Optimal Charge Scheduling for Energy-Constrained Wireless-Powered Network

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***Abstract*—As a candidate power supply solution for the Internet of Things, radio frequency (RF) energy harvesting has attracted great attention recently. In this paper, we consider an RF wireless-powered network, which consists of a dedicated power beacon (PB) and multiple user nodes. The PB is assumed to have limited energy and transfers its power to user nodes wirelessly. The user nodes work only based on energy harvested from the PB, and are assumed to be in either energy harvesting mode, energy consumption mode, or idle mode. To maximize the total harvested energy, we coordinate the behaviors of the PB and user nodes, and propose a general charge scheduling scheme that can achieve the system's maximum harvested energy. We then compare the results of our proposed scheme with the benchmark schemes, and simulation results demonstrate the effectiveness of our proposed scheduling.**

***Index Terms*—charge scheduling, radio frequency (RF) energy harvesting, wireless powered network.**

I. Introduction

With the growing popularity of the Internet of Things (IoT) and machine-to-machine (M2M) communications for automated remote control of electronic devices, more and more IoT applications are being envisioned. To cope with the heavy energy demand of such large-scale networks, new energy harvesting techniques have been considered. Among them, harvesting power from available radio frequency (RF) energy sources has attracted great attention [1].

In the literature, many works have focused on the combination of RF energy harvesting with wireless communication, which consists of two main paradigms called Simultaneous Wireless Information and Power Transfer (SWIPT) and Wireless-Powered Communication Networks (WPCN) [2]. In SWIPT, energy and information are obtained from the received signal simultaneously, while in a WPCN the wireless-powered nodes first harvest energy from RF signals then conduct information transmission based on their harvested energy.

We are interested in the scheduling problem in a purely RF charging setting. Existing works mainly focus on systems with mobile chargers [3]–[7]. The authors of [3] considered a sensor network charged by a mobile charger and investigated the path selection problem to minimize the long-term data loss. By imposing a travel distance per tour constraint on the mobile charger and assuming the energy consumption rates of sensors vary, Ren *et al.*, in [4], studied the charging throughput maximization for a heterogeneous sensor network. In [5], an RFID-based wireless rechargeable sensor network was considered. It was assumed the sensor node needed to charge its onboard energy storage above a threshold in order to power its components, which caused a charging delay. The optimal movement strategy of the RFID reader was then obtained, such that the total time to charge all nodes in the network above their energy threshold was minimized. To prolong the network lifetime, the authors of [6] studied a charging problem whose goal was to find an optimal charging sequence for the mobile charger such that the network lifetime was maximized. Similarly, Xie *et al.* [7] investigated a wireless-powered immortal sensor network also powered by a mobile charger. By requiring all sensor nodes to never cease operational, the traveling path was derived to minimize the total traveling time of the mobile charger.

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All the abovementioned works focused on scenarios with a mobile charger, and only a few investigations have been made of static networks. A static wireless-powered sensor network was considered in [8], where multiple wireless chargers were employed and a charging-oriented and energy balancing protocol were designed by selecting active chargers. In this paper, we consider a static wireless-powered network which consists of a dedicated power beacon (PB) and multiple wireless-powered user nodes. For this energy-constrained wireless-powered network, we propose an optimal charge scheduling to maximize the total harvested energy of all user nodes.

II. System Model and Problem Formulation

We consider a network that consists of an energy-constrained PB that transfers energy to multiple user nodes via RF energy harvesting. The PB is assumed to contain total energy E_{tot}. We denote the k-th user node by U_k and the channel between U_k and the PB by h_k. The user nodes are assumed to be equipped with a single antenna.

When the PB is on, it transmits signal x_s, which is assumed to be an arbitrary complex random signal satisfying $\mathbb{E}[|x_s|^2] = P_0$. The received signal at U_k is then expressed as $y_k = h_k x_s$, by ignoring the receiver noise that is in practice negligible for energy receivers. As a result, the harvested energy per second at U_k is given as

$$e_k^h = \eta \mathbb{E}[|y_k|^2] = \eta P_0 |h_k|^2, k = 1, \ldots, K, \tag{1}$$

where η represents the energy conversion efficiency and is assumed to be a constant.

Each user node is assumed to be equipped with a rechargeable battery with a maximum capacity of E. After the charging period, each user node is assumed to consume an e_c amount of energy per second. [1]

In this wireless charging system, the PB has two modes: the energy transmission mode when it is turned on ($s_p^1 = 1$) and the idle mode when it is off ($s_p^0 = 1$). They are denoted as

$$s_p^j(t) = \begin{cases} 1, & \text{if PB in mode j at time t,} \\ 0, & \text{else.} \end{cases}, j = 0, 1. \quad (2)$$

The user node has three modes: the energy harvesting (EH) mode ($s_i^1 = 1$), the working mode ($s_i^2 = 1$) and the idle mode ($s_i^0 = 1$) when it is turned off, which are denoted as

$$s_i^j(t) = \begin{cases} 1, & \text{if user i in mode j at time t,} \\ 0, & \text{else.} \end{cases}, j = 0, 1, 2. \quad (3)$$

To maximize the aggregate received energy of all user nodes given a time period T and the PB's total energy constraint, we formulate our problem as the following:

$$\max_{\substack{\mathbf{s}^1(t), \\ s_p^1(t)}} \quad \sum_{i=1}^{K} E_i^h(T) \quad (4)$$

$$\text{s.t.} \quad P_0 \int_0^T s_p^1(t)dt \leq E_{tot} \quad (5)$$

$$s_i^0(t) + s_i^1(t) + s_i^2(t) = 1, \forall t \in [0, T], i = 1, ..., K. \quad (6)$$

$$s_p^0(t) + s_p^1(t) = 1, \ \forall t \in [0, T]. \quad (7)$$

$$s_i^j(t) = \{0, 1\}, \ i = 1, ..., K. \ j = 0, 1, 2. \quad (8)$$

$$s_p^j(t) = \{0, 1\}, \ j = 0, 1. \quad (9)$$

$$0 \leq E_i^h(t) - E_i^c(t) \leq E, \forall t \in [0, T], i = 1, ..., K. \quad (10)$$

$$E_i^h(t) = \int_0^t s_p^1(\tau) s_i^1(\tau) e_i(\tau) d\tau, \quad (11)$$

$$E_i^c(t) = \int_0^t s_i^2(\tau) e_c d\tau, \quad (12)$$

where $\mathbf{s}^1(t) = [s_1^1(t), \cdots, s_K^1(t)]$.

(5) is the PB's total energy constraint, (6)–(9) depict the behaviors of the PB and user nodes, and (10) is the energy causality constraint which has to be satisfied for every $t \in [0, T]$.

Note that here the integral appears in both the objective and constraints. And the variables are all 0-1-valued over the given range. We present our proposed solution in the next section.

III. Optimal Charge Scheduling

The optimal solution depends on E_{tot}. Intuitively, if E_{tot} is large enough, then (5) will no longer be a constraint. This will certainly result in different scheduling schemes compared to the case that E_{tot} is bounded by a small value.

[1]Note that here we ignore the specific energy consumption activities conducted by the user nodes, for simplicity. They can be data processing, data storage, or information transmission, as long as an e_c amount of energy is consumed per second.

A. $E_{tot} \geq P_0 T$

We first look into the case that $E_{tot} \geq P_0 T$. Under this condition, (5) becomes useless, which greatly simplifies the optimization problem. We cope with this case by starting from $K = 1$.

When $K = 1$, the problem becomes

$$\max_{\substack{s_1(t), \\ s_p^1(t)}} \quad \int_0^T s_p^1(\tau) s_1^1(\tau) e_1^h(\tau) d\tau \quad (13)$$

$$\text{s.t.} \quad 0 \leq \int_0^t \left\{ s_p^1(\tau) s_1^1(\tau) e_1^h(\tau) - s_1^2(\tau) e_c \right\} d\tau \leq E, \ \forall t \in [0, T], \quad (14)$$

$$(6) - (9).$$

Without the PB's total energy constraint, to ensure the maximal energy receiving at the user node, the PB should be kept on for time duration T. That is, $s_p^1(\tau) = 1, \forall \tau \in [0, T]$. In this case, the user node can harvest energy as long as its battery is not fully charged. Therefore, to maximize the total harvested energy during time period T, there should not be any idle state, and we have $s_1^0(\tau) = 0, \forall \tau \in [0, T]$.

The previous problem is then simplified as

$$\max_{s_1(\tau)} \quad \int_0^T s_1^1(\tau) e_1^h(\tau) d\tau \quad (15)$$

$$\text{s.t.} \quad 0 \leq \int_0^t \left\{ s_1^1(\tau) e_1^h(\tau) - e_c(1 - s_1^1(\tau)) \right\} d\tau \leq E, \ \forall t \in [0, T], \quad (16)$$

$$(6) - (9).$$

By assuming $e_1^h(\tau)$ to be a constant during time period T for simplicity, (16) is further written as

$$\frac{e_c}{e_c + e_1^h} t \leq \int_0^t s_1^1(\tau) d\tau \leq \frac{E + e_c t}{e_c + e_1^h}, \forall t \in [0, T]. \quad (17)$$

When $t = T$, (17) gives the upper bound of the objective, which is

$$\int_0^T s_1^1(\tau) d\tau \leq \min \left\{ \frac{E + e_c T}{e_c + e_1^h}, T \right\}. \quad (18)$$

The second term is due to the time causality constraint.

For the case of $E_{tot} \geq P_0 T$, we conclude the scheduling scheme in the following lemma.

Lemma 3.1: If $E/e_1^h > T$, the PB should be turned on for all T and the user node keeps harvesting energy in T. The maximum harvested energy of the user node is $e_1^h T$.

If $E/e_1^h \leq T$, the user node should assign its charge-discharge process alternately and let the total charging time be $\frac{E + e_c T}{e_c + e_1^h}$ without violating the energy causality constraint. The maximum harvested energy is $e_1^h \frac{E + e_c T}{e_c + e_1^h}$.

Proof: The optimal scheduling scheme of the user node has two different cases. If the battery capacity E is large enough, such that $E/e_1^h > T$, then the battery will not be fully charged even after a consecutive charging period T. Therefore, in this case, the user node should allocate all the time to energy harvesting. On the other hand, if $E/e_1^h \leq T$, due to the battery capacity limitation, there must be some discharging time during T. For the optimal solution, the RHS of (16) achieves equality, and this requires the battery to be fully charged at the end of T. Since here we assume that the charging time and discharging time can be divided arbitrarily, there are numerous possible scheduling schemes to achieve this optimal solution.

Specifically, when $E/e_1^h \leq T$, it takes $t_c = E/e_1^h$ amount of time for the user node to become fully charged from empty. Then the remaining $T - E/e_1^h$ amount of time should be allocated proportionally such that the user node does not go into the idle state. Therefore, $\frac{e_c}{e_c+e_1^h}$ percent of $T - E/e_1^h$ will be assigned for charging, and the total charging time is $\frac{E+e_cT}{e_c+e_1^h}$. One easy scheme to realize this is to leave a t_c amount of the time at the end of T for a consecutive charging period. And arrange the charging and discharing alternately for the beginning, as long as the battery does not become over charged or go into the idle mode. ■

Till now, we have depicted the optimal charge scheduling for one user node under this case.

We then have the scheduling scheme for the multi-user case.

Theorem 3.1: When $E_{tot} \geq P_0T$, for the multi-user case, the optimal scheme is to simply apply the same rule as in lemma 3.1 for each user node.

Proof: It is easy to find that, in this case, the PB is always turned on since it has sufficient energy. Therefore, for the multi-user case, all the user nodes can simply apply the same rule as in the one-user case, since there is always energy available during T and the asynchronicity will not cause any trouble. ■

B. $E_{tot} < P_0T$

With constraint (5), the scheduling scheme needs to be designed delicately. We directly look into the multi-user case. The problem is that, in this case, the PB cannot sustain power transmission for time duration T. The basic idea is to align the charging periods and try to harvest energy as much as possible.

This depends on the relation between $\bar{T}$, ($\bar{T} = \frac{E_{tot}}{P_0}$), and the user nodes' full charging time $\frac{E}{e_k^h}$. We first rank the energy harvesting rates from high to low as e_1^h to e_K^h.

The whole charge scheduling scheme is easy: Let's suppose $\bar{T}$ falls in the range $[\frac{E}{e_i^h}, \frac{E}{e_{i+1}^h}), i \in [1, K]$. This means the first i user nodes can become fully charged in $\bar{T}$, while the rest are unable. Therefore, if $1 \leq i \leq K-1$, for the $(i+1)$-th to K-th user nodes, the optimal scheme is clearly to keep harvesting energy when the PB is on during the time period T since they do not need to worry about over-charging. But for the first i user nodes, the scheduling needs to be more cautious. We conclude this in the following lemma.

Lemma 3.2: If there exists $i \in [1, K-1]$ such that $\frac{E}{e_i^h} \leq \bar{T} < \frac{E}{e_{i+1}^h}$, the optimal scheduling scheme for the first i user nodes is given as follows: Find the largest $k \in [1, i]$ such that $e_k^h > [e_c(T-\bar{T}) + E]/\bar{T}$ is satisfied. [2] The k-th user node switches between charging and discharging, and the PB should be turned on and off accordingly. When the total discharging time equals $T - \bar{T}$, the PB should be kept on for the rest of the time. The remaining user nodes are required to act synchronously. [3]

Proof: For the first i user nodes, the maximum total charging time for each is $\frac{E}{e_i^h} + \min\{\bar{T} - \frac{E}{e_i^h}, (T - \frac{E}{e_i^h})\frac{e_c}{e_c+e_i^h}\}$. This is because each user node has to satisfy both the total charging time constraint and the energy causality constraint.

Next, we clarify the threshold for e_k^h. When $(T - \frac{E}{e_k^h})\frac{e_c}{e_c+e_k^h} < \bar{T} - \frac{E}{e_k^h}$, which is equivalent to $e_k^h > \frac{e_c(T-\bar{T})+E}{\bar{T}}$, the k-th user node is limited by the energy causality constraint. The energy harvesting rates of the first k user nodes are all larger than e_k^h. Therefore, they are all limited by the energy causality constraint and cannot use up $\bar{T}$ charging time. Moreover, the total charging times of the 1-st to the $(k-1)$-th user nodes are all less than that of the k-th user node; thus they can all achieve their maximum harvested energy by following U_k's scheduling. They need to align the discharging periods with the k-th user node, and allocate the charging and discharging time proportionally during the k-th user node's charging periods.

The $(k+1)$-th to the i-th user nodes will use up $\bar{T}$ charging time. In addition to following the k-th user node's scheduling, they are also required to keep charging while the PB is turned on during time duration T. Till now, we have presented the charge scheduling scheme for the first i user nodes. ■

Note that the k-th user node is the last that needs to consider over-charging, since the $(k+1)$-th to the K-th user nodes can all use up $\bar{T}$ charging time without violating the energy causality constraint.

We then conclude the whole scheduling scheme for the case that $E_{tot} < P_0T$ in the following theorem.

Theorem 3.2: Calculate $\bar{T} = \frac{E_{tot}}{P_0}$ and sort $\frac{E}{e_i^h}$ in ascending order. Compare $\bar{T}$ with $\frac{E}{e_i^h}$ and find i such that $\frac{E}{e_i^h} \leq \bar{T} \leq \frac{E}{e_{i+1}^h}$.[4] The first i user nodes should adopt the charging scheme in lemma 3.2, and the remaining $(i+1)$-th to K-th user nodes should simply keep charging when the PB is on.

Proof: This is straightforward based on the previous analysis. ■

IV. Simulation Results

In this section, we present simulation results. The channel is assumed to be quasi-static flat fading, and the channel power gains are set to be $|h_k|^2 = 10^{-3}\lambda d_i^{-\theta}$, where λ is an exponentially distributed random variable with mean 1, d_i is the distance between U_i and the PB, and θ is the path-loss exponent. We set $d_i = 1.5\ m$, $\theta = 2$, $K = 10, E = 1, E_{tot} = 1, T = 1$, and $P_0 = 4$ in the rest of this section, unless

[2] If for all $k \in [1, i]$, $e_k^h \leq [e_c(T-\bar{T}) + E]/\bar{T}$, then $k = 1$.

[3] Note that, in this way, the rest of the user nodes need to know the scheduling scheme of the k-th user node.

[4] If all $\frac{E}{e_i^h} \leq \bar{T}$, then $i = K$. If all $\frac{E}{e_i^h} > \bar{T}$, then $i = 0$.

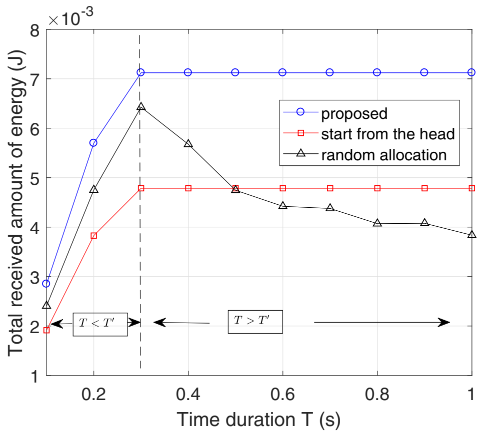

Fig. 1. The total harvested energy versus T.

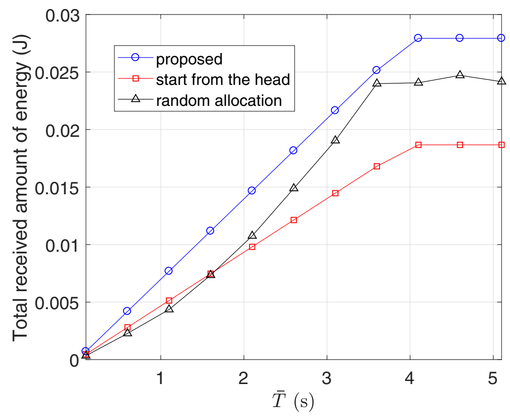

Fig. 2. The total harvested energy versus $\bar{T}$.

otherwise stated. All of the simulation results are generated by averaging over 100 realizations.

We compare the results of our proposed scheme with two benchmark schemes. The first is called start from the head, which means that the PB simply starts charging until its energy is used up. The second benchmark is random allocation, in which the user nodes and the PB decide their behaviors randomly and do not have any scheduling at all.

We first investigate the impact of time duration T in Fig. 1. When the total energy at the PB is given, T affects the corresponding optimal charging strategy. If $T < T'$[5], the PB has enough energy to perform charging all the time. Thus, at this stage, the total received energy increases with T. However, when $T > T'$, increasing T will not improve the total received energy, since at this stage, charging time is no longer the limitation. It is shown by the figure that our proposed scheme outperforms the benchmarks for all values of T.

Next, in Fig. 2, we consider the impact of $\bar{T}$. $\bar{T}$ affects the system's performance similarly to the analysis of T. After exceeding a certain value, increasing $\bar{T}$ no longer brings improvement.

Finally, Fig. 3 gives the total received energy versus the number of user nodes K. As we expected, the total amount of harvested energy increases with K, which simply comes from the fact that more user nodes can collect more energy at the same time.

V. Conclusion

In this paper, we have considered charge scheduling for a wireless-powered network which consists of a dedicated PB and multiple wireless-powered user nodes. With an energy-constrained PB, we have proposed an optimal charge scheduling that can achieve the system's maximum energy harvesting efficiency. Simulation results demonstrate the effectiveness of our proposed scheme.

[5] T' is determined by the user node with the best channel condition. $T' = \frac{E}{e_1^h} + \left(\bar{T} - \frac{E}{e_1^h}\right)\left(1 + \frac{e_1^h}{e_c}\right)$, if $\bar{T} > E/e_1^h$. Otherwise, $T' = \bar{T}$.

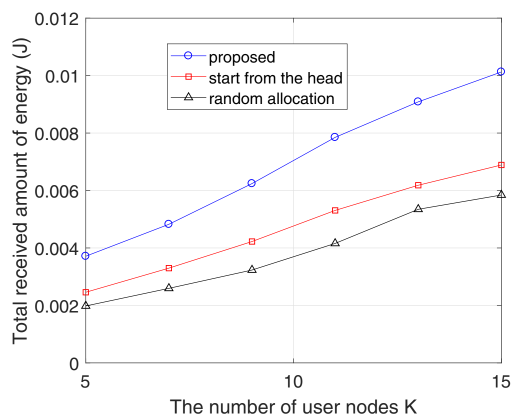

Fig. 3. The total harvested energy versus K.

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