig. 2(i). Similar to the Powercast TX91501B, it operates at a center frequency of 915 MHz, delivers a power output of 3 watts EIRP, and utilizes DSSS modulation. However, the beam pattern of the Powercast TX91503 is characterized by a width of 70 degrees and a height of 130 degrees, employing horizontal polarization.

2) Energy Receiver: A battery-free IoT node is assembled as an energy receiver consisting of three components: an antenna, an energy harvesting module, and a wireless sensor node. The DA-915-01 dipole antenna and the PA-915-01 patch antenna are selected for omnidirectional and directional RF power receiving. The DA-915-01 dipole antenna utilized

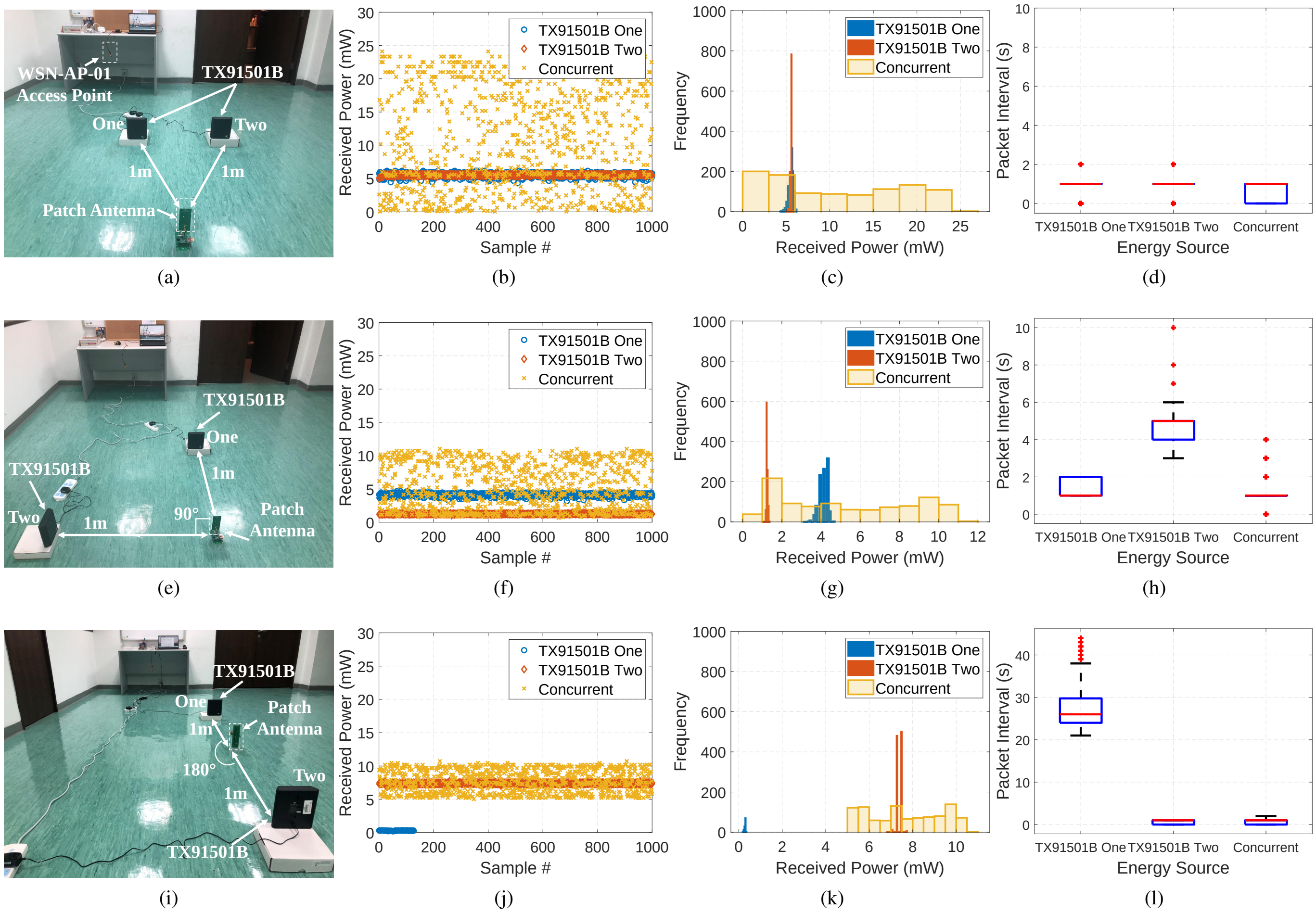


Fig. 3. Measurement scenarios and results of concurrent wireless power transmitting to a receiver with a directional antenna.

has a gain of 1 dBi. It is an omni-directional antenna with vertically polarized radiation. On the other hand, the PA-915-01 patch antenna has a gain of 6.1 dBi. This antenna exhibits a more directional radiation pattern. Its energy pattern has a beamwidth of 122 degrees in the horizontal plane and 68 degrees in the vertical plane. The P2110-EVB evaluation board is responsible for energy harvesting to convert RF energy into DC power. It is then stored in a 50 mF capacitor for providing energy to a WSN-EVAL-01 wireless sensor node. Moreover, the P2110-EVB board can sample the received wireless signal and indicate the power strength from energy transmitter(s).

3) Terminal Emulator: The wireless sensor node is active when the storage capacitor's voltage reaches a selected threshold (1.25 V). It then sends data regarding the receiver signal strength indicator (RSSI) measured by the P2110-EVB board. Next, the data is received by a WSN-AP-01 access point connecting to a computer. Finally, a HyperTerminal emulator program records these RSSI values and packet interval for statistics and analysis.

B. Reality 1: Instantaneous Received Power Is Not Steady

1) Experimental Setup: The first set of experiments aims to demonstrate the distributed received power at a location with concurrent radiative WPT. The setup is shown in Fig. 2(a), Fig. 2(e), and Fig. 2(i), respectively. We first place two TX91501B wireless power transmitters in the same direction to charge a battery-free IoT node with a dipole antenna. Both the distances of the two charging paths are the same with a one-meter space. Next, one TX91501B equipment is moved to power the IoT node in the opposite direction but with the same charging distance. Finally, we use a TX91503 wireless power transmitter to replace one TX91501B for equipment diversity. In each scenario, we first turn on one of the wireless power transmitters separately and then let them work concurrently. One thousand samples are collected in each run.

2) Observation Results: The instantaneous received power in the above three scenarios is shown in Fig. 2(b), Fig. 2(f), and Fig. 2(j). As can be seen from the results, a single power transfer provides steady instantaneous received power. But the values during concurrent powering are not stable and present a considerable fluctuation. For example, the maximum capacity could reach four times the intensity with a single power transfer, and the minimum value drops to zero. This feature is exciting as the high instantaneous power can be exploited to trigger an energy-harvesting circuit from a cold start.

Besides the temporal profiles, these sample data are also presented with histograms, as shown in Fig. 2(c), Fig. 2(g), and Fig. 2(k). From the results, we learn that the instantaneous received power with concurrent radiative WPT at a fixed location is spread widely. It is quite different from that with a single power transfer. More importantly, this fact is in contrast to the common assumption, namely, the received power is constant in the time domain during concurrent radiative WPT. In addition, we analyze the time differential between the 1000 received packets in the three cases using box plots, which is shown in Fig. 2(d), Fig. 2(h), and Fig. 2(l). Interestingly, the packet interval is more stable than that does during a single power transfer.

C. Reality 2: Antenna Type Should Not Be Neglected

1) Experimental Setup: In order to understand how the antenna type affects concurrent radiative WPT, a second set of experiments is conducted. Here, the DA-915-01 patch antenna is equipped on the battery-free IoT node. Unlike the DA-915-01 dipole antenna, whose gain is 1.0 dBi, the patch antenna has a gain of 6.1 dBi. In addition, it is a directional antenna with 122° horizontal and 68° vertical energy patterns. For all the experiment scenarios, the charging paths are the same, with a distance of one meter. But the angles between the TX91501B wireless power transmitters and IoT node are changed, which is shown in Fig. 3(a), Fig. 3(e), and Fig. 3(i), respectively. We collect 1000 samples in all runs except the third case, where only 127 packets are reported in 60 minutes due to the weak received energy when the TX91501B transmitter charges the node in the opposite direction of the directional antenna.

2) Observation Results: From the results of the instantaneous received power, its distribution, and packet interval, we observe that antenna directivity is a critical factor affecting the energy harvesting behavior in concurrent radiative WPT. First, the instantaneous received power using a directional antenna fluctuates over time with a broader range than that of an omnidirectional antenna. For instance, the peak power during concurrent energy transfer could reach 25 mW in the first scenario, whereas its value is around 6 mW when using a dipole antenna. Furthermore, the power distribution is heavily affected by the position of energy transmitters. For example, the received power fluctuates between 0 and 12 mW when the charger is placed in a side direction, while on the front side of the antenna, it is between 0 and 25 mW. Finally, a rather surprising outcome is that when a wireless power transmitter is placed at 180 degrees of the receiving antenna, although it has little impact on the packet interval because of the small antenna gain at this direction, the lower limit of the instantaneous received power is changed from 0 to 5.01 mW.

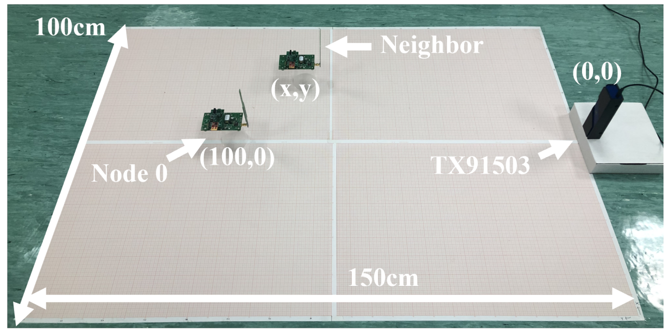
D. Reality 3: Neighbor Nodes Are Not Independent

1) Experimental Setup: The above two sets of experiments investigate concurrent wireless power transmitting, while the objectives of the last experiments are to determine whether there is energy interference between IoT devices during concurrent wireless power receiving. If so, what does the energy interference pattern look like?

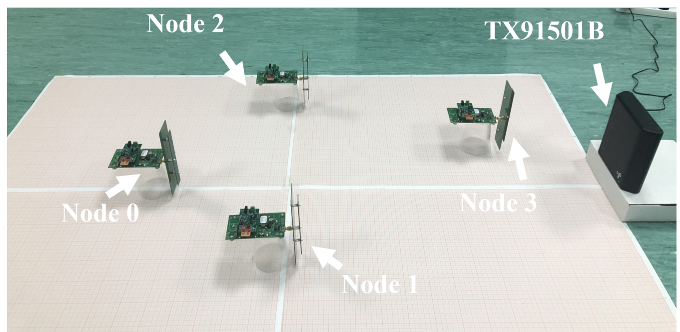
For this purpose, we place a wireless power transmitter and two nodes (Node 0 and Neighbor) in a 150 cm $\times$ 100 cm grid, where the horizontal coordinate is from 0 to 150, and the vertical coordinate is from -50 to 50. As shown in Fig. 4 (a), the wireless power transmitter is fixed at (0,0), while Node 0 is fixed at (100,0). To assess the impact of the neighbor node on the received power of Node 0, we conducted a series of measurements by adjusting the position of the neighbor node in 10-centimeter increments, both vertically and horizontally. This process involved a total of 176 positions ranging from (0,-50) to (150,50).

At each position, we record a minimum of 20 packets and calculated the average received power value. Our evaluation encompassed the testing of two wireless power transmitters, namely TX91501B and TX91503, in conjunction with the PA-915-01 patch antenna and DA-915-01 dipole antenna. This comprehensive assessment yields four images, as depicted in Fig. 5(a) to Fig. 5(d).

2) Observation Results: Fig. 5(a) to Fig. 5(d) illustrate the received power of Node 0 when concurrently receiving wireless power, with the neighbor node positioned at various locations. These four figures correspond to the configurations of TX91501B with a dipole antenna, TX91501B with a patch antenna, TX91503 with a dipole antenna, and TX91503 with

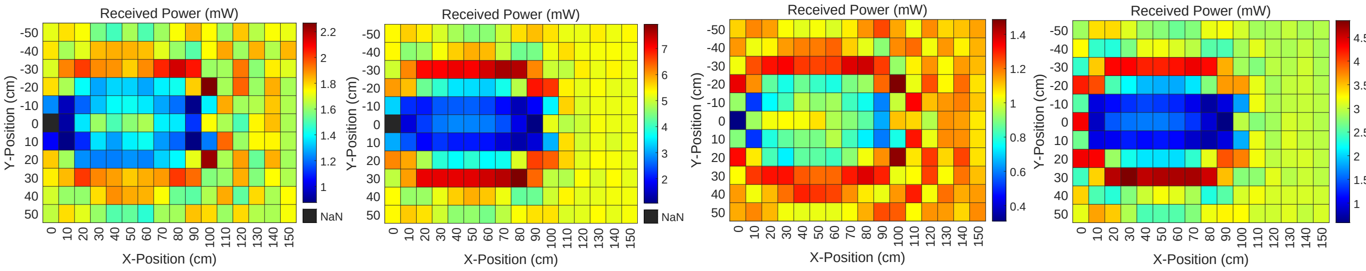


(a) Measurement scenario of concurrent wireless power receiving with two nodes. In this case, the wireless power transmitter used is TX91503, and both Node 0 and the neighbor node are equipped with dipole antennas. The wireless power transmitter remains fixed at coordinates (0,0), while Node 0 is positioned at (100,0). The neighbor node is moved in increments of 10 centimeters, both vertically and horizontally. This process covers a total of 176 positions (x,y), ranging from (0,-50) to (150,50). The measurement results are shown in Fig. 5.

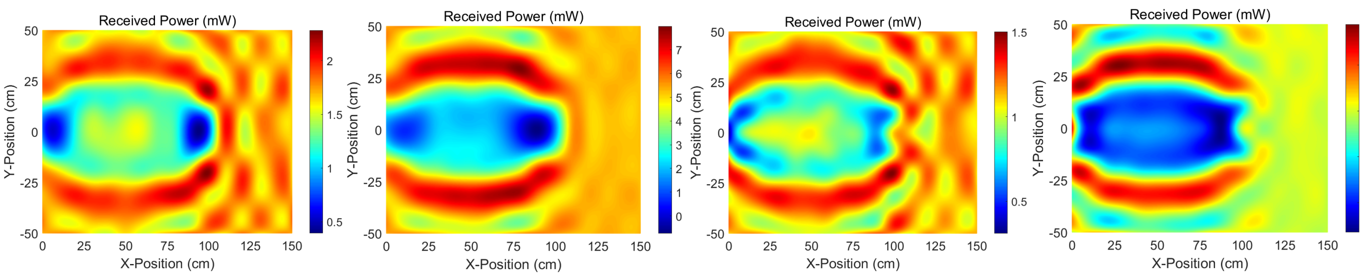


(b) Measurement scenario of concurrent wireless power receiving with different neighbor nodes for Node 0, four distinct topologies are formed by gradually increasing the number of neighbor nodes. These topologies are as follows: Topo 1: Node 0 alone; Topo 2: Node 0 and Node 1 as neighbor nodes; Topo 3: Node 0, Node 1, and Node 2; Topo 4: Node 0, Node 1, Node 2, and Node 3. The measurement results are shown in Fig. 6.

Fig. 4. Measurement scenarios of concurrent wireless power receiving.



(a) TX91501B+dipole antenna (b) TX91501B+patch antenna (c) TX91503+dipole antenna (d) TX91503+patch antenna



(e) TX91501B+dipole antenna (f) TX91501B+patch antenna (g) TX91503+dipole antenna (h) TX91503+patch antenna

Fig. 5. Received power of Node 0 when concurrent wireless power receiving, with the neighbor node positioned at various locations. For example, the color at position (80,-30) indicates the received power value of Node 0 when the neighbor node is positioned at coordinates (80,-30). Fig. 5(a) to Fig. 5(d) demonstrate the measurement results when testing the configurations of TX91501B with a dipole antenna, TX91501B with a patch antenna, TX91503 with a dipole antenna, and TX91503 with a patch antenna, respectively. Fig. 5(e) to Fig. 5(h) demonstrate the corresponding cubic spline interpolation results using MATLAB based on measurement results from Fig. 5(a) to Fig. 5(d).

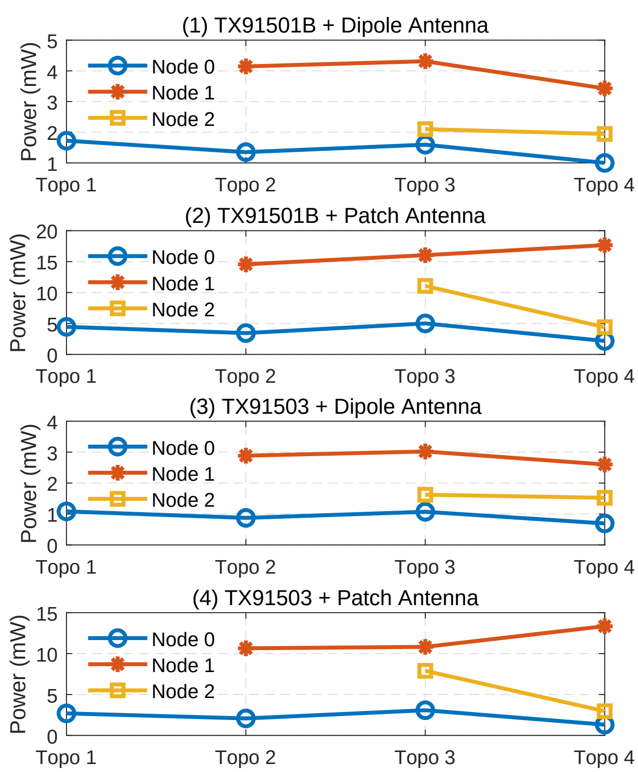


Fig. 6. Measurement results of concurrent wireless power receiving in different topologies and equipment settings.

a patch antenna, respectively. The results clearly demonstrate that Node 0 experiences energy interference in all cases. This observation implies that neighbor nodes are not independent when simultaneously harvesting energy, which differs from the behavior observed in wireless communication scenarios. It is important to note that the value at position (100, 0) corresponds to the scenario where only Node 0 is present, with no neighboring node in close proximity. This serves as a reference point for comparison against the cases when a neighbor node is introduced.

Unfortunately, these data are all in a mess, so we can hardly find more meaningful information, which motivates us to perform two-dimensional data interpolation using MATLAB. The fitting results with cubic spline interpolation are presented in Fig. 5(e) to Fig. 5(h). Surprisingly, a clear energy interference pattern emerges, which is likely a combination of signal penetration, Fresnel Zone, and wave interference. Since this energy interference pattern looks like an octopus, we name it "*Octopus Zone*". In this zone, the warm colors mean constructive energy interference, while the cool colors imply destructive energy interference. Furthermore, the yellow color represents the received power during concurrent power receiving is equal to the value of a single power transfer. Thus, the interference cancellation area is identified.

Lastly, a further analysis is conducted to evaluate energy interference between multiple nodes. As illustrated in Fig. 4(b), the measurement scenario involves concurrent wireless power receiving with different neighbor nodes for Node 0, resulting in the formation of four distinct topologies. These topologies are created by gradually increasing the number of neighbor nodes. The measurement provides an opportunity to assess the impact and behavior of multiple neighbor nodes on the concurrent wireless power receiving process.

A preliminary result of the energy interference between multiple receivers in these four topologies, considering different wireless power transmitters and receiving antennas, is presented in Fig. 6. It is observed that energy interference is a more complex phenomenon, and its characteristics can be influenced by adjusting the number of neighbors. Furthermore, it is noted that different receiving antennas have varying effects on energy interference, even within the same topology. These findings emphasize the importance of considering multiple factors, including the number of neighbor nodes and the choice of receiving antennas, when studying and managing energy interference in concurrent wireless power receiving scenarios.

IV. Insights from Experimental Observations

In this section, we discuss insights and shed light on future research directions inspired by the experimental observations.

1) Dynamic and Stability: We experimentally demonstrate that instantaneous received power in concurrent wireless power transmitting is dynamic over time. A possible explanation for this fact is caused by the inevitable relative carrier frequency offset and phase offset between energy transmitters, the desynchronization due to clock drift, and power offset. While channel uncertainty is a minor factor as the received power is relatively stable in a single WPT. However, much less is known about how these affect concurrent radiative WPT. Therefore, comprehensive investigation in both theoretical analysis and experimental study is urgent. On the other hand, the time differential between received packets is stable, thus accurate modeling its charging rate is helpful for rechargeable IoT devices powered by supercapacitors and rechargeable batteries.

2) Directional and Omnidirectional: The directional receiving antenna significantly impacts concurrent radiative WPT in terms of power intensity and the distribution frequency of received power. Thus, the system model must carefully consider the receiving antenna type to design efficient MAC protocols, routing strategies, scheduling algorithms, and so forth. In addition, more practical theoretical models for both single power transfer and concurrent power transfer are desired, which should take into account critical parameters such as antenna type, charger orientation, and placement angle. Furthermore, although a directional receiving antenna can offer many advantages over an omnidirectional antenna, it has less opportunistic energy harvesting in rich charging networks and less constructive energy interference from behind neighbor devices. Thus, it is worth conducting in-depth investigations to seek the tradeoffs.

3) Related and Independent: Up to now, far too little attention has been paid to the correlation of IoT devices as wireless communication is the primary purpose and network deployment is sparse. However, it is fundamentally different on battery-free IoT networks when energy is mainly supplied via wireless power transmission. Moreover, node density is gradually increasing as more and more IoT systems have been deployed for ubiquitous sensing and computing. The results of our study indicate that neighbor IoT devices are not independent. We learn from the obtained energy interference pattern that the neighbor node in the direct charging path between the wireless power transmitter and receiver hurts the performance, which is mainly due to signal penetration and absorption. The harmful interference is more severe near the source and destination. In other positions, constructive and destructive interference happens in accordance with the Fresnel Zone and wave interference theory. Namely, the power is enhanced if the energy waves are in phase when they arrive at a receiver, while it is negatively affected when the waves are out of phase. These findings will guide the planning of node placement and other schemes.

4) Limitations and Applicability: Lastly, we provide the limitations of the experimental settings in our study and highlight our plans to strengthen the applicability. First, our wireless power transmitting experiment involved the deployment of only two power transmitters with a charging distance of one meter. This limited setup may not fully capture the complexities and variations that may arise in scenarios involving a larger number of transmitters or different charging distances. To address this limitation, we are planning to conduct more comprehensive experiments that involve multiple transmitters and explore a wider range of charging distances. In addition, our experiments are conducted in an environment near the floor surface, which may introduce multipath fading due to reflections and interference. While this is a common scenario in real-world applications, it is worth noting that the floor surface may affect the propagation characteristics of the wireless power transfer. In our future experiments, we will aim to minimize these effects by implementing mitigation techniques, such as raising the devices from the floor or utilizing different floor materials. Furthermore, our current study does not consider antenna size and directionality diversity. In our future experiments, we plan to incorporate antennas with different sizes and directionalities to explore their impact on concurrent power transmitting and receiving.

V. Conclusions

This article set out to experimentally test some widespread assumptions in concurrent radiative WPT since a systematic understanding of its working behavior is still lacking. To this end, we have first reviewed existing research efforts on concurrent radiative WPT from the experimental study, theoretical model, MAC protocol, charging scheduling, and precision energy transfer using distributed antenna systems. After that, we have conducted a series of experimental studies to demonstrate severe discrepancies between the widespread assumptions and realities. The first finding was that instantaneous received power is not steady during concurrent wireless power transmitting, but its packet interval can be approximately regarded as stable. The second finding was that antenna directivity is non-trivial, so this factor must be carefully considered for concurrent energy transmission. One of the more significant findings to emerge from this study is the energy interference pattern of two nodes during concurrent wireless power receiving. Overall, these empirical findings are helpful in expanding our knowledge of concurrent radiative WPT. Finally, we have given an in-depth discussion on the insights and research directions for future work.

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