Exploiting Time of Charge to Achieve Collision-Free Communications in WRSN

Yuelong Tian*† Peng Cheng*† Liang He† Yu Gu† Jiming Chen*
*State Key Lab. of Industrial Control Technology, Zhejiang University, China
†Singapore University of Technology and Design, Singapore
yuelongtian1988@zju.edu.cn, {pcheng, jmchen}@iipc.zju.edu.cn, {he_liang,jasongu}@sutd.edu.sg

***Abstract*—The Wireless Identification and Sensing Platform (WISP) has become a very promising experimental platform of wireless rechargeable sensor networks (WRSN), which integrates the sensing and computation capabilities to the traditional RFID tags. In such kind of networks, the simultaneous transmission may introduce severe communication collisions, which have attracted various research efforts for resolving such collisions at the MAC layer. However, different from existing works, we avoid such communication collisions through proper reader movement by exploiting the differences in the time of charge among rechargeable sensor nodes. We formulate the optimization problem and prove that complexity of the optimal solution is NP-hard, and propose a simple yet effective algorithm to optimize both the reader stop location and stop time for minimizing the total communication delay. Extensive simulation under different system settings show that our design can largely reduce the communication delay and outperform the baseline design by at least 20%.**

Keywords*—*Wireless Rechargeable Sensor Networks, Time of Charge, Collision Region, Reader Movement

I. INTRODUCTION

The recent breakthrough in wireless communications and low-power electronics has enabled wireless energy transfer as a promising alternative to power sensor nodes instead of traditional battery-powered nodes, whose lifetime are highly limited by the storage capacity of batteries. Wireless rechargeable sensor nodes are able to harvest nearby RF signals for their sensing, computing and communication capabilities. With such universal and real-time monitoring capabilities, it is expected that wireless rechargeable sensor networks (WRSN) may significantly improve our living quality. Specially, the applications of wireless rechargeable sensor networks can be found in authentication [1], [2], supply chain monitoring [3], warehouse inventory management [4]–[6], and etc.

The wireless Identification Sensing Platform (WISP) [7] is one representative wireless rechargeable senor network system. When placed close to a RFID reader, the WISP node can harvest the energy from the reader signals for sensing and data processing. Note that such wireless rechargeable sensor network often consists of large number of nodes, part of which response to the reader request simultaneously and thus result in serious communication collisions. What's more, due to the embedded sensing and computation capabilities, wireless rechargeable sensor nodes usually can transfer much longer data packet compared with the traditional RFID tags, which may further increase the collision chances. Existing works on communication collisions mainly focus on node coordination through MAC layer protocol design [8]–[10]. Different from the existing works, we hope to move the coordination job to the reader side in order to simply the protocol and implementation for resource-constrained wireless rechargeable sensor nodes. Specifically, we identify time of charge as the unique feature of wireless rechargeable sensor nodes, e.g., WISP node. The power voltage of node has to be charged over certain threshold for reliable sensing, computing and communication functionalities. Meanwhile, such time of charge for even node is closely correlated with its distance to the RFID reader.

In our previous work [11], we have considered the problem of how to find the optimal reader location in order to minimize the total communication delay while avoiding any communication collisions. However, the paper only handles the static case where the reader is able to charge all nodes. In this paper, we would like to consider a more general problem where the charging range of reader can't cover all nodes from one location. Specifically, in this paper we focus on the scenario where a RFID reader moves and stops at different locations to charge and collect the sensory information from nodes in its surrounding area. Instead of modifying the MAC layer protocols to reduce the collisions in the network, we investigate the problem of how to optimally plan the movement of the RFID reader, such that the communication delay for the reader to collect all sensory information in the network is minimized. Compared with traditional solutions such as various ALOHA-based protocols for RFID systems, our design allows sensor nodes to instantly transmit their information once it collects enough energy, which simplifies the implementation at both the sensor and the reader sides. The major intellectual contributions of this paper are as follows:

- We identify the time of charge as an effective mechanism to avoid communication collisions in wireless rechargeable sensor networks. To our best knowledge, this is the first work that optimizes the reader movement for collision avoidance in communication networks by exploiting such concept.
- Considering the limited charging range of RFID reader, we redefine the concept of collision region for wireless rechargeable sensor networks and formulate the optimization problem for minimizing the communication delay through joint reader stop location and

---

The work was partially supported by NSFC under grant 61222305, ZJUNSF under grant LY14F030016, National Program for Special Support of Top Notch Young Professionals, and SUTD-ZJU/RES/03/2011.

QSHINE 2014, August 18-20, RHODES, Greece

DOI 10.4108/icst.qshine.2014.256209

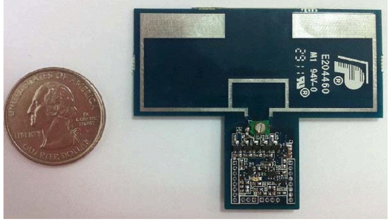


Fig. 1: WISP node

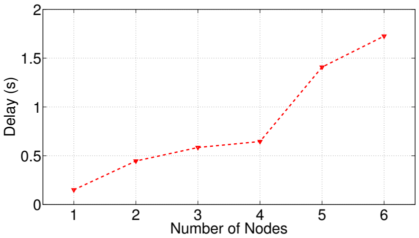


Fig. 2: Empirical Communication delay under ALOHA [11]

duration design.

- We prove the NP-hardness of optimal solution by reducing the original optimization problem to a well-known weighted set-covering problem, and propose an effective heuristic algorithm to obtain an approximated solution. We employ extensive simulations to verify the effectiveness of our proposed design under various system settings.

The rest of this paper is organized as follows. Section II introduces the system preliminaries. The main design is presented in Section III. Section IV shows the evaluation results of the proposed design. Section V surveys the literature and the paper is concluded in Section VI.

II. PRELIMINARIES

A. WISP Nodes

Our design focuses on a wireless rechargeable sensor network consists of the WISP, first developed by Intel Research [7], which is one representative wireless rechargeable sensor network platform. With the inherited capabilities from traditional RFID tags, WISP nodes are also equipped with low-power sensors and micro-controllers. From nearby standard UHF RFID readers through their antennas, WISP nodes can harvest RF energy stored in the equipped capacitors to support their future sensing, computation and communication. Fig. 1 shows one WISP node customized and fabricated at our lab.

B. Wireless Charging Model

We adopt the following charging model of the WISP reader proposed and experimentally verified in [12]

$$P(d) = \frac{G_{tx} G_{rx} \eta}{L_p} \left(\frac{\lambda}{4\pi(d+\beta)} \right)^2 P_{tx}, \tag{1}$$

where P_{tx} is the reader transmission power, d is the distance between the reader and the receiver, G_{tx} is the antenna gain of reader, G_{rx} is the antenna gain of the receiver, λ is the wavelength of the RF wave, η is the rectifier efficiency, L_p is the polarization loss and β is an adjustable parameter for indoor environment. This model is derived from the Friss's free space equation and has been experimentally proved to be a good approximation of charging power. Under static environment and device settings, all parameters in Eq.1 are constant values except for the relative distance d.

We assume that there exists a threshold of distance denoted by r, beyond which the node cannot be wirelessly charged [13]. Then the summarized empirical charging model can be expressed as

$$P(d) = \begin{cases} \frac{\tau}{(d+\beta)^2}, & 0 \leq d < r \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where τ is a constant parameter that captures the impacts of G_{tx}, G_{rx}, P_{tx}, L_p, λ and η on the charging power.

In the previous work [11], we introduce an optimal solution for minimizing the total communication delay for the case when the reader charging range is able to cover the whole region S and thus can stop once collecting all information. However, when the deployment site is large, the node may be far away from the reader such that the wireless charging power would become too low to be harvested. In this paper, we mainly focus on the more generic reader movement scenario where the reader's charging range is limited and it has to move and stop at multiple locations for completing the data collection.

C. Communication Pattern

In [11], We empirically measure the communication delay on our WISP testbed with EPC C1G2 protocol [14], which is widely adopted in existing passive RFID systems. Due to the sensing and computation capabilities, the transmission from WISP nodes to the RFID reader may be bursty, and thus increase the collision probabilities as EPC C1G2 is designed for large number of tags transmitting a small amount of data.

During the experiments, we measure the actual communication delays on our WISP testbed with EPC C1G2 protocol. Multiple (up to 6) WISP nodes are placed in front of the reader, and the communications are performed multiple rounds. 5 sensory readings are collected from each WISP node during each communication round. The average delay of WISPs is shown in Fig. 2, where we can see that the average communication delay significantly increases when more WISP nodes get involved.

D. System Settings

In this paper, we mainly consider the scenario where N wireless rechargeable nodes are randomly deployed in the area S with positions W_1, W_2, …, W_N, accordingly. In order to communicate with all sensor nodes, one reader carried by a robot or vehicle is able to move around in the deployment field [15]. Note that in order to charge the nearby sensors and collect their sensory data, the reader must decide where to stop in the field and turn on its radio for a duration of time. Meanwhile, each sensor will start the communication with the reader once its voltage reaches a threshold. In the ideal case, e.g., there is no communication collision, it will take ϵ seconds for one node to finish its communication with the reader. Additionally, for each individual node, unless it is within the charging range of a reader, it will get back to the fully discharged state once it finishes the communication with the reader. Such setting is reasonable since a typical WISP node with $10\mu F$ capacitor will be fully discharged within $100ms$ if it is outside the charging range of a reader.

It should be noted that our setting and communication pattern is significantly different from existing works as each WISP node instantly transmits all of its data to a reader once its voltage is charged to the working level. We define the process for a reader to accomplish communications with all the nodes in its communication range as a *communication round*.

We will focus on the **Single-Report Pattern**, where a WISP tag will keep silent for several *communication rounds* after its successful communication with the reader. Such **Single-Report Pattern** is also unique to the wireless rechargeable sensor networks. Due to its embedded computational components, a tag is able to decide whether or not to communication with the reader so that the redundant communication collisions can be avoided. Such a Single-Report Pattern is also unique to wireless rechargeable sensor networks and useful for applications such as supply chain monitoring [3] and warehouse inventory management [4], [5]. By designing the optimal reader movement, we aim to eliminate collision of WISP nodes by exploiting their individual charging time differences. Such a novel communication pattern is expected to greatly improve both the communication and energy efficiency.

III. COLLISION-FREE COMMUNICATION DESIGN

In our previous work [11], we focus on the scenario where a RFID reader is required to deployed at a location in order to charge and collect the sensory data from WISP nodes. Instead of designing MAC protocols, we introduce an optimal solution for minimizing the total communication delay for the case when the reader charging range is able to cover the whole region S and thus can stop once collecting all information. Note that, when the deployment site is large, the node may be far away from the reader such that the wireless charging power would become too low to be harvested. Therefore, in this paper, we extend the design concept to handle a more generic reader movement situation, and assume that the RFID reader is carried by a vehicle or robot, and can move to any position in the two dimensional region.

The motivation of our collision free multiple stop data collection is quite clear. Instead of MAC protocol for collision enabled design, our collision free design significantly reduce the process of recharging, which is the main part of the charging delay of collision enabled MAC protocol. When the number of nodes becomes quite large, collision will happen more and recharging process make the collision enabled MAC protocol fail to collect data efficiently. On the contrary, our collision free design collects data by only one round and significantly reduce the delay of recharging process. That's the main reason we propose collision free design in this paper.

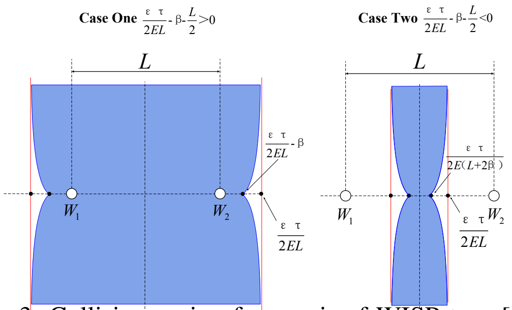


Fig. 3: Collision region for a pair of WISP tags [11]

In this section, we provide the main results on how to handle a more generic reader movement scenario where the reader's charging range is limited and it has to move and stop at multiple locations for completing the data collection.

A. *Revised Collision Region*

In this part, we first explain the collision region which is first defined in our previous work [11]. Then we revise the definition in order to deal with the more generic scenario considered in this paper.

Denote the charging energy for reaching the fixed voltage threshold at individual node as E, and the charging time as T_i for node i. For the collision region proposed in [11], since the charging range of reader is able to cover all node, from the charging model, the charging time for node i can be represented as:

$$T_i = \frac{E(d_i + \beta)^2}{\tau} \tag{3}$$

Therefore, for an arbitrary node pair, e.g., node i and node j, their communication will collide if and only if the following condition is satisfied

$$|T_i - T_j| < \epsilon \tag{4}$$

Therefore, the *Collision Region* for the whole region S with N WISP nodes can be defined as follows [11]:

Definition 1: The *Collision Region* is a set of points within S, such that if the reader stops at any point in it, there exists at least one pair of WISP nodes satisfies Eq. 4.

Consider two nodes W_1 and W_2 with coordinates (x_1, y_1) and (x_2, y_2) and relative distance $L = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$. Denote the location of reader as R with coordinates (x_R, y_R). Then the collision region for W_1 and W_2 must satisfy (4). With some algebraic manipulations, we obtain the exact collision region shown as the shadowed part in Fig. 3. Specifically, there are two cases. When the relative distance of W_1 and W_2 is smaller than a threshold $\frac{\epsilon\tau}{EL} - 2\beta$, the collision region would cover two nodes, which is shown in the left side of Fig 3. Otherwise, the collision region would be in the center between W_1 and W_2. Note that for both cases, the dark lines are the asymptotes for the boundaries of collision regions. For the ease of analysis, we replace the exact collision region by the zone bounded by the asymptotes, which is a good approximation of the actual collision region as shown in Fig. 3. Such approximated collision region is essentially a perpendicular bisector zone with width $\frac{\epsilon\tau}{EL}$ for a given pair of nodes. And

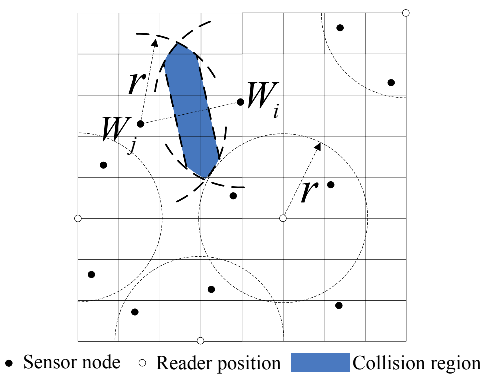


Fig. 4: M×M grids of reader movement scenario

the approximated collision region also guarantees that any location outside this region is collision-free for the node pair W_1 and W_2.

Now we are ready to present the revised collision region. Based on the localization and navigation accuracy, we can divide the two-dimensional plane into $M \times M$ grids as shown in Fig. 4, where each unit is the minimal recognizable distance of the vehicle or robot. Since the reader charging range r is not enough to cover the whole region, we first slightly revise the definition of collision region. Take node W_i and W_j in Fig. 4 for example. Note that in [11], the collision region for a pair of nodes is defined as their perpendicular bisector zone. However, since the reader charging range is now limited as r, we can easily draw circles centered at node W_i and W_j with radius r respectively. Then the intersected region is indeed the revised collision region, which is indicated by the dark region in Fig. 4. With the revised collision region for one pair of nodes, we can obtain the collision region for a given number of nodes in the region S. The key idea is to draw the perpendicular bisector zone for each pair of nodes and the combined zones are the collision region for all nodes in the region.

B. *Optimal Reader Movement for Minimizing the Total Delay*

In this part, we consider the general problem of how to plan the reader stop locations and the stop durations such that the total communication delay is minimized without any communication collisions.

Define $\mathcal{R} = \{R_1, R_2, \ldots,\}$ as the sequence of reader stop locations, and $\mathcal{T}_R = \{T_1, T_2, \ldots,\}$ as the sequence of corresponding stop durations, which are to be assigned. We also denote $\mathcal{W}_i$ as the corresponding set of nodes which are fully charged when the reader stops at R_i for T_i time. Then we aim to solve the following optimization problem

Problem 1: Find an optimal reader stop sequence $\mathcal{R}$ as well as the associated stop duration sequence $\mathcal{T}_R$, such that the total duration time for collecting data from all nodes, i.e., $\sum_i T_i$, is minimized while there is no communication collision within each node set $\mathcal{W}_i$.

1) Problem Difficulties: Problem 1 is intrinsically difficult to solve. One critical challenge is that, different from the one-stop scenario considered in [11], where the collision-free region is static, for the multi-stop scenario, almost any location can be collision-free as long as we can control the reader stop duration so that the fully charged nodes within such a duration do not collide with each other. Moreover, the consecutive stop locations and durations are also affected by the sequence of previous decisions. In order to show the difficulty of Problem 1, we first introduce the weighted set-covering problem (WSCP) which has been proved to be NP-hard [16].

Definition 2: Given a finite set X and a family $\mathcal{F}$ of subsets of X, such that every element of X belongs to at least one subset in $\mathcal{F}$: $X = \bigcup_{S \in \mathcal{F}} S$. Each set S_i in the family $\mathcal{F}$ has an associated weight ω_i. The weighted set-covering problem is to find minimum-weight subset $\mathcal{C} \subseteq \mathcal{F}$ which covers all elements in X : $X = \bigcup_{S \in \mathcal{C}} S$.

If we constrain that each reader stop duration must equal to a constant value T_c which guarantees that all the nodes within the reader charging range r can be fully charged, then our delay minimization problem can be reduced as one WSCP problem. Specifically, let all nodes in the region form the set X, then for each potential reader stop location R_i, the nodes that can communicate with the reader from the set S_i and its corresponding weight $\omega_i = T_c$. Note that the exact number of elements of S_i, i.e., $|S_i|$, is affected by the previous sequence of reader stop locations. Family $\mathcal{F}$ is consisted of S and $X = \bigcup_{S \in \mathcal{F}} S$. To find the optimal reader stop locations, we need to find a set $\mathcal{C} \subseteq \mathcal{F}$ which has the minimum weight. Hence, our problem has been further reduced to a WSCP which is NP-hard. Therefore, our original Problem 1 should be either NP or even harder. Therefore, for the more generic multi-stop case, it is almost impossible to derive the optimal solution as what we have done for one-stop case in [11]. However, we hope to design at least one simple but effective heuristic solution.

2) Approximation Solution: Motivated by the design of one-stop scenario in [11], we first reduce the original Problem 1 to a well-known weighted set-covering problem by utilizing the concept of collision region. Then we propose a heuristic algorithm to obtain an approximated solution.

Considering the additional costs of reader movement, for many real-world applications, it is usually beneficial to reduce the number of reader stop locations for reducing the moving energy [17]. Therefore, in our problem, we let the reader communicate with all nodes within its range r at each stop. Consequently, we can establish the revised collision-free region for all the nodes in the whole region. Thus the problem is reduced to find the optimal reader stop location sequence such that the total stop durations are minimized.

Note that such a reduced problem is still NP-hard as proved in the previous part. We propose a greedy-based algorithm to obtain an approximated solution. From the analysis of coupled charging and communication process, we find that for one-stop scenario, the total communication delay is determined by the longest distance from such nodes to a reader stop location in a collision-free region. Thus if the longest distance is a constant, it should always be better for the reader to cover more number of nodes in order to reduce the average communication delay of each node. Therefore, among all potential collision-free locations, our approximated solution will always search for the one which aims to cover the maximal number of nodes.

Specifically, our design initially establishes the revised collision region for all the nodes in the whole region. Simultaneously, we obtain the collision-free region, which corresponds to all the potential collision-free locations. Then among all potential locations, we search for the optimal location by which the reader can cover the maximal number of uncovered nodes, and choose it as the first reader stop location. The reader then stays at this location until it has communicated with all nodes within its range. After that, we remove the revised-collision region contributed by the those covered nodes, and update the potential collision-free locations. Consequently, we can decide the next reader stop locations in a similar fashion. The whole process will continue until all nodes have been covered.

As shown in Algorithm 1, we first initialize the system variables U, $\mathcal{C}$, and construct $\mathcal{F}$(Line 2). U represents the set of uncovered nodes and equals the X at the initial stage. $\mathcal{F}$ is consisted of the sets of sensor nodes, where each set corresponds to one potential stop location guaranteeing no communication collisions. For each cycle in the loop, we find a set $S \in \mathcal{F}$, such that $\max|S|$, which means that S has the maximal number of nodes (Line 4). Then nodes in S are removed from U as they have been successfully read while $\mathcal{C}$ record such S in each iteration (Line 5 and 6). After that, we update $\mathcal{F}$ based on the remaining uncovered node set U(Line 7). This algorithm will end until $U = \emptyset$.

Algorithm 1 *GA: Greedy Algorithm for Multi-stop Collision-free Communication*

```
1: Input: $X$
2: Initialization: Construct $\mathcal{F}$ for $X$, and let $U \leftarrow X$, $\mathcal{C} \leftarrow \emptyset$
3: while $U \neq \emptyset$ do
4:     select an $S \in \mathcal{F}$ that maximizes $|S|$
5:     $U \leftarrow U - S$
6:     $\mathcal{C} \leftarrow \mathcal{C} \cup \{S\}$
7:     update $\mathcal{F}$
8: end while
9: return $\mathcal{C}$
```

One key step in our design is that we draw the whole collision region at the initial stage so that we can build the potential collision-free locations. Note that the overall collision region consists of all individual collision regions contributed by each pair of sensor nodes. Then after the successful communication with certain nodes at each reader stop location, we can directly remove their contributed collision regions and therefore increase the potential collision-free locations for the following communication rounds. The upper bound of iteration times for our design is N, which is also the maximum number of stop locations. And the total computational complexity is $O(N^3 + N \log M)$.

IV. EVALUATION

In this section, we evaluate the performance by comparing our proposed algorithms with a baseline design through extensive simulations under various network settings.

A. Simulation Setup

In the default setting, we assume sensor nodes are uniformly deployed in a $50m \times 50m$ area. The minimal recognizable distance in the two-dimensional space is set to $1m$. Except where otherwise specified, the default number of nodes is 120. For the charging model, we set $\tau = 36$ and $\beta = 30$, which are obtained by fitting through our experimental data. For each node, the energy threshold is set to be $2J$, which is essential for sensor nodes to support the sensing, computing and communication functionalities reliably [7]. The communication time threshold ϵ is set to be $0.5s$, which is sufficient for one node to transmit 24 bytes to the RFID reader. For each point in the simulation figure, we take average of 10 runs with different random seeds and node deployments for credible results.

B. Baseline Setup

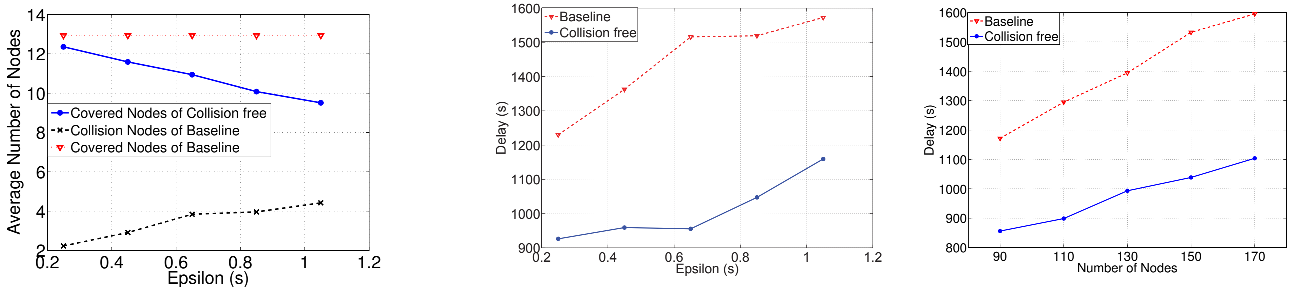
There is no existing works that minimizes the total communication delay through reader movement design in wireless rechargeable sensor networks. In order to compare the system performance of our design, we introduce a baseline design based on the concept of Set-Cover [18]. In the baseline design, the RFID reader covers the maximum number of unread nodes at each stop, and conducts the Basic Frame-Slotted ALOHA (BFSA) protocol to communicate with the fully charged sensor nodes.

C. Performance Evaluation

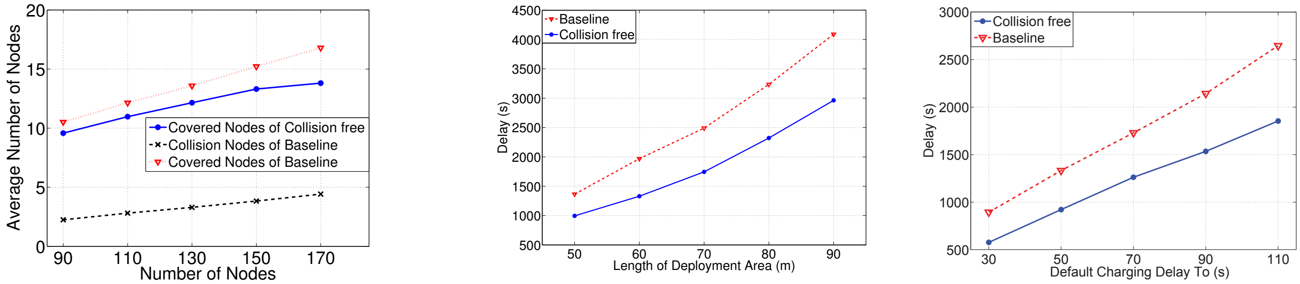
In this part, we demonstrate the system performance of different designs under various system parameters, i.e., the communication time threshold ϵ, the number of nodes N, the deployment size and the on-board capacitor size.

1) Impact of Communication Time Threshold ϵ: We first show how the communication time threshold ϵ affects the total system performance. Since the baseline ALOHA strategy always tries to cover the maximum number of nodes at each stop without considering collisions, it is understandable that under the baseline design the stop location sequence does not change with ϵ for any given node deployment. However, for each stop, since the communication time ϵ increases, the collision is more likely to happen. In fact, as shown in Fig. 5a, we observe that the average communication collision number of each stop for the baseline ALOHA strategy increases from 2.2 to 4.4 when the communication time threshold ϵ grows from $0.25s$ to $1.05s$. Since more collided sensor nodes have to get recharged and then communicate with reader again when collisions increase, the total communication delay of baseline ALOHA design dramatically increases by around $345s$.

On the other hand, based on the analysis in Section III, the width of the collision region associated with each pair of nodes increases linearly with the increase of communication time threshold ϵ. Therefore the remaining collision-free region decreases which limits the candidate locations of reader. In fact, with the increase of ϵ, the reader has to cover less nodes at each stop in order to provide collision-free communication, which also explains the increase of total communication time of our design. From Fig. 5b, it can also be observed that for various settings of communication time threshold ϵ, our collision-free approach exhibits more than 25% improvement of total communication time. For example, when the communication time threshold $\epsilon = 0.65s$, the average time delay is 8s for our collision-free design while the ALOHA based design takes more than 12.7s to read each node in average.



(a) Average Number of Nodes vs. Epsilon (b) Delay vs. Epsilon (c) Delay vs. Density



(d) Average Number of Nodes vs. Density (e) Delay vs. Deployment Area (f) Delay vs. Default Charging Delay

Fig. 5: Delay and average covered nodes

2) Impact of Node Density: In order to compare the total communication delay of our collision-free design with the baseline ALOHA method under different node densities, we vary the node number from 90 to 170 in the $50m \times 50m$ area.

Total delays of different node densities are shown in Fig. 5c. For the baseline ALOHA method, since the reader tends to cover more nodes at each stop, it is expected to cause more collision and therefore enlarge the total delay. However, our collision-free design helps to choose locations without communication collision while the reader is still be able to cover as many nodes as possible. However, such an increase is still slower than the increase of total nodes. Therefore, we can observe the approximately linear increase of total delay for our collision-free design in Fig. 5c. Besides, from Fig. 5c, it can be seen that our proposed collision-free delay reduces the total delay by at least 20%.

3) Impact of Deployment Size: We compare the total communication delay for different network deployment sizes under the default node density. Specifically, we vary the areas from $50m \times 50m$ to $90m \times 90m$ with a step length of $10m$. The total communication delays for baseline ALOHA design and our collision-free design are plotted in Fig. 5e. With the fixed charging range r and node density, for both designs, the reader has to stop for more times to charge and communicate with sensor nodes in a larger area. Therefore, we can observe that the total communication delays for both designs increase linearly with the growing deployment size. On the other hand, our collision-free design outperforms the baseline ALOHA design under all deployment sizes with at least 25% improvement of the total delay. It can also be observed that the performance gap between our design and the baseline ALOHA design also becomes larger with the increase of deployment size, which proves that the effectiveness of our collision-free design for large-scaled systems.

4) Impact of Capacitor Size: In this subsection, We investigate how the capacitor size will affect the the total communication delay, which is important for the designer to decide the appropriate capacitor size. For easing the presentation, we adopt the default charging time T_0 for the wisp tag when it is fully charged under the maximal charging power (right next to the reader), to differentiate the various on-board capacitor sizes. Fig. 5f shows the total communication delays of our design and the baseline approach with various default charging time T_0 under the default network settings. It can be observed that the total communication delays for both designs increase almost linearly along with the default charging time T_0 as the reader will have to stay more time for fully charging each wisp tag. Meanwhile, it is also interesting to see that the performance difference between our design and the baseline design also becomes larger as T_0 increases. For example, when T_0 increases from $30s$ to $110s$, the improvement of total communication delay of our collision-free design increases from 317.4s to 792.6s. The underlying reason is that with a larger default charging time T_0, the collided nodes under the baseline design will require more time to be fully charged for the second time in order to communicate with the reader while our collision-free design avoids any communication collision.

V. RELATED WORK

Different efforts have been devoted to minimizing the communication delay in traditional RFID systems. Based on the underlying techniques, they are primarily two types of anti-collision algorithms, i.e., slotted ALOHA based protocols [14] and tree based protocols [9].

Kodialam et al. [8] propose a collision-based estimator and a set of probabilistic node number estimators for reducing collision in slotted ALOHA. Based on a continuous-time model, Zhen et al. [19] propose a method for calculating the reading time for N nodes with guaranteed unsuccessful probability. Under the Markov process assumption for the reading process, Vogt [20] calculates the time for identifying all nodes with any given assurance level. Most recently,by revising the existing EPC C1G2 protocol, Gummeson et al. [10] propose a coordinated bulk transfer protocol, which enables the wireless rechargeable sensor to transfer data in a burst in order to increase the goodput and reduce the communication overhead.

On the other hand, by detecting the collisions, tree based protocols deterministically split the group of nodes into subgroups until all nodes are identified [21]–[23]. Since tree based protocols usually introduce high computational overhead and long delay, they are less applicable in large-scaled systems.

Our work is the first work to optimize the total communication delay by planning the reader movement within the WRSNs. Different from related work [24]–[27], our work mainly focuses on intra-network optimization for both charging delay and communication delay, and the increase of charging efficiency in hardware domain [13], [28] can simultaneously improve the system performance of our design.

VI. CONCLUSIONS

In this paper, we have investigated the optimal movement plan of the RFID reader to achieve collision-free communications in wireless rechargeable sensor networks. First, we have identified the time of charge as a novel design dimension to avoid communication collisions, and have introduced the concept of revised collision region for wireless rechargeable sensor networks. Based on the properties of collision region, since the charging range of RFID reader is not enough to cover all nodes, we have proved that the problem of minimizing communication delay in such networks is NP-hard, and have proposed an effective greedy-based heuristic by utilizing the properties of revised collision region. We have performed detailed performance evaluations through both analysis and large-scale simulations. Our future work will focus on the testbed evaluation of the presented designs.

REFERENCES

[1] Y. Shu, F. Jiang, Z. Dai, J. Chen, Y. Gu, and T. He, “Demo: WISP-based Access Control Combining Electronic and Mechanical Authentication,” in *ACM SenSys*, 2011.

[2] L. Yang, J. Han, Y. Qi, and Y. Liu, “Identification-free Batch Authentication for RFID Tags,” in *IEEE ICNP*, 2010.

[3] “European Retailer Throttleman Improves Supply Chain with RFID,” http://www.alientechnology.com/docs/CS_Throttleman.pdf.

[4] D. J. Bijwaard, W. A. van Kleunen, P. J. Havinga, L. Kleiboer, and M. J. Bijl, “Industry: Using Dynamic WSNs in Smart Logistics for Fruits and Pharmacy,” in *ACM SenSys*, 2011.

[5] G. Liu, W. Yu, and Y. Liu, “Resource Management with RFID Technology in Automatic Warehouse System,” in *IEEE IROS*, 2006.

[6] C.-H. Lee and C.-W. Chung, “Efficient Storage Scheme and Query Processing for Supply Chain Management Using RFID,” in *ACM SIGMOD*, 2008.

[7] 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 T. Instrum. Meas.*, vol. 57, no. 11, pp. 2608–2615, 2008.

[8] M. S. Kodialam and T. Nandagopal, “Fast and Reliable Estimation Schemes in RFID Systems,” in *ACM Mobicom*, 2006.

[9] Y. Zheng, M. Li, and C. Qian, “PET: Probabilistic Estimating Tree for Large-Scale RFID Estimation,” in *IEEE ICDCS*, 2011.

[10] J. Gummeson, P. Zhang, and D. Ganesan, “Flit: A bulk transmission protocol for RFID-scale sensors,” in *ACM MobiSys*, 2012.

[11] Y. Tian, P. Cheng, L. He, Y. Gu, and J. Chen, “Optimal Reader Location for Collision-Free Communication in WRSN,” submitted to IEEE Globecom,2014.

[12] S. He, J. Chen, F. Jiang, D. Yau, G. Xing, and Y. Sun, “Energy provisioning in wireless rechargeable sensor networks,” *IEEE Transactions on Mobile Computing*, vol. 12, no. 10, pp. 1931–1942, 2013.

[13] “Powerharvester receivers,” http://www.powercastco.com.

[14] EPCglobal, “EPC Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz - 960 MHz Version 1.0.9,” 2005.

[15] “Diakinisis Automates Major Distribution Center with RFID,” http://www.alientechnology.com/docs/CS_Diakinisis.pdf.

[16] G. Gambosi, M. Protasi, and M. Talamo, “Preserving Approximation in the Min-Weighted Set Cover Problem,” *Discrete Applied Mathematics*, vol. 73, no. 1, pp. 13–22, 1997.

[17] G. Xing, T. Wang, W. Jia, and M. Li, “Rendezvous Design Algorithms for Wireless Sensor Networks with A Mobile Base Station,” in *ACM Mobihoc*, 2008.

[18] G. Zhou, D. Moshkovitz, and S. Safra, “Algorithmic construction of sets for k-restrictions,” *ACM Transactions on Algorithms*, vol. 2, no. 2, pp. 153–177, 2006.

[19] B. Zhen, M. Kobayashi, and M. Shimizu, “To Read Transmitter-only RFID Tags with Confidence,” in *IEEE PIMRC*, 2004.

[20] H. Vogt, “Efficient Object Identification with Passive RFID Tags,” in *Pervasive*, 2002, pp. 98–113.

[21] J. Capetanakis, “Tree Algorithms for Packet Broadcast Channels,” *IEEE Transactions on Information Theory*, vol. 25, no. 5, pp. 505 – 515, 1979.

[22] J.-R. Cha and J.-H. Kim, “Novel Anti-collision Algorithms for Fast Object Identification in RFID System,” in *IEEE ICPADS*, 2005.

[23] F. Zhou, C. Chen, D. Jin, C. Huang, and H. Min, “Evaluating and Optimizing Power Consumption of Anti-collision Protocols for Applications in RFID Systems,” in *ISLPED*, 2004.

[24] L. Fu, P. Cheng, Y. Gu, J. Chen, and T. He, “Minimizing Charging Delay in Wirelessly Rechargeable Sensor Networks,” in *IEEE INFOCOM*, 2013.

[25] P. Cheng, S. He, F. Jiang, Y. Gu, and J. Chen, “Optimal Scheduling for Quality of Monitoring in Wireless Rechargeable Sensor Networks,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 6, pp. 3072–3084, 2013.

[26] Y. Shu, P. Cheng, Y. Gu, J. Chen, and T. He, “TOC: Localizing Wireless Rechargeable Sensors with Time of Charge,” in *IEEE INFOCOM*, 2014.

[27] R. Deng, Y. Zhang, S. He, J. Chen, and X. Shen, “Globally Optimizing Network Utility with Spatiotemporally-Coupled Constraint in Rechargeable Sensor Networks,” in *Proc. IEEE GLOBECOM*, 2013, pp. 5121–5126.

[28] M. Marroncelli, D. Trinchero, V. Lakafosis, and M. Tentzeris, “Concealable, low-cost paper-printed antennas for wisp-based rfids,” in *IEEE RFID’11*, 2011.