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Next-generation RF-powered networks for Internet of Things: Architecture and research perspectives

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ABSTRACT

Wireless power transfer technique aiming at wireless energy provision has emerged as a prominent solution to the architecture of long-term and self-sustainable wireless systems. Particularly, by integrating this approach with data communication, radio frequency (RF)-powered networks such as radio frequency identification systems have been ubiquitously deployed in recent years and are considered as one of the key components of both the Internet of Things and the Fourth Industrial Revolution. However, the lack of function diversity at end devices makes the conventional RF-powered networks merely support some simple and dull operations. In this context, various types of new devices with more intelligence and the ability of harvesting wireless power have been designed of late. Unfortunately, inevitable energy loss occurring in wireless propagation usually leads to time-consuming power transfer and network throughput degradation. Bearing this in mind, in this paper, we present a blueprint for the construction of next-generation RF-powered networks which intend to provide flexible network functions, prompt wireless power transfer, and high network throughput. Several relevant challenges and opportunities are also provided as a guidance on the formation of this new architecture-based Internet of Things.

1. Introduction

As an extension of the conventional Internet which gives people the ability to interact with global information and services mainly through the World Wide Web, the Internet of Things (IoT) enables the interconnection among everyday physical objects/devices (e.g., gas meters, streetlights, and pallets) to expand the Internet's advantages into all aspects of our daily life. Nonetheless, the limitation of device battery lifetime becomes the major impediment to the construction of long-term and self-sustainable IoT world. Fortunately, wireless power transfer technique whereby a coordinator can offer devices energy via radio frequency (RF) electromagnetic waves exhibits the possibility of wireless battery charging to reduce the overhead of battery maintenance (Bi et al., 2015; Kamalinejad et al., 2015). Since these devices conduct energy harvesting merely based on incident RF signals, we call them as *RF-powered devices* (RPDs). Furthermore, the coordinator is typically deployed to not only transfer power but also communicate with RPDs for physical world monitoring. We call such a system as an *RF-powered network*. Radio frequency identification (RFID) systems are hitherto the only widely deployed example of RF-powered networks and they are applied in various fields such as inventory and logistics management, object tracking, and intelligent transportation systems. Such a system operating on standardized bands with the center frequencies of, for example, 13.56 MHz (i.e., high frequency – HF) and 915 MHz (i.e., ultra high frequency – UHF) typically employs a reader (coordinator) to collect the preconfigured identifiers of numerous tags/RPDs. In this context, RFID is considered as one of the most viable technologies to accelerate the formation of IoT (Myung and Lee, 2006; Ji et al., 2015; Park et al., 2017; Myung et al., 2007; Wang et al., 2018; Tang et al., 2016; Bu et al., 2018). However, most commodity tags merely support several lightweight and fundamental operations such as ALOHA-based channel access and identifier transmission. Moreover, they are born without any programmability and sensing capability, which imposes restrictions on the implementation of advanced functionalities. On the other hand, leveraging several pervasive signals (e.g., Wi-Fi and LTE) other than the standardized ones for energy harvesting seems to be a promising scenario.

In this context, designing a new type of RPD with more intelligence and the ability of energy harvesting in various bands has attracted growing attention from both academia and industry recently. Fig. 1

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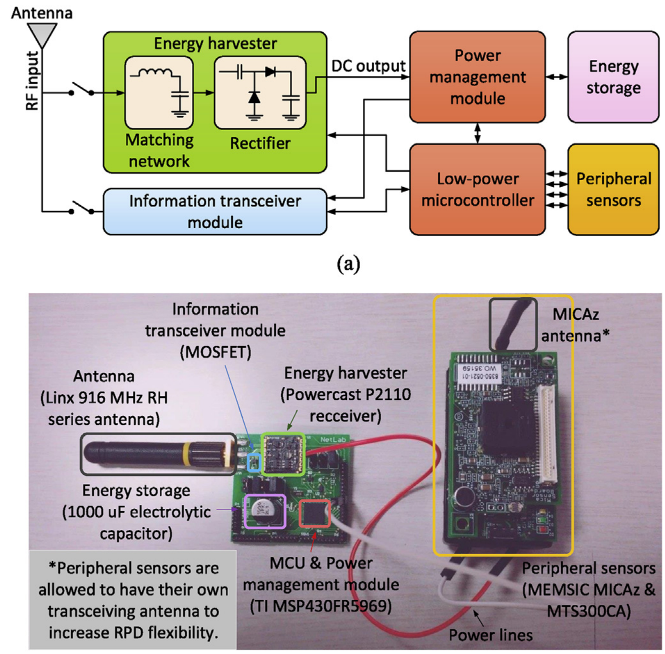


Fig. 1. RPD architecture. (a) A typical RPD design block diagram. (b) A customized RPD prototype with separated sensors.

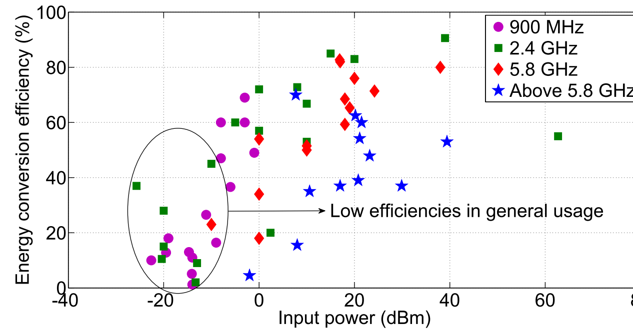


Fig. 2. Energy conversion efficiency of state-of-the-art rectifiers.

(a) illustrates a general design block diagram of an emerging RPD. The low-power microcontroller unit (MCU) providing the programmability and the power management module presiding over the energy regulation of other modules constitute the "brain" of the RPD. Particularly, when the available energy at the energy storage is determined to be insufficient, the MCU requests the coordinator for wireless power transfer and sets the RPD into energy harvesting mode. In this case, the RPD equalizes the impedances of its antenna and the remaining circuit via an impedance matching network so as to maximize the input wireless power in a certain frequency band with the center frequency of, for example, 915 MHz or 2.437 GHz (Wi-Fi channel 6). The matched RF signal is then converted into DC voltage typically through a diode-based rectifier as the power supply to the brain for subsequent operations. Based on this working principle, we have developed an RPD prototype as presented in Fig. 1 (b). Instead of onboard sensors, this RPD integrates an MTS300CA, a separated sensor board parasitizing a MICAz mote, with other modules embedded on a same board, which makes it feature more flexible sensing capabilities (MEMSIC MTS300 Sensor Board; MEMSIC MICAz). In this context, it is motivated to construct more flexible RF-powered networks than the RFID systems with a coordinator and numerous RPDs instead of the traditional tags. On top of that, this design philosophy caters to the architecture principles of intelligent IoT and hence the emerging Fourth Industrial Revolution (Torr, 2016; Schwab, 2016). Nevertheless, since the fading of RF signals during wireless propagation results in that only a small fraction of wireless power can arrive at RPDs in general usage, the energy conversion efficiency of state-of-the-art rectifiers is limited to a low level, which is quantified in Fig. 2 (Valenta and Durgin, 2014). As a consequence, RPDs need to consume large amount of time to cumulate sufficient energy for required operations, which increases the communication latency and hence induces the degradation of overall network throughput.

Therefore, we expect to achieve the architecture of next-generation RF-powered networks (NGRPNs) with high energy harvesting rate and network throughput. Evidently, the most pivotal issue is to improve the incident wireless power at the RPD. To this end, a plausible solution is to compulsively raise the output power of the coordinator. Unfortunately, it is well known that the current level of daughterboard development limits the output power boost to a fixed value. In this context, by observing that multiple coordinators with overlapping transmission ranges can be always seen in our daily life (e.g., distribution of multiple data sinks in a large-scale wireless sensor network or high-density Wi-Fi deployment in an indoor environment), we envisage multisource wireless power transfer for the construction of NGRPNs. In other words, we consider utilizing multiple coordinators to transfer power to RPDs with the necessity for energy harvesting before information transmissions. Meanwhile, for high network throughput, it is necessary to allocate several coordinators for the communications with RPDs having sufficient energy to immediately convey information. Unlike traditional RF-powered networks that focus on exploiting a single coordinator for wireless power transfer and information collection irrespective of the potential of multiple coordinator-based network operations (Lu et al., 2015; Ha et al., 2018), NGRPNs embody an emerging and promising wireless network architecture that fully utilizes existing network resources to put in place long-term and self-sustainable IoT systems.

This work stems from our previous study that targets at designing a medium access control protocol to account for joint wireless power transfer and data collection in an NGRPN (Shao et al., 2016). This paper makes additional contributions summarized as follows. i) We provide an overview of state-of-the-art design block diagram of RPDs and present our customized RPD prototype. ii) For the ease of NGRPN implementation in practice, we present detailed high-level description of the state diagrams of both coordinator and RPD. iii) Based on the overall architecture and basic operations of NGRPNs, we demonstrate two corresponding application scenarios to explain how the benefits introduced by NGRPNs are manifested in real life. iv) In addition to the experimental two-source wireless power transfer evaluation and the straightforward distance-based coordinator selection approach in (Shao et al., 2016), we further conduct simulative evaluation regarding more complicated case of wireless power transfer to show the research opportunity and insight for coordinator selection in NGRPNs. v) Instead of the one-fold medium access control design in (Shao et al., 2016), we provide a holistic summary of research perspectives in NGRPNs with detailed challenges, opportunities, and related studies in the literature.

The organization of this paper is: Section 2 presents the general architecture and applicable scenarios of NGRPNs; In Section 3 and Section 4, we discuss the key enabling technology of NGRPNs, i.e., multisource wireless power transfer, and provide some consequent research challenges with corresponding opportunities, respectively; Section 5 draws the conclusion.

2. Architectural design and use cases of NGRPNs

In order to go beyond conventional read/write operations in the legacy RF-powered networks (i.e., RFID systems) and accommodate the requirements of IoT, NGRPNs exploit the emerging RPDs with more intelligence, employ multiple coordinators to promptly offer RPDs sufficient energy, and orchestrate several coordinators for information acquisition to reduce the influence of wireless power transfer on the overall network throughput.

2.1. Generic network configuration

As illustrated in Fig. 3, the NGRPN aims at large-scale deployment and hence includes multiple coordinators as the gateways (gateway layer) to the network management center (control layer) as well as an enormous variety of distributed RPDs (RPD layer) as the bridge connecting the cyber and physical worlds. The network management center communicates with all the coordinators through high speed data links while the signal transmissions between the coordinators and RPDs proceed wirelessly. A coordinator is accomplished to both transfer wireless power to and exchange information with the RPDs. Each RPD, on the other hand, performs preprogrammed algorithms to report its identifier or deliver requested information pertaining to its environs to a corresponding coordinator.

The fundamental network operation is to harness all the coordinators to aggregate the "information" from all the planted RPDs. Unfortunately, some RPDs may undergo energy deficiency due to previous operations and hence need to be recharged before information transmission. Bearing this in mind, we classify the RPDs into two categories according to a statistically or empirically preset energy threshold as depicted in Fig. 3: *energy demand RPD* (EDD) and *information transmission RPD* (ITD). EDDs need sufficient energy replenishment before information transmission while ITDs are capable of immediate information conveying. Particularly, multiple coordinators are assigned for wireless power transfer to a certain EDD. Moreover, several coordinators are allocated for information aggregation proceeding together with the wireless power transfer process to boost the overall network throughput. As with the RFID systems, both the wireless power and information are carried by the signals within an identical frequency band. Typically, this power provision approach is referred to as in-band wireless power transfer. For the diversification of IoT infrastructure, this band may be the one occupied by Wi-Fi signals (Talla et al., 2015) rather than being limited to the standardized ones in RFID systems.

In this context, as shown in the state diagrams in Fig. 3, each coordinator and RPD have four and seven states, respectively. In particular, the "RPD association" state for coordinators represents the processes of channel access for RPDs and task assignment for coordinators. Note that among the coordinators allocated to transfer power to an EDD, one of them is selected to be also in charge of data collection from the EDD after the completion of wireless energy harvesting, which corresponds to the "data reporting request" condition in the state diagram of RPD. This selection may be oriented to the best coordinator-EDD channel quality derived from the comparison of received EDD signal strength at all the candidate coordinators, or the least inter-coordinator interference based on the information regarding the task assignment of other coordinators. Besides, it is worth noting that RPDs in the "information transmission" state can opt for sending their identifiers with or without sensed data according to the data requests from corresponding coordinators. On the other hand, for the call flow for RPD data collection, the case of EDDs is more complicated than ITDs due to the necessity of wireless energy harvesting process. More specifically, since the residual energy levels of all accessed EDDs are different and it is difficult for the management center to centrally compute their necessary energy harvesting times for full energy replenishment due to the randomness of wireless channels, the derivation of individual energy harvesting time of EDDs proceeds in a distributed manner. Afterwards, when the network operation arrangement regarding wireless power transfer to and data collection from all accessed RPDs is accomplished, all network operations start and the wireless power transfer process lasts for the pre-computed energy harvesting duration (i.e., t as depicted in Fig. 3).

2.2. Proof-of-concept network operations

NGRPNs with low-cost RPDs and high energy harvesting rate enable several promising IoT applications. Particularly, it adheres to the contemporary requirements of promptly acquiring physical-world information such as detecting luxury movement in museums and monitoring perishable goods in markets.

2.2.1. Detection of luxury movement with computational RFID (CRFID) systems

CRFID systems employ multiple RFID readers (coordinators) and computational RFID tags (RPDs), abbreviated as C-tags, to achieve more intelligent operations. In particular, Wireless Identification and Sensing Platform (WISP), Moo, and Farsens wireless battery-free sensors are the pioneers of C-tags which validate the feasibility of implementing advanced algorithms at battery-free RPDs (WISP; Moo; Farsens RFID Sensors). With such C-tags, an applicable scenario of the CRFID systems is to detect luxury movement in a museum or a store with high speed and low cost. In detail, we affix each luxury with a C-tag programmed to have the functionality of signal detection. In normal case (i.e., a luxury/C-tag keeps static), the received signal feature (e.g., phase or average strength) at a C-tag from each vicinal reader will follow a specific statistical distribution. However, when the C-tag moves a certain distance due to some factors such as theft and severe vibration, drastic change of the distribution corresponding to each reader may occur. Unfortunately, the C-tag may suffer from energy shortage after executing the power-consuming signal detection algorithm and hence fails to report its identifier for the notification of associated luxury movement, which results in tremendous financial loss. To eliminate this concern, a CRFID system designates multiple RFID readers for high-speed energy replenishment to enable prompt detection of luxury movement.

2.2.2. Monitoring of perishable goods with wireless rechargeable sensor networks (WRSNs)

ZigBee Alliance recently released ZigBee 3.0 that is a low-cost and low-power wireless mesh network standard supporting the connection of energy-harvesting-enabled sensors (ZigBee Alliance, 2016; Links, 2016). Motivated by this, we consider an NGRPN-embodied WRSN where multiple data sinks (coordinators) are planted to collect the characteristics (e.g., temperature, humidity, and gas components) of an interested area through a large number of rechargeable sensors (RPDs) distributed for environment sensing. The rechargeable sensors harvest the transmitted wireless power from the data sinks for both the sensing and data reporting operations. An exemplary application of WRSNs is to monitor perishable goods in a market with electrochemical sensors that can detect the concentration of chemical and biological agents (International Sensor Technology, 2015). In detail, when the concentration of a certain agent exceeds a predefined threshold or an abnormal substance emerges, the network operator can promptly obtain the information from the sensors and make corresponding countermeasures. Particularly, if there exist several EDDs, multiple data sinks are allocated to offer them high-speed energy provision so as to decrease the extra time consumed in the wireless energy harvesting process and hence avoid goods deterioration.

3. Exploration of multisource wireless power transfer

It seems that the more the coordinators are utilized for wireless power transfer, the more the harvested energy at an RPD is. However, due the fact that each power flow is typically carried by a continuous wave (CW), i.e., a sinusoid wave with constant amplitude and frequency, multiple received power flows at an RPD may combine constructively or destructively due to their phase differences as illustrated in Fig. 4. Accordingly, we envision that the confluence of multiple power flows at an RPD does not necessarily induce higher power than

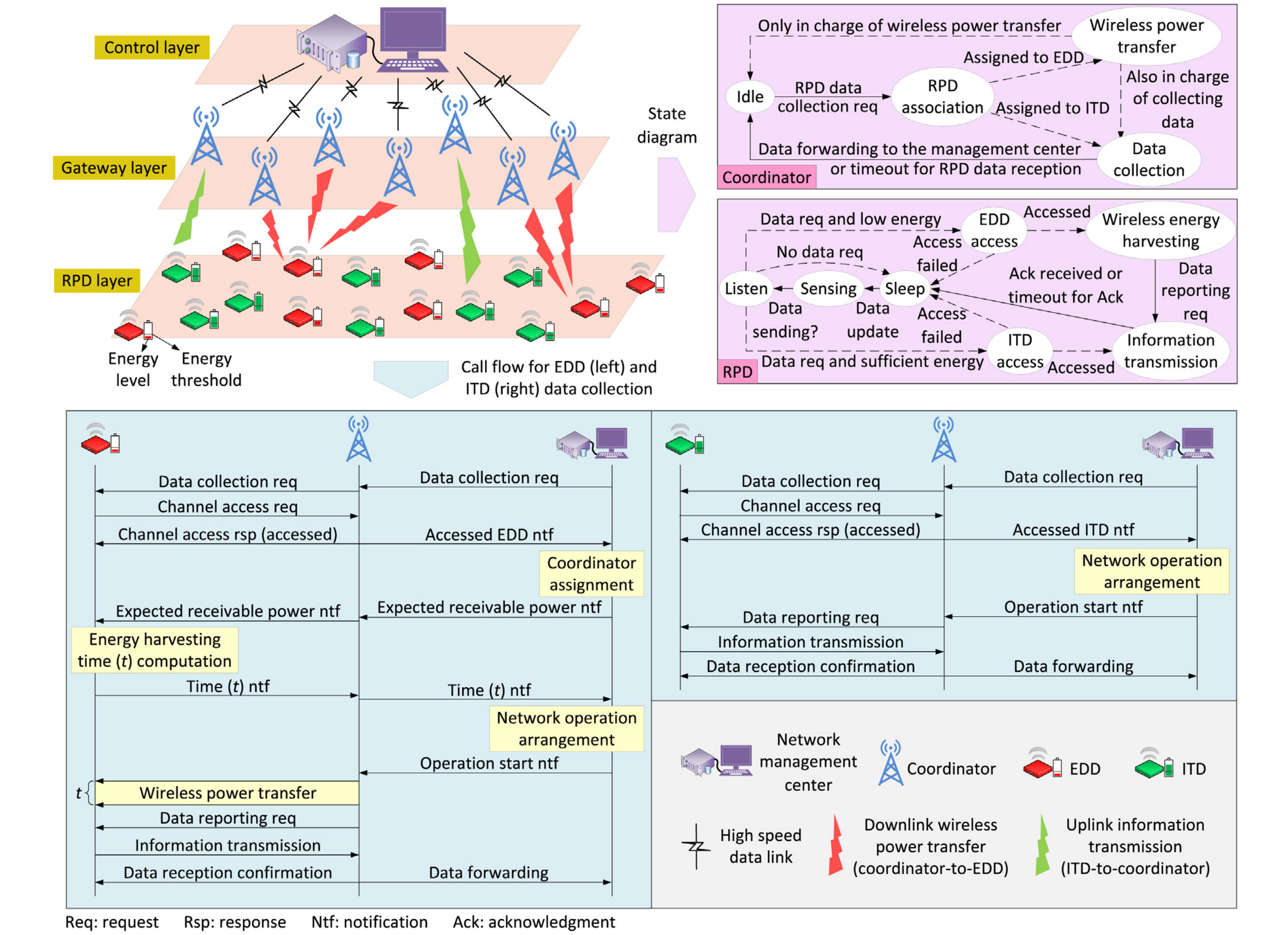


Fig. 3. Basic network structure of an NGRPN. Multiple coordinators are designated for wireless power transfer to an EDD (energy demand RPD) for harvested-power improvement. Meanwhile, several coordinator-ITD (information transmission RPD) pairs are established to avert severe network throughput decrement stemming from the channel occupation for wireless power transfer. Given a certain state in the state diagrams of coordinator and RPD, the solid line indicates the only state transition path, whereas the dotted line shows one of several possible state transition paths.

the case of single power flow.

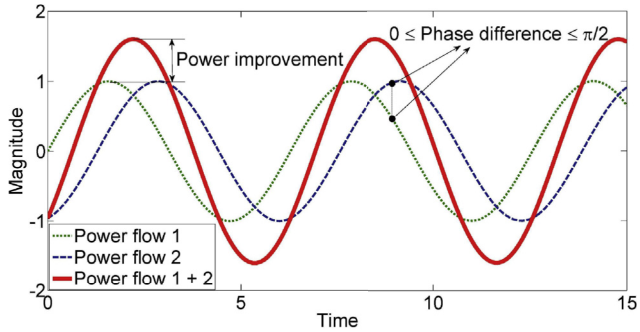
3.1. Pilot experiment

In order to observe what will occur when multiple power flows combine in practice, we conduct a preliminary two-source-based pilot experiment (Shao et al., 2016) as shown in Fig. 5 (a) which consists of:

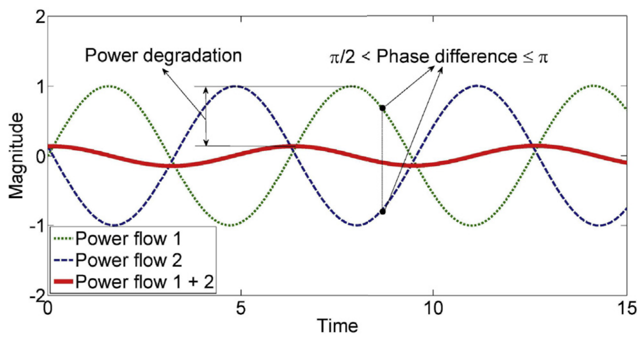
- A Linux PC-controlled USRP N210 software-defined radio generating CWs with the center frequency of 915 MHz (i.e., the wavelength is $\lambda \approx 33$ cm in vacuum) as adopted in the UHF RFID systems (USRP N210);
- A Mini-Circuits ZN2PD2-63-S+ 0-degree power splitter providing two identical power flows in terms of amplitude and phase at the output (ZN2PD2);
- Tow Powercast omnidirectional antennas (915 MHz) connected to the power splitter for imitating two-source (Coordinator 1 and 2) wireless power transfer (Powercast);
- An RPD (precisely, only the energy harvesting part in Fig. 1) composed of a Powercast P2110 Energy Harvesting Evaluation Board and a directional antenna (915 MHz) (Powercast);
- An Agilent InfiniiVision MSO-X 4034A oscilloscope measuring the harvested energy at the RPD (InfiniiVision MSO-X 4034A Oscilloscope).

We additionally address several crucial issues concerning accurate data collection. i) To achieve precise synchronization between the two coordinators, we opt for two LMR-200 coaxial cables with the time delay of only 4 ns/m between the power splitter and the two antennas (LMR-200 Communications Coax). ii) Multipath effect is unpredictable in practice and may blur the relation of our environment setting to the efficiency of wireless power transfer. To mitigate its impact as much as possible, we refer to the well-known Friis transmission formula and fine-tune the output power of USRP N210 by taking into consideration the attenuation over the power splitter and coaxial cable. iii) Since the RPD is designed to be able to harvest energy from 850 MHz to 950 MHz, we have to deal with the energy interference from existing radios such as LTE. By considering that the interference cannot be avoided in our experiment, we resort to analyzing the obtained data and then disregard inconsistent results. iv) We place the two antennas approximately in the same direction so as to align the two power flow paths to the greatest extent. Meanwhile, the antenna spacing is set to be larger than $\frac{\lambda}{4}$ (8.25 cm) for reduction of mutual coupling.

In this context, we conduct environment repeatedly and observe similar results for each of the three wireless power transfer cases. With occasional fluctuation (due to multipath effect, interference, etc.) in the results excluded, Fig. 5 (d) shows the most representative and distinguishable charging (high voltage level)/discharging (low voltage level)



(a)



(b)

Fig. 4. Power variation for two-source wireless power transfer in comparison with a single power flow. (a) Constructive combination of two power flows (power improvement). (b) Destructive combination of two power flows (power degradation).

processes for the three cases. In Fig. 5 (d), we compare the charging time with a single coordinator (Fig. 5 (a) with Coordinator 2 disconnected) and two coordinators under two cases:

- In case 1 (Fig. 5 (b)), it is observed that employing an additional coordinator (Coordinator 2) with the same distance to the RPD as Coordinator 1 indeed introduces power boost compared with the single-coordinator case;
- In case 2 (Fig. 5 (c)), while Coordinator 2 is closer to the RPD in comparison with case 1, the charging time unexpectedly becomes much longer than both the single-coordinator case and case 1.

These phenomena conform to what are presented in Fig. 4 and validate our speculation. In detail, the signal phase mismatching ranging in $[0, \frac{\pi}{2}]$ (i.e., in-phase case) induces significant energy enhancement while that in $(\frac{\pi}{2}, \pi]$ (i.e., out-of-phase case) leads to dramatic power degradation. In addition, we have

$$\Delta\phi = \frac{2\pi\,|d_1 - d_2|}{\lambda} \bmod 2\pi, \tag{1}$$

where $\Delta\phi$ is the phase difference of two power flows and d_1 (d_2) is the distance between the Coordinator 1 (2) and the RPD. In this context, recall the result regarding case 1, since the coordinator-RPD distances are the same, the phase mismatching is 0, which induces reduction of the charging time. By contrast, in case 2, the coordinator-RPD distance difference is half of the wavelength (i.e., phase mismatching of π), which leads to considerably long charging latency.

3.2. Extensive simulation

In addition to the results obtained above, we conduct extensive simulations via MATLAB regarding multisource wireless power transfer with three-fold purpose:

- Seamlessly characterizing how the change of RPD location affects incident power;
- Investigating multisource wireless power transfer with more complicated combination of coordinator-RPD pair;
- Envisaging an adaptive coordinator selection approach and validating its feasibility to maximize the incident power at an RPD.

To this end, we consider four coordinators each of which has two working modes (i.e., radio-on and radio-off) and is able to cover the whole 4 m × 4 m area as shown in Fig. 6. Each power flow is carried by a CW with the frequency of 915 MHz as adopted in the above experiment. Moreover, we make the modeling of RF signal propagation according to the wireless propagation characteristics regarding an electromagnetically short antenna. In detail, the near-field is the region within the radius of $d < \frac{\lambda}{2\pi}$ where the signal power attenuates with the distance d away from the source. The far-field is the area where $d \geq \frac{\lambda}{2\pi}$ and the signal strength decreases with d^2. In this context, we quantify the averaged incident signal power at the RPD with the location granularity of 0.05 m within the area according to the following two scenarios.

3.2.1. Scenario 1

We activate one coordinator having the shortest distance with the RPD and denote the averaged incident power at the RPD as P_{Single}. Afterwards, we observe P_{All} which is the incident power on average when all the coordinators are radio-on and compute the power enhancement $P_{\text{All}} - P_{\text{Single}}$. Fig. 7 presents $P_{\text{All}} - P_{\text{Single}}$ in decibel. We figure out that within the circle with the origin at $(0, 0)$ and the approximate radius of 35 cm, $P_{\text{All}} - P_{\text{Single}}$ is extremely sensitive to the location of RPD. This is due to the fact that the incident signal powers from all the four coordinators are comparable with each other. Accordingly, notable power fluctuation of the combined signal occurs and this phenomenon shows great changes as the movement of the RPD within this area. Remarkably, the four-source wireless power transfer technique attains the power boost of 12 dB at the origin $(0, 0)$ under the fact that the combined signal at this point is still a continuous wave and that its power can be simply calculated as $0.5 \times A^2$ where A is the amplitude of the received signal at the RPD. Besides, unlike the result in the previous pilot experiment, the existence of two out-of-phase coordinators does not necessarily indicate power degradation compared with the case of a single coordinator when three or more coordinators are available for power transfer. This accords with our expectation that for a certain location, the multisource wireless power transfer technique may still surpass the case with a single coordinator though there exist several pairs of out-of-phase coordinators among all the available ones. As a matter of fact, it is not that straightforward to figure out how multiple power flows combine at a certain location when more than two coordinators are employed for wireless power transfer since the distances between every two coordinators may be different. On the other hand, when the RPD is in the vicinity of a coordinator, its location has less impact on the value of $P_{\text{All}} - P_{\text{Single}}$ since the incident power from the closest coordinator dominates. These valuable observations provide a guidance on the architecture of NGRPNs with mobile RPDs considered.

3.2.2. Scenario 2

We consider adaptively selecting a portion of mutually in-phase coordinators for power transfer. To this end, we control the working mode (radio-on/off) of each coordinator to make different power flow combinations at the RPD for every tested location. We conduct 2^4 trials among which the maximum received power on average is denoted as P_{Max} and calculate $P_{\text{Max}} - P_{\text{Single}}$. Note that we focus on presenting the corresponding results herein other than algorithm proposal for adaptive coordinator selection. Fig. 8 shows that $P_{\text{Max}} > P_{\text{Single}}$ is satisfied in most locations through this adaptation process, which validates that the multisource wireless power transfer approach is feasible to achieve power improvement at the RPD in general. Furthermore, in order to

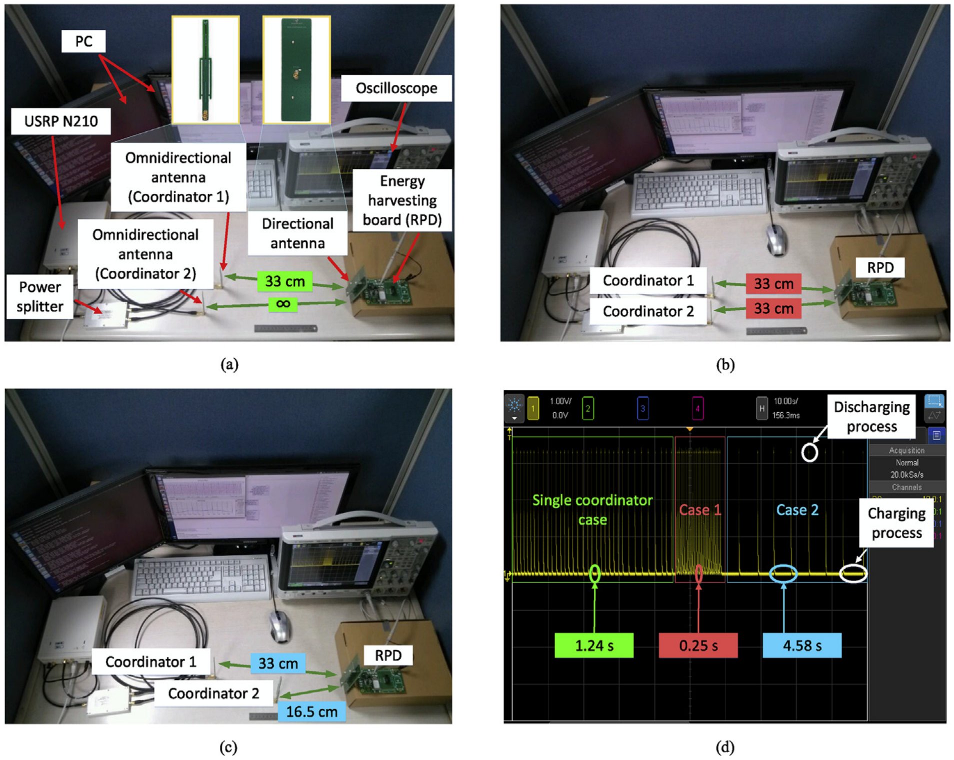


Fig. 5. Experiment regarding two-source wireless power transfer. (a) Experiment setup and the single-coordinator case by excluding Coordinator 2. (b) Case 1 with two in-phase coordinators. (c) Case 2 with two out-of-phase coordinators. (d) Charging time comparison among the three cases. Charging and discharging processes proceed repeatedly at the RPD.

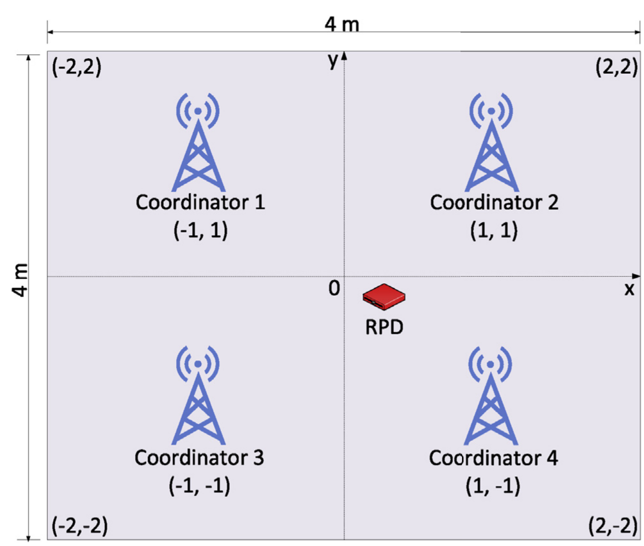


Fig. 6. Simulation model regarding four-source wireless power transfer.

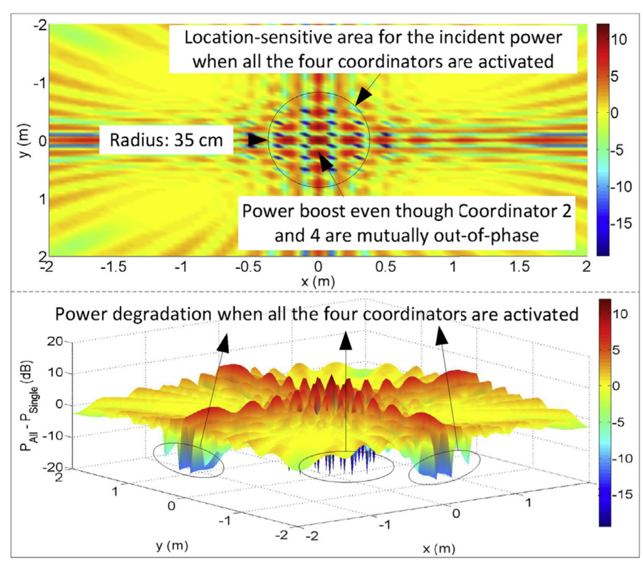


Fig. 7. Simulation result in terms of the power improvement when all the coordinators are turned on.

protrude the importance of the coordinator selection process, we depict Fig. 9 to quantify the received power difference $P_{\mathrm{Max}} - P_{\mathrm{All}}$. In other words, we are interested in investigating the power boost introduced by an adaptive coordinator selection process in comparison with the naive approach of employing all available coordinators for wireless power transfer. The results show that the locations with approximately 12 dB power increment correspond to the ones where dramatic power degradation occurs in Fig. 7. In addition, the maximum value of $P_{\mathrm{Max}} - P_{\mathrm{All}}$ is close to 24 dB which is achieved near to the location $(0, 0)$. It is worth noting that $P_{\mathrm{Max}} - P_{\mathrm{All}} = 0$ dB at the origin $(0, 0)$, which signifies that employing all the four coordinators for wireless power transfer is the best option since the power flows from every two of them combine constructively at this location. Together with Fig. 8, we figure out that an adaptive coordinator selection process can eliminate the power degradation caused by the naive utilization of four coordinators and induce even tremendous power increment compared with the case of a single coordinator.

Note that due to the existence of unpredictable signal distortion caused by diverse factors (e.g., multipath effect and channel dynamics) in practice, the simulative results above may fail in perfectly conforming to real-world wireless power transfer behavior. However, by inves-

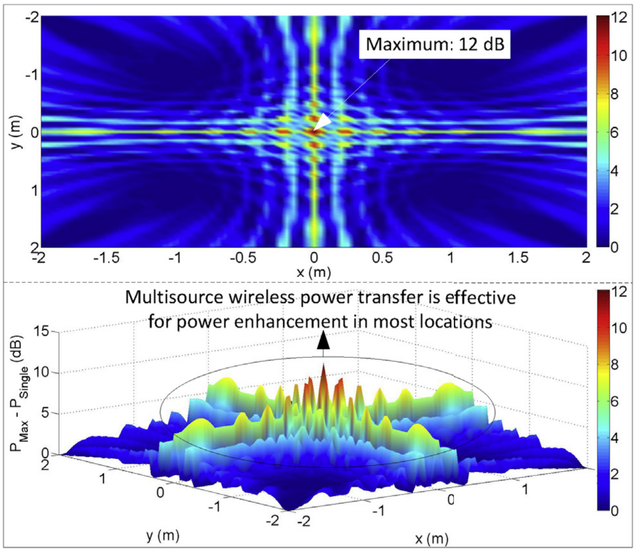


Fig. 8. Simulation result in terms of the maximum power increment with an adaptive coordinator selection process.

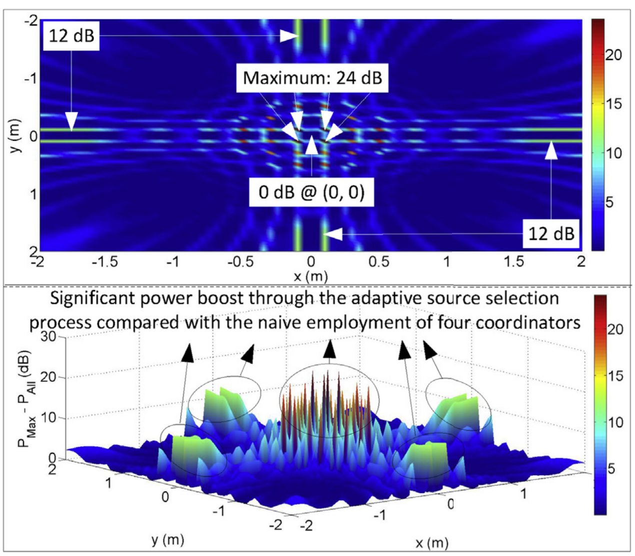


Fig. 9. Simulation result in terms of the difference between the power enhancement in Figs. 7 and 8.

tigating both the environmental results in Fig. 5 (d) and the simulative data, we believe that these results can be used to derive a basic analytic model for multisource wireless power transfer. Network operators can then refine this model through massive in-situ measurement studies and statistical analyses to figure out the optimal solution for charging a certain RPD and to fully benefit from the adoption of multisource wireless power transfer technique.

4. Future research perspectives

NGRPNs advocate an emerging system architecture and hence incur fruitful research issues as presented in Table 1.

4.1. Network planning

Given a specific environment where we intend to deploy an IoT system with numerous RPDs planted in some locations to obtain corresponding physical information, network planning mainly encompasses cost-efficient topology design of coordinators. Particularly, in order to enable multisource wireless power transfer, it is necessary to take into consideration the transmission range overlapping of multiple coordinators as well as potential inter-coordinator interference caused by wireless power transfer or information transmission.

4.2. Network resource management

Typically, the number of employed coordinators is much less than that of distributed RPDs in an NGRPN. Moreover, a common wireless channel is shared among multiple RPDs for wireless power transfer and communication. Accordingly, it is significant for the network operators to appropriately allocate the limited resources to accommodate the needs of RPDs and maintain the network performances to some extent. Readers can find some preliminary results regarding this issue from several perspectives such as channel access and coordinator allocation in (Shao et al., 2016).

4.3. Advanced techniques for network performance boost

Aside from the primitive network problems, several advanced techniques show the potentials to build high-performance and robust NGRPN-based IoT systems.

4.3.1. Power-optimized waveforms (POW)

Due to the fact that diode-based rectifier in the energy harvester cannot be activated until a peak voltage (0.7 V for silicon diodes and 0.3 V for germanium ones typically) is applied, the constant amplitude of CW indicates low energy harvesting rate at the RPDs. In this context, POW is proposed to increase the rectifier power efficiency by exploiting multitone signals to offer larger peak voltage to RPDs (Trotter et al., 2009; Trotter and Durgin, 2010).

4.3.2. 16-QAM (quadrature amplitude modulation) backscatter modulator

Backscatter communication where an RPD absorbs or backscatters the coordinator signals to achieve the delivery of bit ‘0’ or ‘1’ is the main feature of UHF RFID systems. It enables ultra-low-power communication since no exclusive RF signal transmitter is needed. However, due to the energy constraint of RFID tags, only amplitude shift keying (ASK) modulation which is simple but limited to low data rate is supported. In this context, S. J. Thomas et al. have developed a 16-QAM backscatter modulator supporting low-power (1.49 mW) and high-data-rate (96 Mbps) backscatter communication (Thomas and Reynolds, 2012).

4.3.3. Ultra-low-power device-to-device (D2D) communication

To reduce the power consumption of RPDs in communicating with remote coordinators, multihop communication systems are considered as a better choice where D2D communication is the fundamental issue. Of late, several emerging studies show the potential to implement an ultra-low-power D2D communication framework. P. Nikitin et al. have shown that RFID tag-to-tag backscatter communication is feasible with a dedicated RFID reader (Nikitin et al., 2012). By building a prototype with a customized CW generator as the external wireless power source, A. Athalye et al. have validated that a novel phase cancellation approach can also enable ultra-low-power D2D communication (Shen et al., 2016; Karimi et al., 2017). To take a step further, S. Gollakota et al. have demonstrated that even the signals from a remote TV tower are available for inter-RPD communication (Liu et al., 2013; Parks et al., 2014).

4.3.4. Chronological wireless power and information transfer (CWPIT) and simultaneous wireless information and power transfer (SWIPT)

To provision high network throughput, we need to know the impact of wireless energy harvesting on the information transmission procedure. To this end, CWPIT studies uplink information transmission

Table 1
Research perspectives in NGRPNs.

Issue		Objective	Challenges	Opportunities
Network planning		Determine the topology of coordinators to enable multisource wireless power transfer to all RPDs	1) Probable covering failure for some RPDs if deployed randomly 2) Cost increment if deployed uniformly	An optimization problem with the purpose of maximizing the total number of coordinator-RPD pairs is supposed to be solved
Network resource management	Channel access	Schedule the channel usages at EDDs and ITDs	1) Difficulty in determining the access order for EDDs and ITDs 2) Possibility of packet decoding failure at the RPDs located in the overlapped transmission range of multiple coordinators where packet collision occurs	1) Give higher priority to EDDs for multisource wireless power transfer, or to ITDs for throughput boost at the beginning of information aggregation 2) Design novel carrier waves enabling the decoding of collided packets
	Coordinator allocation	Select the coordinators for wireless power transfer and information aggregation, respectively	1) Lack of theoretical modeling of multisource wireless power transfer 2) Necessity of scheduling information query process for maximum network throughput improvement	1) Modeling of multisource wireless power transfer by considering the signal phase mismatching phenomenon 2) "Phase adaptation" where coordinators cooperatively adjust signal phases to make the power flows combine constructively at an RPD
	Power/information-related interference	Schedule wireless power transfer and information aggregation to maintain the network throughput and avoid their mutual interference	1) Power-information interference at coordinators and RPDs 2) Interinformation interference at coordinators	Spectrum sensing algorithm design or power/information transfer scheduling
	Holistic RPD monitoring	Obtain current RPD status (e.g., identifier, presence or absence) in real time	1) Collision of RPD responses due to the usage of a common wireless channel 2) Time-consuming process in large-scale networks	Design time-efficient RPD monitoring protocols relevant to RPD counting, missing RPD detection, etc.
Advanced techniques for network performance boost	Power-optimized waveforms (Trotter et al., 2009; Trotter and Durgin, 2010)	Design novel waveforms instead of conventional CW to increase the energy conversion efficiency of rectifiers	Difficulty in voltage regulation and signal demodulation due to large ripple in the rectifier output	Circuit design, e.g., adding a charge pump integrated circuit with an external capacitor, to reduce the ripple
	16-QAM backscatter modulator (Thomas and Reynolds, 2012)	Achieve a new type of backscatter communication with the features of low power, high date rate, and long range	No comparison with an active signal transmitter in terms of data rate, power consumption, and communication range	Development of promising RPDs with more advanced backscatter modulators implemented
	Ultra-low-power device-to-device communication (Nikitin et al., 2012; Shen et al., 2016; Karimi et al., 2017; Liu et al., 2013; Parks et al., 2014)	Enable multihop information delivery to reduce the power consumption of RPDs	1) Operation is generally limited in near field 2) Extension of communication range dramatically decreases data rate	Implement high-performance-oriented communication techniques under the consideration of RPD capability
	CWPIT (Chen et al., 2014) and SWIPT (Zhang and Ho, 2013; Pan et al., 2017)	Analysis of rate-energy tradeoff for chronological downlink power and uplink information transfer (CWPIT) or concurrent downlink information and power transfer (SWIPT)	1) Limited to physical layer techniques 2) Lack of validation with off-the-shelf energy harvesting and communication modules	1) Cross-layer design especially for physical layer and medium access control layer 2) Hardware implementation
	Safe charging (Dai et al., 2014a, 2014b)	Deliver more energy to target while no other locations have electromagnetic radiation above a certain threshold	1) NP-hardness 2) More complicated when each employed coordinator (charger) is power-adjustable	Solving multiple subproblems to find an approximate solution
	Countermeasures to location spoofing	Prevent improper coordinator allocation caused by mendacious device location information	Difficulty in pinpointing the exact locations of malicious RPDs	1) Crowdsourcing at multiple contiguous coordinators to detect location spoofing 2) Protocol design to suppress the occurrence of location spoofing
	Wireless energy crowdharvesting	Multisource wireless power transfer to multiple accessed EDDs	1) In general, the best combination of coordinators for wireless power transfer is different for each EDD 2) More complicated in the case of mobile RPDs	1) Graphical coordinator selection algorithm based on the distance/phase difference among all coordinator-EDD pairs 2) Design of real-time trajectory tracking techniques for mobile RPDs

after downlink wireless power transfer given a total duration constraint (Chen et al., 2014). More specifically, CWPIT circumvents analyzing rate-energy tradeoff (i.e., the tradeoff between information and power transfer rates) by adjusting the power transfer duration. On the other hand, SWIPT focuses on concurrent downlink wireless power and information transfer (Zhang and Ho, 2013; Pan et al., 2017). Particularly, a "time-splitting" RPD separates multiple symbols in a packet into two parts where one is for energy harvesting and the other is for information decoding. A "power-splitting" RPD splits an incident RF signal to feed its energy harvester and information transceiver modules, respectively.

4.3.5. Safe charging

With the multisource wireless power transfer approach, electromagnetic radiation in some unintentional locations may exceed a predefined threshold, thereby incurring a safety issue to human health particularly in densely populated areas. In this context, it is necessary to comprehensively study the safe charging problem which aims at employing multiple coordinators to transfer more energy to an RPD on the premise of keeping the radiation in other locations below a threshold (Dai et al., 2014a, 2014b).

4.3.6. Countermeasures to location spoofing

Except the traditional security and privacy issues especially related to wireless communications such as eavesdropping and jamming, location spoofing where a malicious RPD reports mendacious location information to the network management center should be given more attention. This is because the induced improper coordinator allocation for power transfer can lead to the waste of network resources as well as the network performance deterioration.

4.3.7. Wireless energy crowdharvesting

Instead of multisource wireless power transfer to a single EDD in NGRPNs, wireless energy crowdharvesting signifies multisource-enabled multi-EDD energy replenishment. In this case, it is generally difficult to figure out the best coordinator combination which can maximize the harvested power at every accessed EDDs and this problem becomes more intractable for mobile RPDs. In this context, we may have to change the focal point from individual power maximization to be maximizing the overall received power at all the EDDs or the minimum one among all the EDDs.

5. Conclusion

Over the past 20 years, numerous telecommunication systems have been distributed pervasively on the earth. Yet timely diversification of system functionalities and improvement of system performances cannot always be realized. Among the various issues supposed to be considered in these processes, the energy limitation of devices is one of the most crucial factors restricting the implementation of emerging techniques. Fortunately, the multisource wireless power transfer mechanism we have demonstrated not only shows the potential to provide “infinite” energy, but also enables prompt and reliable energy replenishment. We believe that this technique can propel the architecture of high-performance IoT and the enabled NGRPNs will play an important role in the Fourth Industrial Revolution.

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