Towards Balanced Energy Charging and Transmission Collision in Wireless Rechargeable Sensor Networks

Ruilong Deng, Shibo He, Peng Cheng, and Youxian Sun

Abstract: **By integrating sensing and computing capabilities into the traditional radio frequency identification (RFID) tags, the wireless identification and sensing platform (WISP) opens up a new research area referred to as wireless rechargeable sensor networks (WRSNs). Since WISPs need to be fully charged and then can start communication with the reader, thus the energy charging and transmission collision of WISPs are different from those of RFID tags. If the reader power is large, WISPs will be charged fast and start data transmission almost at the same time, which results in heavy transmission collision and the communication delay would be extremely large. However, if the reader power is small, WISPs will be charged slow and start data transmission one by one even without collisionh between any two WISPs, but the charging period of the whole network would be extremely large. Therefore, this paper aims at determining an optimal reader power towards balanced energy charging and transmission collision, such that the total duration for all WISPs to be fully charged and completely communicated is minimized. Firstly, we investigate on dynamic reader power with transmission collision avoidance, and static reader power towards balanced energy charging and transmission collision. Then, we derive the optimal reader power in three cases: (i) One reader and ray-uniformly distributed WISPs; (ii) one reader and randomly distributed WISPs; and (iii) multiple readers and randomly distributed WISPs. Finally, the theoretical analysis is verified through extensive evaluations.**

Index Terms: **Energy charging, optimal reader power, transmission collision, wireless rechargeable sensor network.**

I. INTRODUCTION

WITH rapid development of microelectronics and wireless communication in recent decades, wireless sensor networks (WSNs) have been widely used in a broad range of applications including military battlefield, medical health, traffic management, environmental monitoring, space exploration, and so on [1]–[14]. Although sensor nodes are low-cost, small-sized, and easy for deployment, they are powered by batteries and replacing the battery is not feasible in many applications. Hence, a critical issue in WSNs is to prolong the network lifetime. Recent years have witnessed the emergence of a promising approach to address such a challenge, where the network lifetime of WSNs can be extended by harvesting energy from environment. Known examples of harvestable energy resources include solar [15], electromagnetic waves [16], thermal [17], wind [18], and vibration [19].

Nowadays, harvesting energy from electromagnetic waves has been applied from identification to functionalities. The Intel Research Center and University of Washington have collaborated to develop a wireless identification and sensing platform (WISP), where the energy from electromagnetic waves can be harvested, stored, and utilized for powering the operations of the micro-controller unit (MCU), i.e., sensing, computing, and communication [20]–[22]. With such advantages, WISPs own far more abilities beyond the traditional radio frequency identification (RFID) tags, e.g., the reader can read not only the static ID information but also an enormous amount of sensory data from WISPs. Besides, with the excellent thin shape and the advantage of getting rid of batteries, they are widely applied to many fields ranging from individual activity recognition to large-scale urban monitoring, opening up a new research area referred to as wireless rechargeable sensor networks (WRSNs) [23]–[31].

Consider a WRSN with multiple homogeneous WISPs, which are charged by the reader for sensing, computing, and communication. Assume that the location of the reader has been fixed in the network. Since WISPs need to be fully charged and then can start communication with the reader, thus the energy charging and transmission collision of WISPs are different from those of RFID tags. If the reader power can be dynamically adjusted, we can completely avoid transmission collision, as well as minimize the total duration for all WISPs to be fully charged and completely communicated. However, if the reader power is statically fixed, we consider two extreme charging scenarios. On one hand, if the reader power is large, WISPs will be charged fast and start data transmission almost at the same time, which results in heavy transmission collision and the communication delay would be extremely large. On the other hand, if the reader power is small, WISPs will be charged slow and start data transmission one by one even without collision between any two WISPs, but the charging period of the whole network would be extremely large. Therefore, there exists a fundamental tradeoff between the charging period and communication delay. To this end, this paper aims at determining an optimal reader power towards balanced energy charging and transmission collision, such that the total duration for all WISPs to be fully charged and completely communicated is minimized. Firstly, we investigate on dynamic reader power with transmission collision avoid-

Manuscript received June 01, 2016; approved for publication by Jang-Won Lee, Division II Editor, May 17, 2017.

This research was supported by the National Natural Science Foundation of China (NSFC) under grant 61402405 and Zhejiang Provincial Natural Science Foundation under grant LR16F020001.

The authors are with the State Key Laboratory of Industrial Control Technology, Zhejiang University, Hangzhou, 310027, China, email: {rldeng, s18he, pcheng, yxsun}@iipc.zju.edu.cn.

S. He is the corresponding author.

Digital object identifier: 10.1109/JCN.2017.000058

ance, and static reader power towards balanced energy charging and transmission collision. Then, we derive the optimal reader power in three cases: (i) One reader and ray-uniformly distributed WISPs; (ii) one reader and randomly distributed WISPs; and (iii) multiple readers and randomly distributed WISPs. Finally, the theoretical analysis is verified through extensive evaluations.

The remainder of this paper is organized as follows. We describe the system model in Section II. In Section III, we investigate on dynamic reader power with transmission collision avoidance. In Section IV, we investigate on static reader power towards balanced energy charging and transmission collision. The optimization problem is formulated in Section V and solved in Section VI. The solution is verified by numerical results in Section VII and experimental results in Section VIII, and concluding remarks are drawn in Section IX.

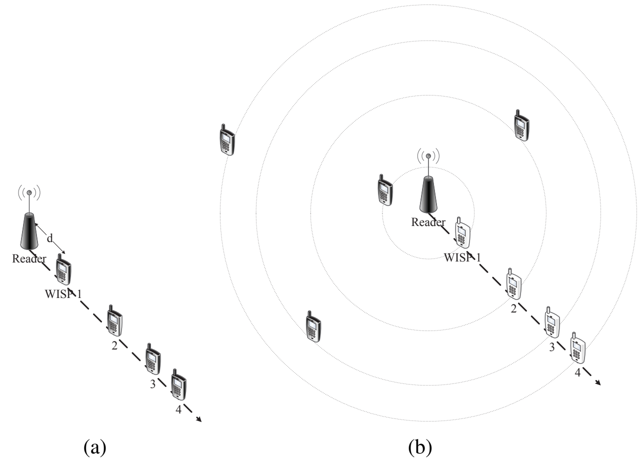


Fig. 1. Distribution of WISPs: (a) Ray distribution and (b) any distribution.

II. SYSTEM MODEL

Consider a WRSN with multiple homogeneous WISPs. Depending on different applications, WISPs can be static (e.g., they are fixed to the points of interest for environment monitoring) or mobile (e.g., they are worn by human users for activity recognition). In this paper, we only consider the first case, i.e., the locations of WISPs (specially, the distance from each WISP to the reader) are fixed and known as a priori. The second case will be further considered in our future work.

A. Energy Charging

According to the Friis's free space equation, a WISP that is d distance away from the reader with the power p, will receive the power p_r from electromagnetic waves,

$$p_r = G_s G_r \left(\frac{\lambda}{4\pi}\right)^2 \frac{p}{d^2}, \tag{1}$$

where G_s is the reader antenna gain, G_r is the WISP antenna gain, and λ is the electromagnetic wavelength. Based on (1), assume that a WISP needs at least ε energy to conduct sensing, computing, and communication, so the charging period required by the d distance away WISP is calculated as

$$t_c = \frac{\varepsilon}{p_r} \triangleq \eta \frac{d^2}{p}, \tag{2}$$

where

$$\eta \triangleq \frac{\varepsilon}{G_s G_r} \left(\frac{4\pi}{\lambda}\right)^2 \tag{3}$$

is a positive constant. Thus, (1) can be simplified as

$$p_r = \frac{\varepsilon p}{\eta d^2}. \tag{4}$$

For simplicity but without loss of generality, assume that WISPs are distributed on the same ray from the reader and there is at most one WISP at one point, as shown in Fig. 1(a). A set $\mathcal{N}$ of WISPs are orderly numbered by i ($i = 1, 2, \cdots, n$) along the ray from the reader. Note that any distribution of WISPs can be mapped into that on the same ray from the reader, through a series of concentric circles, as shown in Fig. 1(b).

B. Transmission Collision

WISPs implement the electronic product code (EPC) class 1 generation 2 (C1G2) communication protocol [32], [33] to address transmission collision, which is based on the framed slotted ALOHA (FSA), the same as that for RFID tags [34], [35]. In other words, when multiple WISPs begin data transmission at the same time, the communication delay of these WISPs is similar to that under the RFID environment. Thus, the detail of FSA is introduced as follows.

FSA defines functional commands for the reader to control the communication with WISPs, among which SELECT and ACK are of the most importance. At the beginning of a frame, the reader broadcasts a SELECT command with the frame size f, which indicates that the entire frame is split into f slots. After receiving the SELECT command, each WISP randomly chooses a number i from 1 to f and replies to the reader within the ith slot. Due to the randomness, there will be three cases for these slots. The first is called an "idle" slot with no WISP replying. The second is called a "single" slot with only one WISP replying. Then the reader sends an ACK command and this very WISP completes communication and keeps silent in the following slots. The third is called a "collision" slot with two or more WISPs replying. If the reader finds any collision within the frame, it will launch another frame until each WISP completes once communication with the reader.

Due to the stochastic nature of FSA, we cannot expect to read all WISPs with complete certainty, but we can reach a higher assurance if we are willing to launch more frames and wait for their completion. The resultant communication delay increases nearly linearly with the number of collided WISPs [36]. That is, when a number m ($m > 1$) of WISPs start data transmission at the same time, the data transmission duration required to guarantee the assurance level at 0.99 is calculated as

$$t_d(m) = \alpha m, \tag{5}$$

where α is called the proportionality coefficient. For example, it takes approximately 3 seconds to read a full set of 30 WISPs with such a high assurance level [36].

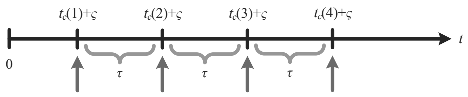


Fig. 2. Dynamic reader power with transmission collision avoidance.

III. DYNAMIC READER POWER WITH TRANSMISSION COLLISION AVOIDANCE

Consider that the reader power can be dynamically adjusted. Assume that each WISP starts sensing, computing, and communication when it is fully charged. The duration for sensing and computing is denoted by ς, where ς is a positive constant. Thus, the moment when the ith WISP (d_i distance away from the reader) starts data transmission is ς duration after it is fully charged. Assume that each WISP needs at most τ duration to complete data transmission, where τ is a positive constant. In order to completely avoid transmission collision, as well as minimize the total duration for all WISPs to be fully charged and completely communicated, all WISPs should start data transmission one by one and the time difference between any two adjacent WISPs to start data transmission should satisfy the following condition, as shown in Fig. 2:

$$\Delta t_c = [t_c(i+1) + \varsigma] - [t_c(i) + \varsigma] = \tau \quad \forall i \in \mathcal{N}. \tag{6}$$

Let $t_c(1)$ denote the charging period of the first WISP. To minimize the charging period, the reader power should be set at its upper bound $p^{\max}$ until the first WISP is fully charged (or “awake”). That is,

$$t_c(1) = \eta \frac{d_1^2}{p^{\max}}. \tag{7}$$

The first WISP needs ς duration to complete sensing and computing. Without collision, it needs τ duration to complete data transmission. Then, after the moment when the first WISP is fully charged and completely communicated, the second WISP should start data transmission. That is,

$$t_c(2) + \varsigma = t_c(1) + \varsigma + \tau. \tag{8}$$

Let p_2 denote the reader power within the duration from the first WISP awakes to the second WISP awakes. The second WISP is fully charged after receiving the power $\frac{\varepsilon p^{\max}}{\eta d_2^2}$ for the duration $t_c(1)$ and the power $\frac{\varepsilon p_2}{\eta d_2^2}$ for the duration $t_c(2) - t_c(1) = \tau$. That is,

$$\varepsilon = \frac{\varepsilon p^{\max}}{\eta d_2^2} t_c(1) + \frac{\varepsilon p_2}{\eta d_2^2}\tau. \tag{9}$$

Combining with (7), we obtain

$$p_2 = \eta \frac{d_2^2 - d_1^2}{\tau}. \tag{10}$$

From the above, we have the following theorem:

Theorem 1: In order to completely avoid transmission collision, as well as minimize the total duration for all WISPs to be fully charged and completely communicated, the reader power should be dynamically adjusted as follows:

1. Within the duration from the beginning to the first WISP awakes at $\eta \frac{d_1^2}{p^{\max}}$, the reader power should be set at

$$p_1 = p^{\max}. \tag{11}$$

2. Within the duration from the ith WISP awakes at $\eta \frac{d_1^2}{p^{\max}} + (i-1)\tau$ to the $(i+1)$th WISP awakes at $\eta \frac{d_1^2}{p^{\max}} + i\tau$, the reader power should be set at

$$p_{i+1} = \eta \frac{d_{i+1}^2 - d_i^2}{\tau} \quad i = 1, 2, \cdots, n-1. \tag{12}$$

Then, the total duration for all WISPs to be fully charged and completely communicated is

$$t_t(n) = \eta \frac{d_1^2}{p^{\max}} + \varsigma + n\tau. \tag{13}$$

Proof: We prove (12) by mathematical induction. Initially, (12) is trivially true for $i = 1, \cdots, k-1$. For $i = k$, consider that the $(k+1)$th WISP is fully charged after receiving the power $\frac{\varepsilon p^{\max}}{\eta d_{k+1}^2}$ for the duration $t_c(1)$, the power $\frac{\varepsilon p_2}{\eta d_{k+1}^2}$ for the duration τ, so on and so forth, the power $\frac{\varepsilon p_k}{\eta d_{k+1}^2}$ for the duration τ, and the power $\frac{\varepsilon p_{k+1}}{\eta d_{k+1}^2}$ for the duration τ. That is,

$$\varepsilon = \frac{\varepsilon p^{\max}}{\eta d_{k+1}^2} t_c(1) + \frac{\varepsilon p_2}{\eta d_{k+1}^2}\tau + \cdots + \frac{\varepsilon p_k}{\eta d_{k+1}^2}\tau + \frac{\varepsilon p_{k+1}}{\eta d_{k+1}^2}\tau. \tag{14}$$

Combining with (7) and (12) for $i = 1, \cdots, k-1$, we obtain $p_{k+1} = \eta \frac{d_{k+1}^2 - d_k^2}{\tau}$, which proves Theorem 1 by mathematical induction. □

Note that although the dynamic reader power could completely avoid transmission collision, the implement issue lies in that the reader power needs to be frequently adjusted, which is difficult to achieve in real practice. Therefore, we further consider the case of the static reader power in the following section.

IV. STATIC READER POWER TOWARDS BALANCED ENERGY CHARGING AND TRANSMISSION COLLISION

Instead of the dynamic reader power with transmission collision avoidance, which is hard to implement in real practice, we would rather consider the case of the static reader power towards the balanced energy charging and transmission collision.

A. *Transmission Collision Avoidance*

Consider that the reader power is statically fixed. We first investigate on the reader power to guarantee no transmission collision between any two WISPs. The moment when the ith WISP (d_i distance away from the reader) starts data transmission is ς duration after it is fully charged, i.e.,

$$t_c(i) = \eta \frac{d_i^2}{p}. \tag{15}$$

In order to completely avoid transmission collision, the time difference between any two adjacent WISPs to start data transmission should satisfy the following condition:

$$\Delta t_c = [t_c(i+1) + \varsigma] - [t_c(i) + \varsigma] \geq \tau \quad \forall i \in \mathcal{N}. \tag{16}$$

This is the general collision-free condition for any distribution of WISPs. For special cases, we can obtain the specific requirements of the reader power:

1. For the ray-uniform distribution, i.e., $d_{i+1} - d_i = \delta, \forall i \in \mathcal{N}$, where δ is a positive constant, from (15) and (16) we have

$$\Delta t_c^{\min} = \min_{i \in \mathcal{N}} \left[\eta \frac{(2d_i + \delta)\,\delta}{p} \right] = \tau. \tag{17}$$

Thus, the reader power should be set at $p = \frac{\eta}{\tau}(2d_1 + \delta)\,\delta$, where d_1 is the distance from the nearest (or "first" fully-charged) WISP to the reader.

2. For the ray-quadratic distribution, i.e., $d_{i+1}^2 - d_i^2 = \theta, \forall i \in \mathcal{N}$, where θ is a positive constant, from (15) and (16) we have

$$\Delta t_c^{\min} = \eta \frac{\theta}{p} = \tau. \tag{18}$$

Thus, the reader power should be set at $p = \frac{\eta}{\tau}\theta$.

Note that from the above two special cases, the collision-free reader power is independent of the number of WISPs. If there is a large number of WISPs in the WRSN, the charging period of the whole network would be extremely large, which is of course undesirable in practice. The alternative is that we increase the reader power, however, there would be transmission collision among some WISPs, which results in some communication delay. Therefore, there exists a fundamental tradeoff between the charging period and communication delay. To this end, we aim at determining an optimal reader power towards balanced energy charging and transmission collision, such that the total duration for all WISPs to be fully charged and completely communicated is minimized.

B. Energy Charging-Transmission Collision Analysis

Let $t_c(1)$ denote the charging period of the first WISP. It needs ς duration to complete sensing and computing. Without collision, it needs τ duration to complete data transmission. Then, after the moment when the first WISP is fully charged and completely communicated, i.e.,

$$t_t(1) = t_c(1) + \varsigma + \tau, \tag{19}$$

there are a number $(x_2 - 1)$ of WISPs that are ready for data transmission. We can calculate x_2 by

$$x_2 = \arg\max_{x_2} \left[t_c(x_2) + \varsigma \le t_t(1) \right]. \tag{20}$$

Note that according to the FSA communication protocol, these $(x_2 - 1)$ WISPs cannot start data transmission when they complete sensing and computing. In fact, they begin communication with the reader at the same time when the first WISP completes data transmission, i.e., $t_t(1)$. Here we assume $x_2 - 1 \ge 2$, which is common in practice for a high-power reader. Thus, the number $(x_2 - 1)$ of WISPs will collide with each other during data transmission. The resultant communication delay is dependent on the number of collided WISPs, which can be simply immigrated from that under the RFID environment. That is, the number $(x_2 - 1)$ of collided WISPs need $\alpha(x_2 - 1)$ duration to complete data transmission.

Then, similarly, after the moment

$$t_t(x_2) = t_t(1) + \alpha(x_2 - 1), \tag{21}$$

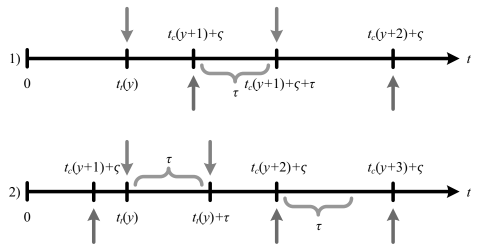


Fig. 3. Two cases in Lemma 1.

there are a number $(x_3 - x_2)$ of WISPs that are ready for data transmission, where

$$x_3 = \arg\max_{x_3} \left[t_c(x_3) + \varsigma \le t_t(x_2) \right]. \tag{22}$$

These $(x_3 - x_2)$ WISPs start communication with the reader at the same time, i.e., $t_t(x_2)$, and need $\alpha(x_3 - x_2)$ duration to complete data transmission.

Then, again, after the moment

$$t_t(x_3) = t_t(x_2) + \alpha(x_3 - x_2) = t_t(1) + \alpha(x_3 - 1), \tag{23}$$

there are a number $(x_4 - x_3)$ of WISPs that are ready for data transmission, where

$$x_4 = \arg\max_{x_4} \left[t_c(x_4) + \varsigma \le t_t(x_3) \right]. \tag{24}$$

Remark 1: So on and so forth, we can conclude that after the moment

$$\begin{aligned} t_t(x_{k-1}) &= t_t(1) + \alpha(x_{k-1} - 1) \\ &= t_c(1) + \varsigma + \tau + \alpha(x_{k-1} - 1), \end{aligned} \tag{25}$$

there are a number $(x_k - x_{k-1})$ of WISPs that are ready for data transmission, where

$$x_k = \arg\max_{x_k} \left[t_c(x_k) + \varsigma \le t_t(x_{k-1}) \right]. \tag{26}$$

V. PROBLEM FORMULATION

Consider the case of ray-uniformly distributed WISPs, where δ is the constant distance between any two adjacent WISPs. For ease of presentation, assume $d_1 = \delta$, and thus the ith WISP is $i\delta$ distance away from the reader, whose charging period is calculated as

$$t_c(i) = \eta \frac{(i\delta)^2}{p} \triangleq i^2 \kappa, \tag{27}$$

where

$$\kappa \triangleq \eta \frac{\delta^2}{p}. \tag{28}$$

Lemma 1: For ray-uniformly distributed WISPs, if there exists one WISP (not the first three) that does not collide with others during data transmission, then collision will never happen for any farther WISP.

Proof: After the moment when a number y $(y \ge 3)$ of WISPs are fully charged and completely communicated, if there is at most one WISP that is ready for data transmission, then the $(y + 1)$th WISP does not collide with others. Thus, we need to prove that collision will never happen for the $(y+2)$th WISP. Consider the following two cases (as shown in Fig. 3):

1. During data transmission of the yth WISP, no more WISP is ready for data transmission. In other words, the $(y+1)$th WISP will complete sensing and computing after the yth WISP completes data transmission, i.e., $t_c(y+1)+\varsigma > t_t(y)$. Obviously we have $\alpha > \tau$, since data transmission with collision will take more time than that without collision. Based on (25) and (27), we obtain $\tau < (y+2)\,\kappa$, from which we can further derive $t_c(y+2)+\varsigma > t_c(y+1)+\varsigma+\tau$. That is, the $(y+2)$th WISP will complete sensing and computing after the $(y+1)$th WISP completes data transmission. Therefore, the $(y+2)$th WISP does not collide with others.
2. During data transmission of the yth WISP, only the $(y+1)$th WISP is ready for data transmission. In other words, the $(y+2)$th WISP will complete sensing and computing after the yth WISP completes data transmission, i.e., $t_c(y+2)+\varsigma > t_t(y)$. Based on (25) and (27), we obtain $\tau < \frac{(y^2+4y+3)}{y}\kappa$, from which we can further derive $t_c(y+3)+\varsigma > t_c(y+2)+\varsigma+\tau$. That is, the $(y+2)$th and $(y+3)$th WISPs will not both complete sensing and computing during data transmission of the $(y+1)$th WISP. Therefore, the $(y+2)$th WISP does not collide with others.

From the above, if the $(y+1)$th WISP does not collide with others, then collision will never happen for the $(y+2)$th WISP. By mathematical induction, Lemma 1 can be iteratively proved. □

Lemma 2: For ray-uniformly distributed WISPs, if there exists one WISP that collides with others during data transmission, then collision will always happen for any nearer WISP (except the first one).

Proof: Assume that there exists one WISP which collides with others, and one adjacent nearer WISP (not the first one) without collision. From Lemma 1 we know that such a case does not exist, which proves Lemma 2 by contradiction. □

From the above, we have the following theorem:

Theorem 2: For ray-uniformly distributed WISPs, there are a total of three cases for data transmission collision, according to the reader power p: (i) If p is small enough, no collision will happen within the network; (ii) if p is large enough, all WISPs will collide with each other except the first one; and (iii) if p is moderate, there will be collision in the front part of the ray but no collision in the rear part.

From the above energy charging-transmission collision analysis, the farthest (or "last" fully-charged) WISP in the network may not start data transmission when it completes sensing and computing. In fact, it will begin communication with the reader after all other WISPs complete data transmission. Therefore, the total duration for the whole network to be fully charged and completely communicated is strictly dependent on the charging period and delay duration of the last WISP. Note that the delay duration of a WISP includes two aspects: One is the duration from when it is ready for data transmission to when it begins communication, and the other is the communication delay. If the WISP does not collide with others, the data transmission duration is τ; otherwise, the communication delay is dependent on the number of collided WISPs.

For a total of n ray-uniformly distributed WISPs, we have the following optimization problem:

$$\min_{p>0}\ t_t(n)\,. \tag{29}$$

VI. SOLUTION

A. One Reader and Ray-Uniformly Distributed WISPs

Note that the optimization problem includes the following three cases:

1. If the nth WISP completes sensing and computing after the $(n-1)$th WISP completes data transmission, i.e., $t_c(n)+\varsigma > t_t(n-1)$, then the nth WISP does not collide with others and we have $t_t(n)=t_c(n)+\varsigma+\tau$;
2. If the nth WISP completes sensing and computing after the $(n-2)$th WISP completes data transmission but before the $(n-1)$th WISP completes data transmission, i.e., $t_t(n-2) < t_c(n)+\varsigma < t_t(n-1)$, then the nth WISP does not collide with others and we have $t_t(n)=t_t(n-1)+\tau = t_c(1)+\alpha(n-2)+\varsigma+2\tau$;
3. If the nth WISP completes sensing and computing before the $(n-2)$th WISP completes data transmission, i.e., $t_c(n)+\varsigma < t_t(n-2)$, then the nth WISP at least collides with the $(n-1)$th WISP. According to Lemma 2, all WISPs will collide with each other except the first one and from (25) we have $t_t(n)=t_c(1)+\alpha(n-1)+\varsigma+\tau$.

From the above, together with (25) and (27), we can transform the former problem (29) equivalently into a more specific one:

$$\min_{p>0}\begin{cases}\eta\frac{n^2\delta^2}{p}+\varsigma+\tau, & p<\eta\frac{(n^2-1)\delta^2}{\alpha(n-2)+\tau}\\ \eta\frac{\delta^2}{p}+\alpha(n-2)+\varsigma+2\tau, & \text{otherwise}\\ \eta\frac{\delta^2}{p}+\alpha(n-1)+\varsigma+\tau, & p>\eta\frac{(n^2-1)\delta^2}{\alpha(n-3)+\tau}.\end{cases} \tag{30}$$

Since the piecewise objective function of the equivalent problem (30) is strictly monotone decreasing with the reader power p, the problem can be further simplified as

$$\min_{p>0}\begin{cases}\frac{n^2[\alpha(n-2)+\tau]}{n^2-1}+\varsigma+\tau\triangleq t_1, & p=\eta\frac{(n^2-1)\delta^2}{\alpha(n-2)+\tau}\\ \frac{n^2[\alpha(n-2)+\tau]-\alpha}{n^2-1}+\varsigma+\tau\triangleq t_2, & p=\eta\frac{(n^2-1)\delta^2}{\alpha(n-3)+\tau}\\ \alpha(n-1)+\varsigma+\tau\triangleq t_3, & p\to\infty.\end{cases} \tag{31}$$

Obviously, we have $t_2 < t_1$. Then, we consider

$$t_1-t_3=\frac{\alpha(n-1)-(\alpha-\tau)\,n^2}{n^2-1}. \tag{32}$$

Since $\frac{\alpha}{\alpha-\tau} < \frac{n^2}{n-1} < n$ is easily held for a large n, we have $t_2 < t_1 < t_3$. Therefore, the optimal reader power is

$$p^*=\eta\frac{(n^2-1)\,\delta^2}{\alpha(n-3)+\tau}, \tag{33}$$

which is dependent on the total number of WISPs. The minimum total duration for the whole network to be fully charged and completely communicated is

$$t_t^*(n)=\frac{n^2[\alpha(n-2)+\tau]-\alpha}{n^2-1}+\varsigma+\tau, \tag{34}$$

which is also dependent on the total number of WISPs.

From the above, the optimal condition of the problem is that the nth WISP completes sensing and computing just after the $(n-2)$th WISP completes data transmission, i.e.,

$$t_c(n) + \varsigma = t_t(n-2) = t_c(1) + \alpha(n-3) + \varsigma + \tau. \quad (35)$$

Under this optimal condition, the minimum total duration for the whole network to be fully charged and completely communicated is calculated as

$$t_t^*(n) = t_c(1) + \alpha(n-2) + \varsigma + 2\tau. \quad (36)$$

B. One Reader and Randomly Distributed WISPs

From the above, we formulate and solve the optimization problem in the case of one reader and ray-uniformly distributed WISPs. In fact, the optimal solution can be trivially extended to the general case of ray-randomly distributed WISPs. Due to the randomness of the WISP distribution, assume that the ith WISP is d_i distance away from the reader, so its charging period is the same as (15). The optimal condition of the problem is the same as (35). Therefore, the optimal reader power is

$$p^* = \eta \frac{d_n^2 - d_1^2}{\alpha(n-3) + \tau}, \quad (37)$$

which is dependent on the total number of WISPs, and the distance from the first WISP to the reader and that from the last WISP to the reader. From (15) and (36), the minimum total duration for the whole network to be fully charged and completely communicated is

$$t_t^*(n) = \frac{\left(\frac{d_n}{d_1}\right)^2 [\alpha(n-2) + \tau] - \alpha}{\left(\frac{d_n}{d_1}\right)^2 - 1} + \varsigma + \tau, \quad (38)$$

which is dependent on the total number of WISPs, and the ratio between the distance from the first WISP to the reader and that from the last WISP to the reader.

As aforementioned in Section II, any distribution of WISPs can be mapped into that on the same ray from the reader, through a series of concentric circles, as shown in Fig. 1(a). Thus, we further analyze the case of one reader and randomly distributed WISPs in a two-dimensional area. In this case, it is not so easy to identify the nearest (or "first" fully-charged) WISP and farthest (or "last" fully-charged) WISP, compared with those in ray distribution. The first and last fully-charged WISP can be identified by $f = \arg\min_{i\in\mathcal{N}} d_i$ and $l = \arg\max_{i\in\mathcal{N}} d_i$, respectively. Thus, similarly, the optimization problem is

$$\min_{p>0} \; t_t(l). \quad (39)$$

The optimal condition of the problem is

$$t_c(l) + \varsigma = t_c(f) + \alpha(n-3) + \varsigma + \tau. \quad (40)$$

Under this optimal condition, the minimum total duration for the whole network to be fully charged and completely communicated is calculated as

$$t_t^*(l) = t_c(f) + \alpha(n-2) + \varsigma + 2\tau. \quad (41)$$

The optimal reader power is

$$p^* = \eta \frac{d_l^2 - d_f^2}{\alpha(n-3) + \tau}. \quad (42)$$

The minimum total duration for the whole network to be fully charged and completely communicated is

$$t_t^*(l) = \frac{\left(\frac{d_l}{d_f}\right)^2 [\alpha(n-2) + \tau] - \alpha}{\left(\frac{d_l}{d_f}\right)^2 - 1} + \varsigma + \tau. \quad (43)$$

C. Multiple Readers and Randomly Distributed WISPs

In the case of multiple readers and randomly distributed WISPs, the optimization problem becomes more complex. Assume that there is a set $\mathcal{M}$ of readers with fixed locations, which are orderly numbered by j $(j = 1, 2, \cdots, m)$. Let p_j denote the power of the jth reader, and d_{ij} for the distance from the ith WISP to the jth reader. According to the Friis's free space equation, the aggregate power received by the ith WISP under the multi-reader environment is expressed as

$$p_r(i) = \frac{\varepsilon}{\eta} \sum_{j\in\mathcal{M}} \frac{p_j}{d_{ij}^2}, \quad (44)$$

so its charging period is calculated as

$$t_c(i) = \frac{\varepsilon}{p_r(i)} = \frac{\eta}{\sum\limits_{j\in\mathcal{M}} \frac{p_j}{d_{ij}^2}}. \quad (45)$$

The first and last fully-charged WISP can be identified by

$$\begin{cases} f = \arg\min\limits_{i\in\mathcal{N}} t_c(i) = \arg\max\limits_{i\in\mathcal{N}} \sum\limits_{j\in\mathcal{M}} \frac{p_j}{d_{ij}^2} & (46a) \\ l = \arg\max\limits_{i\in\mathcal{N}} t_c(i) = \arg\min\limits_{i\in\mathcal{N}} \sum\limits_{j\in\mathcal{M}} \frac{p_j}{d_{ij}^2}, & (46b) \end{cases}$$

respectively. The optimal condition of the problem is the same as (40), i.e., more specifically,

$$\frac{\eta}{\sum\limits_{j\in\mathcal{M}} \frac{p_j}{d_{lj}^2}} + \varsigma = \frac{\eta}{\sum\limits_{j\in\mathcal{M}} \frac{p_j}{d_{fj}^2}} + \alpha(n-3) + \varsigma + \tau. \quad (47)$$

Note that (46a), (46b), and (47) are strictly coupled with each other, which cannot be directly tackled. However, if we assume that the multiple readers adopt the same power, the optimization problem can be decoupled and solved. If we define $p = p_j, \forall j \in \mathcal{M}$ and $\kappa_i = \sum_{j\in\mathcal{M}} \frac{1}{d_{ij}^2}$, then (45)-(47) can be transformed into

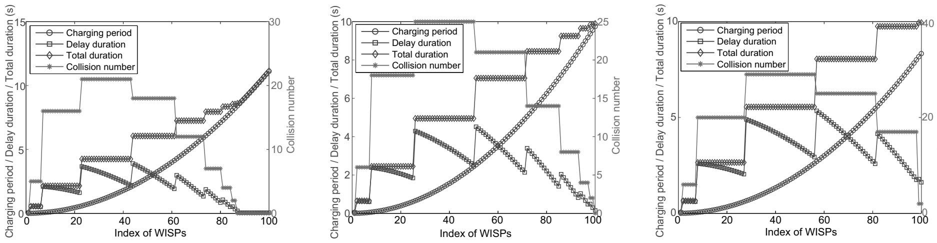
$$t_c(i) = \frac{\eta}{p\kappa_i}, \quad (48)$$

and

$$\begin{cases} f = \arg\max\limits_{i\in\mathcal{N}} \kappa_i \\ l = \arg\min\limits_{i\in\mathcal{N}} \kappa_i \\ \frac{\eta}{p\kappa_l} = \frac{\eta}{p\kappa_f} + \alpha(n-3) + \tau. \end{cases} \quad (49)$$

Therefore, the optimal reader power is

$$p^* = \eta \frac{\frac{1}{\kappa_l} - \frac{1}{\kappa_f}}{\alpha(n-3) + \tau}. \quad (50)$$



(a) (b) (c)

Fig. 4. Charging period, delay duration, total duration, and collision number in the case of one reader and ray-uniformly distributed WISPs: (a) Reader power equals 9 W, (b) reader power equals 10.2554 W, and (c) reader power equals 12 W.

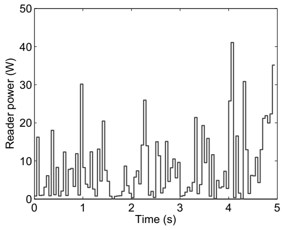


Fig. 5. Dynamic reader power with transmission collision avoidance.

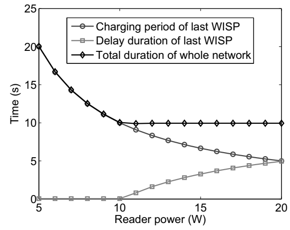


Fig. 6. Reader power impacts charging, delay, and total duration.

The minimum total duration for the whole network to be fully charged and completely communicated is

$$t_t^*(l) = \frac{\frac{\kappa_f}{\kappa_l}\left[\alpha(n-2)+\tau\right]-\alpha}{\frac{\kappa_f}{\kappa_l}-1} + \varsigma + \tau. \tag{51}$$

VII. NUMERICAL RESULTS

A. Dynamic Reader Power With Transmission Collision Avoidance

Consider that the reader power can be dynamically adjusted. We can completely avoid transmission collision, as well as minimize the total duration for all WISPs to be fully charged and completely communicated. The simulation is in the case of one reader and randomly distributed WISPs. The simulation parameters are set as $\eta = 1$, $\varsigma = 0.01$ s, $\tau = 0.05$ s, and $p^{\max} = 50$ W. The total number of WISPs in the network is $n = 100$. The 100 WISPs are randomly distributed in a two-dimensional area, e.g., a 10 m$\times$10 m square area. From Theorem 1, in order to completely avoid transmission collision, as well as minimize the total duration for all WISPs to be fully charged and completely communicated, the reader power should be dynamically adjusted as shown in Fig. 5, and the total duration is $t_t(n) = 5.0103$ s.

B. Static Reader Power Towards Balanced Energy Charging and Transmission Collision

Consider that the reader power is statically fixed. We aim at determining an optimal reader power towards balanced energy charging and transmission collision, such that the total duration for all WISPs to be fully charged and completely communicated is minimized.

B.1 One Reader and Ray-Uniformly Distributed WISPs

The first simulation is in the case of one reader and ray-uniformly distributed WISPs. The simulation parameters are set as $\alpha = 0.1$ and $d_1 = \delta = 0.1$ m. From (33) and (34), we calculate the optimal reader power $p^* = 10.2554$ W and the minimum total duration $t_t^*(n) = 9.911$ s, which can be verified by the simulation.

Firstly, we study the impact of the reader power on the charging period and delay duration of the last WISP and hence the total duration of the whole network, as shown in Fig. 6. The reader power varies from 5 W to 20 W, with a step size of 1 W. It is observed that the charging period of the last WISP decreases with the reader power. When the reader power is small, the delay duration of the last WISP is almost zero, which is $\tau = 0.05$ s in fact; however, when the reader power is large, the delay duration of the last WISP increases with the reader power. The total duration of the whole network is the sum of the charging period and delay duration of the last WISP. When the reader power is small, the total duration decreases with the reader power; however, when the reader power is large, the total duration remains almost the same even though the reader power increases.

From Fig. 6 we can see that the optimal reader power to minimize the total duration lies between 10 W and 11 W. For ease of illustration, we specifically focus on the details of energy charging process when the reader power equals 9 W, $p^* = 10.2554$ W, and 12 W, respectively, as shown in Fig. 4. It is observed that when the reader power equals p^*, the last WISP just does not have collision during data transmission (see Fig. 4(b)). If the reader power is smaller, the delay duration of the last WISP is almost zero, and the total duration only depends on the charging period of the last WISP (see Fig. 4(a)). Thus, we can increase the reader power to reduce the total duration. However, if the reader power is larger, the last WISP will collide with others and its delay duration becomes larger (see Fig. 4(c)). Although

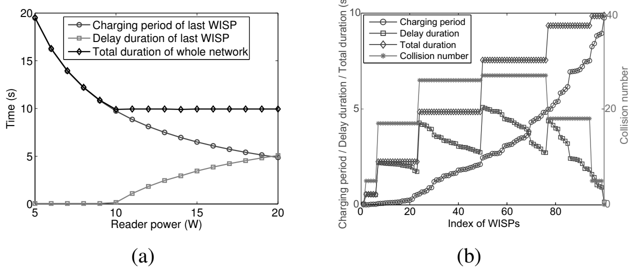


Fig. 7. One reader and ray-randomly distributed WISPs: (a) Reader power varies from 5 W to 20 W and (b) reader power equals $p^* = 9.9906$ W.

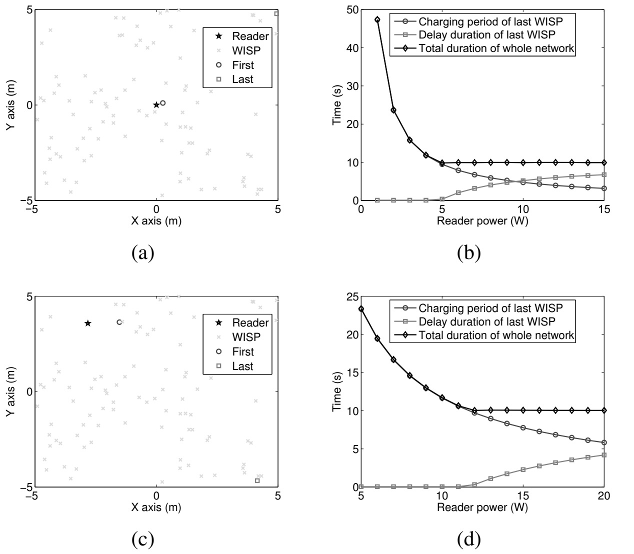


Fig. 8. One reader and randomly distributed WISPs in a square area: (a), (b) Reader at the center of area, and (c), (d) reader at a random location.

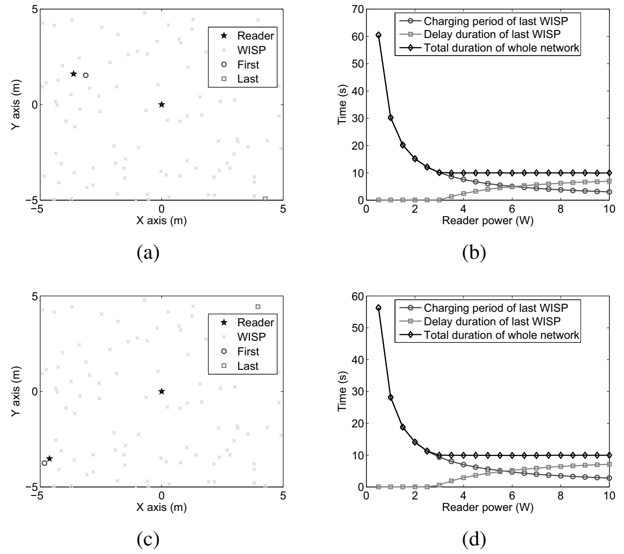


Fig. 9. Multiple readers and randomly distributed WISPs in a square area: (a), (b) Reader at a random location 1, and (c), (d) Reader at a random location 2.

the charging period of the last WISP decreases, the total duration dose not decrease.

B.2 One Reader and Randomly Distributed WISPs

The second simulation is in the case of one reader and ray-randomly distributed WISPs. The simulation parameters are set as the same, except the 100 WISPs are randomly distributed, e.g., $d_1 = 0.0458$ m and $d_{100} = 9.8697$ m. From (37) and (38), we calculate the optimal reader power $p^* = 9.9906$ W and the minimum total duration $t_t^*(n) = 9.9102$ s, which can be verified by the simulation, as shown in Fig. 7.

Further, consider that the 100 WISPs are randomly distributed in a two-dimensional area, e.g., a 10 m$\times$10 m square area. The simulation results are shown in Fig. 8. The reader is placed at the center of the area in Figs. 8(a) and 8(b), while it is placed at a random location in Figs. 8(c) and 8(d). It is observed that, the optimal reader power when it is placed at the center of the area is smaller than that for a random location, while the total duration of the whole network is almost the same.

B.3 Multiple Readers and Randomly Distributed WISPs

The third simulation is in the case of multiple readers and randomly distributed WISPs. The simulation parameters are set as the same, except the number of readers is more than one. For ease of illustration, we take two readers for example. It can be extended to more readers, with similar results. One reader is placed at the center of the area, while the other is placed at a random location. The simulation results are shown in Fig. 9. It is observed that, the optimal reader power under the multi-reader environment is smaller than that with only one reader, while the total duration of the whole network is almost the same.

B.4 Comparison

We compare the optimal and collision-free solutions in the case of multiple readers and randomly distributed WISPs. Different number of WISPs are randomly distributed in a 10 m$\times$10 m square area, with different number of readers which are also randomly deployed. Firstly, it is observed in Fig. 10 that the optimal reader power is much larger than the collision-free one, while the total duration for the whole network under the optimal reader power is much shorter than that under the collision-free one. Besides, in both cases, the reader power decreases with the WISP number, while the total duration has an approximately linear increase with the WISP number. Finally, as shown in Fig. 11, different number of readers with the optimal power will obtain almost the same total duration. However, the more readers we deploy, the smaller the aggregate power is.

VIII. EXPERIMENTAL RESULTS

In order to clarify the necessity of the proposed algorithm, we conduct the collision rate experiment with multiple WISPs. During the experiment, we place multiple WISPs in front of the antenna of a reader, and perform reader-WISP communications in multiple rounds as we increase the number of WISPs from 1 to 6. Specifically, reader requires WISPs for 2 minutes and the time of delay in Fig. 12 includes WISP charging time, sensing and computing duration, as well as sending back 14 replies. The time of delay is the most direct form of expression of the collision rate. All experiments are conducted in the same condition

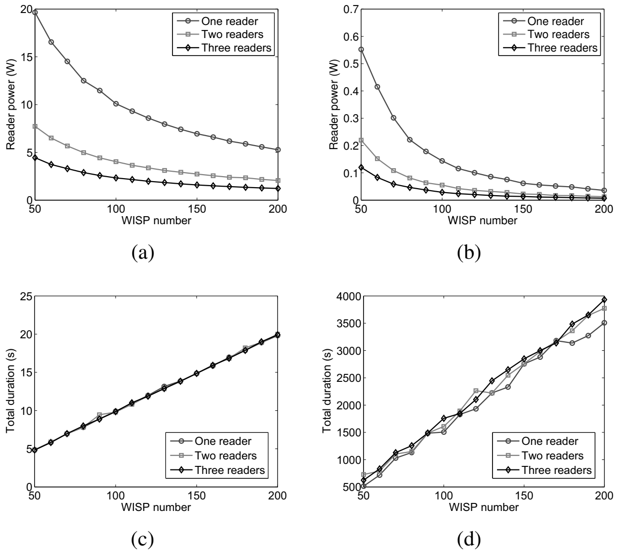


Fig. 10. Comparison between optimal and collision-free solutions: (a) Optimal reader power, (b) collision-free reader power, (c) optimal total duration, and (d) collision-free total duration.

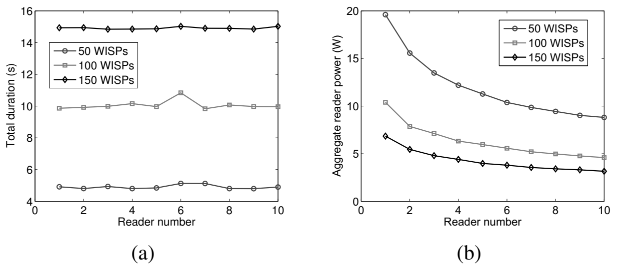


Fig. 11. Optimal solution with different reader numbers: (a) Total duration and (b) aggregate reader power.

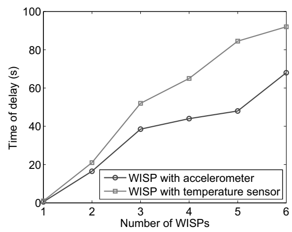


Fig. 12. Time of delay with multiple WISPs.

and we repeat each test for 5 times.

In Fig. 12, we can see that the time of delay grows when the number of WISPs increases. From Table 1, we find that the delay variances in real experiments are small compared with the total time of delay. Consequently, we can conclude that although different WISPs have different delays, the collision rate is still highly correlated to the number of WISPs.

IX. CONCLUSION

This paper aims at determining an optimal reader power towards balanced energy charging and transmission collision, such that the total duration for all WISPs to be fully charged and completely communicated is minimized. Firstly, we investigate on dynamic reader power with transmission collision avoidance, and static reader power towards balanced energy charging and transmission collision. Then, we derive the optimal reader power in three cases: (i) One reader and ray-uniformly distributed WISPs; (ii) one reader and randomly distributed WISPs; and (iii) multiple readers and randomly distributed WISPs. Finally, the theoretical analysis is verified through extensive evaluations.

Table 1. Delay variances with multiple WISPs (s).

Number of WISPs	1	2	3	4	5	6
WISP with accelerometer	0.03	1.52	3.33	4.01	4.72	6.48
WISP with temperature sensor	0.09	2.08	4.80	7.22	9.41	9.13

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: A survey,” *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, Mar. 2002.

[2] X. Cao, J. Chen, Y. Zhang, and Y. Sun, “Development of an integrated wireless sensor network micro-environmental monitoring system,” *ISA Transactions*, vol. 47, no. 3, pp. 247–255, July 2008.

[3] J. Chen, X. Cao, P. Cheng, Y. Xiao, and Y. Sun, “Distributed collaborative control for industrial automation with wireless sensor and actuator networks,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 4219–4230, Feb. 2010.

[4] Q. Yu, J. Chen, Y. Fan, X. S. Shen, and Y. Sun, “Multi-channel assignment in wireless sensor networks: A game theoretic approach,” in *Proc. IEEE INFOCOM*, Mar. 2010, pp. 1127–1135.

[5] Y. Wang, K. Wu, and L. M. Ni, “Wifall: Device-free fall detection by wireless networks,” *IEEE Trans. Mobile Comput.*, vol. 16, no. 2, pp. 581–594, Feb. 2017.

[6] J. Chen *et al.,* “Utility-based asynchronous flow control algorithm for wireless sensor networks,” *IEEE J. Sel. Areas Commun.*, vol. 28, no. 7, pp. 1116–1126, Aug. 2010.

[7] X. Li *et al.,* “Smart community: An Internet of things application,” *IEEE Commun. Mag.*, vol. 49, no. 11, pp. 68–75, Nov. 2011.

[8] R. Deng, J. Chen, J. Fan, and Y. Sun, “A general approach for building linux on sensor node imote2,” *Computer Standards & Interfaces*, vol. 34, no. 1, pp. 101–108, Jan. 2012.

[9] R. Deng, J. Chen, C. Yuen, P. Cheng, and Y. Sun, “Energy-efficient cooperative spectrum sensing by optimal scheduling in sensor-aided cognitive radio networks,” *IEEE Trans. Veh. Technol.*, vol. 61, no. 2, pp. 716–725, Feb. 2012.

[10] L. Wang, K. Wu, J. Xiao, and M. Hamdi, “Harnessing frequency domain for cooperative sensing and multi-channel contention in crahns,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 440–449, Jan. 2014.

[11] G. Wang, K. Wu, and L. M. Ni, “CSMA/SF: Carrier sense multiple access with shortest first,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1692–1702, Mar. 2014.

[12] A. N. Alvi *et al.,* “Enhanced TDMA based MAC protocol for adaptive data control in wireless sensor networks,” *J. Commun. Netw.*, vol. 17, no. 3, pp. 247–255, June 2015.

[13] H. Byun, S. Son, and S. Yang, “Biologically inspired node scheduling control for wireless sensor networks,” *J. Commun. Netw.*, vol. 17, no. 5, pp. 506–516, Oct. 2015.

[14] R. Deng, S. He, and J. Chen, “Near-optimal online algorithm for data collection by multiple sinks in wireless sensor networks,” *IEEE Trans. Control Netw. Syst.*, to be published.

[15] D. Dondi, A. Bertacchini, D. Brunelli, L. Larcher, and L. Benini, “Modeling and optimization of a solar energy harvester system for self-powered wireless sensor networks,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2759–2766, July 2008.

[16] S. He *et al.,* “Energy provisioning in wireless rechargeable sensor networks,” *IEEE Trans. Mobile Comput.*, vol. 12, no. 10, pp. 1931–1942, Oct. 2013.

[17] Y. K. Tan and S. K. Panda, “Energy harvesting from hybrid indoor ambient light and thermal energy sources for enhanced performance of wireless

sensor nodes," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4424–4435, Sept. 2011.

[18] Y. K. Tan and S. K. Panda, "Optimized wind energy harvesting system using resistance emulator and active rectifier for wireless sensor nodes," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 38–50, Jan. 2011.

[19] T. J. Kazmierski, L. Wang, G. V. Merrett, B. M. Al-Hashimi, and M. Aloufi, "Fast design space exploration of vibration-based energy harvesting wireless sensors," *IEEE Sensors J.*, vol. 13, no. 11, pp. 4393–4401, Nov. 2013.

[20] M. Philipose, J. R. Smith, B. Jiang, A. Mamishev, S. Roy, and K. Sundara-Rajan, "Battery-free wireless identification and sensing," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 37–45, Jan.-Mar. 2005.

[21] J. R. Smith, A. P. Sample, P. S. Powledge, S. Roy, and A. Mamishev, "A wirelessly-powered platform for sensing and computation," in *Proc. UbiComp,* Sept. 2006, pp. 495–506.

[22] A. P. Sample, D. J. Yeager, P. S. Powledge, A. V. Mamishev, and J. R. Smith, "Design of an RFID-based battery-free programmable sensing platform," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 11, pp. 2608–2615, Nov. 2008.

[23] P. Cheng, S. He, F. Jiang, Y. Gu, and J. Chen, "Optimal scheduling for quality of monitoring in wireless rechargeable sensor networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 3072–3084, June 2013.

[24] Z. Ren, P. Cheng, J. Chen, D. K. Yau, and Y. Sun, "Dynamic activation policies for event capture in rechargeable sensor network," *IEEE Trans. Parallel Distrib. Syst.*, vol. 25, no. 12, pp. 3124–3134, Dec. 2014.

[25] J. Chen, S. He, and Y. Sun, *Rechargeable Sensor Networks: Technology, Theory, and Application-Introducing Energy Harvesting to Sensor Networks*. World Scientific Publishing Company, 2014.

[26] A. Ammar and D. Reynolds, "An adaptive scheduling scheme for cooperative energy harvesting networks," *J. Commun. Netw.*, vol. 17, no. 3, pp. 256–264, June 2015.

[27] Y. Shu, P. Cheng, Y. Gu, J. Chen, and T. He, "TOC: Localizing wireless rechargeable sensors with time of charge," *ACM Trans. Sensor Netw.*, vol. 11, no. 3, p. 44, May 2015.

[28] L. Fu, P. Cheng, Y. Gu, J. Chen, and T. He, "Optimal charging in wireless rechargeable sensor networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 278–291, Jan. 2016.

[29] R. Deng, Y. Zhang, S. He, J. Chen, and X. Shen, "Maximizing network utility of rechargeable sensor networks with spatiotemporally coupled constraints," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 5, pp. 1307–1319, May 2016.

[30] R. Deng, H. Liang, J. Yong, B. Chai, and T. Yang, "Distributed rate control, routing, and energy management in dynamic rechargeable sensor networks," *Peer-to-Peer Netw. Appl.*, vol. 10, no. 3, pp. 425–439, May 2017.

[31] J. Ren *et al.,* "Joint channel access and sampling rate control in energy harvesting cognitive radio sensor networks," *IEEE Trans. Emerg. Topics Comput.*, to be published.

[32] EPCglobal, "EPC Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz–960 MHz Version 1.2.0," 2008.

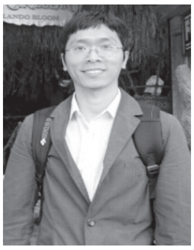
[33] A. P. Sample and J. R. Smith, "The wireless identification and sensing platform," *Wirelessly Powered Sensor Networks and Computational RFID*, pp. 33–56, 2013.

[34] H. Wu and Y. Zeng, "Efficient framed slotted aloha protocol for RFID tag anticollision," *IEEE Trans. Autom. Sci. Eng.*, vol. 8, no. 3, pp. 581–588, Aug. 2011.

[35] Y.-B. Kim, "On the optimal configuration of framed slotted ALOHA," *EURASIP J. Wireless Commun. Netw.*, vol. 2016, no. 1, p. 202, Dec. 2016.

[36] H. Vogt, "Efficient object identification with passive RFID tags," *Pervasive Computing*, pp. 98–113, 2002.

Ruilong Deng received the B.Sc. and Ph.D. degrees both in Control Science and Engineering from Zhejiang University, Hangzhou, Zhejiang, China, in 2009 and 2014, respectively. He was a Visiting Scholar at Simula Research Laboratory, Fornebu, Norway, in 2011, and the University of Waterloo, Waterloo, ON, Canada, from 2012 to 2013. He was a Research Fellow at Nanyang Technological University, Singapore, from 2014 to 2015. Currently, he is an AITF Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada. His research interests include smart grid, cyber security, and wireless sensor network. He serves/served as an Editor for IEEE/KICS Journal of Communications and Networks, and a Guest Editor for IEEE Transactions on Emerging Topics in Computing and IET Cyber-Physical Systems: Theory & Applications. He also serves/served as a Technical Program Committee (TPC) Member for IEEE GLOBECOM, IEEE ICC, IEEE SmartGridComm, EAI SGSC, etc.



Shibo He is currently a Professor with Zhejiang University. He was an Associate Research Scientist from March 2014 to May 2014, and a Postdoctoral Scholar from May 2012 to February 2014, with Arizona State University, Tempe, AZ, USA. He received the Ph.D. degree in control science and engineering from Zhejiang University, Hangzhou, China, in 2012. His research interests include wireless sensor networks, crowdsensing and big data analysis, etc. He serves on the Editorial Board of IEEE Transactions on Vehicular Technology, Springer Peer-to-Peer Networking and Application, and KSII Transactions on Internet and Information Systems, and is a Guest Editor of Elsevier Computer Communications and Hindawi International Journal of Distributed Sensor Networks. He served as Symposium Co-chair for IEEE ICC 2017, Finance & Registration chair for ACM MobiHoc 2015, Web Co-Chair for IEEE MASS 2013, and Publicity Co-chair of IEEE WiSARN 2010 and FCN 2014.

Peng Cheng received the B.E. degree in automation and the Ph.D. degree in control science and engineering from Zhejiang University, Hangzhou, China, in 2004 and 2009, respectively. He is currently a Full Professor with the College of Control Science and Engineering, Zhejiang University. His current research interests include networked sensing and control, cyber-physical systems, and robust control and applications. He serves as an Associate Editor of Wireless Networks and the International Journal of Communication Systems, and a Guest Editor of the IEEE Transactions on Control of Network Systems. He served as a Local Arrangement Chair of the IEEE International Symposium on Mobile Ad Hoc Networking and Computing in 2015, and the Publicity Co-Chair of the IEEE Mobile Adhoc and Sensor Systems in 2013.

Youxian Sun received the Diploma degree from Zhejiang University, Hangzhou, China, in 1964. In 1964, he joined the Department of Chemical Engineering, Zhejiang University. From 1984 to 1987, he was an Alexander Von Humboldt Research Fellow and a Visiting Associate Professor with the University of Stuttgart, Stuttgart, Germany. Since 1988, he has been a Full Professor with Zhejiang University. In 1995, he was elevated to Academician of the Chinese Academy of Engineering, Beijing, China. He is currently the Director of the Institute of Industrial Process Control and the National Engineering Research Center of Industrial Automation, Zhejiang University. He is the author/co-author of 450 journal and conference papers. His current research interests include modeling, control, and optimization of complex systems, as well as robust control design and its applications. He is the President of the Chinese Association of Automation. He also has served as the Vice-Chair of the Pulp and Paper Committee of the International Federation of Automatic Control and Vice President of the China Instrument and Control Society.