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Lifetime Maximization for Sensor Networks with Wireless Energy Transfer

Rong Du*, Carlo Fischione*, Ming Xiao†

* Automatic Control Department, † Communication Theory Department

KTH Royal Institute of Technology, Stockholm, Sweden

Email: {rongd, carlofi, mingx}@kth.se

Abstract—In Wireless Sensor Networks (WSNs), to supply energy to the sensor nodes, wireless energy transfer (WET) is a promising technique. One of the most efficient procedures to transfer energy to the sensor nodes consists in using a sharp wireless energy beam from the base station to each node at a time. A natural fundamental question is what is the lifetime ensured by WET and how to maximize the network lifetime by scheduling the transmissions of the energy beams. In this paper, such a question is addressed by posing a new lifetime maximization problem for WET enabled WSNs. The binary nature of the energy transmission process introduces a binary constraint in the optimization problem, which makes challenging the investigation of the fundamental properties of WET and the computation of the optimal solution. The sufficient condition for which the WET makes WSNs immortal is established as function of the WET parameters. When such a condition is not met, a solution algorithm to the maximum lifetime problem is proposed. The numerical results show that the lifetime achieved by the proposed algorithm increases by about 50% compared to the case without WET, for a WSN with a small to medium size number of nodes. This suggests that it is desirable to schedule WET to prolong lifetime of WSNs having small or medium network sizes.

I. INTRODUCTION

Wireless sensor networks (WSNs) are usually designed for long term monitoring of important or relevant environments, such as forests [1], water pipelines [2], and battlefields [3]. Generally, WSNs consist of sensor nodes that are powered by batteries. Since battery replacement is uneasy or even impossible, the WSNs stop working once the batteries run out. Therefore, designing long living WSNs is always an important issue for WSN-based applications.

To prolong the WSNs lifetime, energy harvesting [4], [5] is a promising technique. Energy from the environment, such as solar [6], wind [7], and vibrations [8], can be harvested by sensor nodes to charge their batteries. Although such energy can be considered as infinite and environmental friendly, the harvesting of the ambient energy is normally unpredictable and uncontrollable [9]. This is a major limitation of energy harvesting. On the other hand, the harvesting of the radio-frequency (RF) energy from the electromagnetic radiation of a source node can be better controlled. This makes it possible to transfer energy wirelessly from a source node to a target node, with the use of rectifying antenna (rectenna). Therefore,

Fig. 1. Wireless energy transfer enabled wireless sensor network having (a) a star topology; (b) a tree topology

in this paper, we investigate wireless energy transfer (WET) to prolong the lifetime of WSNs.

In this paper, we consider a WSN where sensor nodes measure data and transmit them to a base station, whereas the base station collects data and transmits energy to sensor nodes wirelessly, as shown in Fig. 1. The sensor nodes are battery powered, and hence are energy limited. On the other hand, the base station is grid powered, and thus has an unlimited energy supply. However, the energy transfer capability is limited due to circuit constraint and safety reasons [10]. In practice, the base station can use a sharp beam [11] to transfer energy to an individual node at a time, employing a certain amount of time. Therefore, an essential scheduling problem arises when deciding to which sensor node the base station has to transfer the energy from time to time. Such a scheduling problem should aim at maximizing the network lifetime. The contribution of this paper is as follows.

- We formulate a lifetime maximization problem for WET enabled WSN for star topology networks (Fig. 1 (a)). Based on the optimization problem, we establish a sufficient condition for which the lifetime of the WET enabled WSN is potentially infinite by carefully determining the WET schedule.
- Given when the sufficient condition is not satisfied, we proposed an algorithm with low-complexity to achieve

the maximum network lifetime.

- Based on the result from the star topology network, we further generalize the study to a network with tree topology (Fig. 1 (b)).

The organization of the paper is as follows. We present the related works in Section II. The optimal WET scheduling problem to maximize network lifetime is formulated in Section III, where the condition to have infinite lifetime is also given. In Section IV, an algorithm with low-complexity is given to solve the scheduling problem, together with the study of its performance. In Section V, numerical results from simulations are given to show the performance of the proposed algorithm. The paper is concluded in Section VI.

II. RELATED WORKS

To prolong the WSNs lifetime, traditional methods include scheduling the awake/sleep period of the sensor nodes [2], and determining the transmission range and routing of the sensor nodes [12]. However, as long as the batteries of sensor nodes are not rechargeable, they will run out eventually [4].

By using rechargeable batteries, the network lifetime is potentially infinite. Generally, the batteries of sensor nodes are charged by the energy harvested from the ambient environment, such as solar [6], wind [7], and vibrations [8]. In [13], how to schedule the sensing time of sensor nodes to maximize the sensing utility of an energy harvesting WSN has been considered. In [14], the problem of maximizing the long term transmitted data utility at the fusion center of an energy harvesting WSN has been studied. Every node can determine whether it should transmit or discard the data, according to the data utility, energy level, and the energy harvesting process. When the knowledge of state-of-charge is imperfect, a decentralized algorithm based on game theory has been proposed in [15]. However, since the arrival of ambient energy is uncontrollable, the performance of the WSN may be compromised.

The recent development of the WET provides another possible solution to charge devices remotely [16]. This energy source can be controlled better than the ambient energy mentioned above. Therefore, the WET is attracting research attentions. There are interesting results about WET for general wireless networks. WET has been considered to improve the throughput of the network. In [17], a maximizing information flow problem has been considered for the case where received energy can be reused for transmission. In [18], the performance of packet transmission of wireless sensor nodes powered by RF energy has been studied. Beside, several works have discussed the operations and architectures [19] to simultaneously transfer information and energy [20].

In addition to general wireless networks, WET has also been considered to prolong the lifetime of sensor networks. In [21], the problem of using charging vehicle to charge the sensor nodes has been investigated. It assumes that the charging efficiency of the energy provider, compared to the energy consumptions of the nodes, is large enough, such that the network lifetime is infinite. In this case, the authors tried

to find the path of the vehicle to minimize the time of the vehicle on road. The authors further studied a similar problem where the stopping locations of the vehicle are also required to be determined [22]. However, if the charging capability is not large enough, the solutions above may be not practical. In [9], a problem to maximize the network lifetime by determining the path of the vehicle has been considered. An algorithm that charges the node with the minimal nodal lifetime has been proposed. However, the algorithm requires estimating the future energy consumptions of the sensor node, and its optimality is not shown. Also, the battery buffers are not considered in these works.

Different from the studies above, in this paper, we consider WET for WSN having static nodes with finite battery buffer. We study the sufficient condition that the scheduling of the energy transfer has to satisfy for infinite network lifetime. For the case that the condition is not met, an algorithm with low complexity to maximize the network lifetime is proposed, with discussions on the optimality of the proposed algorithm.

III. PROBLEM FORMULATION

We start by considering a star topology WSN with one base station and N sensor nodes as shown in Fig. 1 (a). Later, the results will be later generalized to tree topology as shown in Fig. 1 (b). The base station collects data from sensor nodes, and also transmits energy wirelessly to the sensor nodes. The sensor nodes, which are energy limited, are responsible for sensing and data uploading to the base station. Their batteries are rechargeable and they are equipped with rectenna. Thus, we assume that they can receive energy from the base station.

Time is slotted into periods, which consists of energy transmission phase and data uploading phase. Notice that the WET efficiency, i.e., the ratio of the energy received at a sensor node to the energy transmitted at the base station, is not high, the base station forms a single sharp beam to increase the harvested energy [11]. Thus, the base station transfers energy to a single sensor node during a time slot period [9]. After the energy transmission phase, all the sensor nodes, $v_i, i = 1, \dots, N$, upload their measurements to the base station in the data uploading phase. Suppose that the maximum energy that the base station can be transferred in each period is normalized to be 1. Denote $x_i(t) = 1$ if the base station transfers energy to sensor node v_i at period t , otherwise, $x_i(t) = 0$. However, at the sensor node side, the received energy is less than 1, due to path loss and energy conversion loss. Thus, we denote $\alpha_i x_i(t)$ the energy that sensor node v_i receives at t , with WET efficiency $0 \leq \alpha_i < 1$ [23].

Assume that for any sensor node v_i , its battery buffer is B_i , whereas its current energy state at period t is $E_i(t)$. Initially, $E_i(0)$ are assumed to be known. Suppose that the event to be monitored at each sensor node is time sensitive, i.e., all measurements should be transmitted to the base station within a period. Furthermore, we denote the arrival rate of the event to be monitored by each sensor node by λ_i . Note that λ_i could be different among different sensor nodes, since events may occur with different probability at different locations, or the

sampling rate for different parameters are different. Without loss of generality, we normalize the length of an event message to be 1. Thus, λ_i is also the data size for transmission of v_i in each period. Denote $f_i(\lambda_i)$ the energy consumption of v_i in each period, which includes the energy consumption of sensing, transmission of data of length λ_i . Then, we have that the energy state of sensor node v_i follows

$$E_i(t+1) = \min\{E_i(t) + \alpha_i x_i(t), B_i\} - f_i(\lambda_i). \quad (1)$$

Here, we assume that the battery buffer of sensor nodes are large, i.e., $B_i \gg f_i(\lambda_i), B_i \gg 1, \forall i$. This is generally true for WSNs, since the sensor nodes are usually designed for a long-term monitoring [24].

Since the events to be monitored are not delay-tolerant, we say that the network expires once any of the sensor node does not have enough energy to transmit the measurements to the base station. Then, the base station must determine the WET schedule, i.e., which sensor node to transfer energy to in each period, such that the network lifetime is maximized. The problem is formulated as follows:

$$\max_{\mathbf{x}(t)} T \quad (2a)$$

$$\text{s.t.} \quad \min\{E_i(t) + \alpha_i x_i(t), B_i\} \geq f_i(\lambda_i), \forall i, t, \quad (2b)$$

$$E_i(t+1) = \min\{E_i(t) + \alpha_i x_i(t), B_i\} - f_i(\lambda_i), \forall i, t, \quad (2c)$$

$$\sum_i x_i(t) \leq 1, \forall t, \quad (2d)$$

$$x_i(t) = \{0, 1\}, \forall i, t, \quad (2e)$$

where $\mathbf{x}(t) = [x_1(t), \dots, x_N(t)]^T, \forall t$, Constraint (2b) represents that sensor nodes must have enough energy to upload data for all the periods, Constraint (2c) describes the dynamic of the energy states of each sensor node, directly follows from Eq. (1), and Constraints (2d) and (2e) represent that the base station can transfer energy to at most one sensor node at each period due to the sharp beam, coherently with current technology [9], [11]. The problem is not trivial due to the binary constraints and the undetermined number of the variables, which depends on the unknown maximum lifetime, as well as due to the lack of an explicit analytical expression for the cost function. However, we will give a solution method later in Section. IV.

Remark 1: Given a WET schedule, one can reorder the charging sequence and keep the network lifetime unchanged. This indicates that there are multiple optimal solutions for Problem (2).

Notice that if the energy consumptions of the sensor nodes are small enough compared to the received energy from WET, the network could be immortal as stated by the following proposition:

Proposition 1: Consider Problem (2) with $f_i(\lambda_i) \ll E_i(0), \forall i$. Suppose the following condition is satisfied:

$$\sum_{i=1}^N \frac{f_i(\lambda_i)}{\alpha_i} < 1. \quad (3)$$

Then, a WET schedule exists with high probability such that the network is immortal, i.e., $T \rightarrow \infty$.

Proof: Due to the limited space, the proof is in the technical report [25]. ■

On the other hand, if Condition (3) is not satisfied, we have the following result for the network lifetime:

Proposition 2: Consider Problem (2). Suppose $\sum_i f_i(\lambda_i)/\alpha_i > 1$. Then the network lifetime is upper bounded by

$$\bar{T} = \frac{\sum_{i=1}^N \frac{E_i(0)}{\alpha_i}}{\left(\sum_{i=1}^N \frac{f_i(\lambda_i)}{\alpha_i}\right) - 1}.$$

Proof: Due to the limited space, the proof is in the technical report [25]. ■

Remark 2: This upper bound corresponds to the case where all the sensor nodes expire at the same time. However, this is not easy to achieve when the number of sensor nodes increases. Therefore, this bound is loose, as will be shown in Section. V.

Remark 3: Suppose that $E(0) = E_i(0) = E_j(0)$, $\alpha = \alpha_i = \alpha_j$ and $\lambda = \lambda_i = \lambda_j, \forall i, j$. Denote $\bar{T}(N)$ the network upper bound as a function of N . Then, we have $\lim_{N \rightarrow \infty} \bar{T}(N) = E(0)/f(\lambda)$. Notice that with the same setting, if energy transfer is not adopted, the network lifetime is also $E(0)/f(\lambda)$. This clearly suggests that WET is not particularly beneficial for WSNs with large number of nodes (with large N), and with high data generation rate ($\sum_{i=1}^N f_i(\lambda_i)/\alpha_i > 1$).

Since the WSN is not immortal if Condition (3) is not satisfied, a solution algorithm to Problem (2) is needed to prolong network lifetime, which is discussed in the next section.

IV. SOLUTION METHOD

Since WSNs are desired to work as long as possible, it is important to find an optimal or near optimal solution for Problem (2). Recall that it is not trivial due to the binary constraint in the problem, a naive solution method is using dynamic programming. However, it is time-consuming for problems with large state space, which is the battery state of the sensor nodes in our case. Therefore, we give a greedy based algorithm with low complexity to solve Problem (2) if Condition (3) is not met, and analyse the fundamental performance of the algorithm. We will start by the star topology, and the results will be generalized to the tree topology.

A. Solution for infinite energy buffer

First of all, let us relax the constraint of energy buffer size, i.e., we let $B_i \rightarrow \infty$ for all the nodes, such that we do not need to consider the case of energy buffer overflow. Notice that since the network lifetime is determined by the sensor node with the minimum lifetime, an intuition is to maximize the minimum lifetime among the sensor nodes. Based on this observation, a straightforward algorithm, which is named greedy-based charging (GBC) algorithm, is shown in

Algorithm 1 Greedy-based charging (GBC) algorithm**Input:** $E_i(0)$, $f_i(\lambda_i)$, α_i .**Ensure:** WET schedules, $x_i(t)$, $\forall i$.

```

1: Set  $x_i(t) \leftarrow 0, \forall t, i$ , and set  $t \leftarrow 0$ .
2: while  $\min\{E_i(t)\} > 0$  do
3:    $k \leftarrow \arg \min_i \{E_i(t)/f_i(\lambda_i)\}$ .
4:   Set  $x_k(t) \leftarrow 1$ .
5:    $t \leftarrow t + 1$ .
6: end while
7: return  $\mathbf{x}(t)$ .

```

Algorithm 1. In such an algorithm, Lines 3 to 4 represent that the base station transfers energy to the sensor node that has the smallest lifetime. Then, we have the following proposition:

Proposition 3: The time complexity of the GBC algorithm is $O(N)$.

Proof: Due to the limited space, the proof is in the technical report [25]. ■

Regarding the performance of the GBC algorithm, we have the following theorem:

Theorem 1: Consider optimization Problem (2). If $\sum_{i=1}^N f_i(\lambda_i)/\alpha_i > 1$, and $B_i \rightarrow \infty, \forall i$, then the GBC algorithm achieves an optimal WET schedule in terms of network lifetime.

Proof: Notice that the base station can only transfer energy to at most one sensor node, and also one sensor node receives energy in each period of the optimal schedule. We represent a WET schedule by a sequence of the subscript of the charged sensor nodes, i.e., $S = \{s_1, s_2, \dots, s_t\}$ represents a schedule that transfers energy to v_{s_1} at $t = 0$ ($x_{s_1}(0) = 1$), then transfers to v_{s_2} at $t = 1$ ($x_{s_2}(1) = 1$) and so on.

Consider a WSN with initial energy $\mathbf{E}(0) = [E_1(0), E_2(0), \dots, E_N(0)]^T$. Suppose sensor node v_j has the smallest lifetime, i.e., $j \triangleq \arg \min_i \{E_i(0)/f_i(\lambda_i)\}$. Suppose a WET schedule, $S_1 = \{j, S^*\}$, such that $i \neq j$, and S^* is the optimal WET schedule given $\mathbf{E}(1) = [E_1(0) - f_1(\lambda_1), \dots, E_{j-1}(0) - f_{j-1}(\lambda_{j-1}), E_j(0) + \alpha_j - f_j(\lambda_j), E_{j+1}(0) - f_{j+1}(\lambda_{j+1}), \dots, E_N(0) - f_N(\lambda_N)]^T$. Then, we need to prove that we can find another schedule $S_2 = \{j, S'\}$, which gives a lifetime not less than the one given by S_1 . The proof consists in two different cases depending on whether $j \in S^*$.

Case i): If $j \in S^*$, then assume that the first j in S^* is indexed by T_1 , i.e., $S^*(T_1) = j$. Then we can construct $S_2 = \{j, S'\}$ by right circular shift, i.e., $S'(t) = S_1(t)$ for $t < T_1$ whereas $S'(T_1) = i$ and $S'(t) = S^*(t)$ for $t > T_1$, such that the network lifetime given by S_2 is no less than the lifetime given by S_1 .

Case ii): If $j \notin S^*$, then we know that the length of S^* , which is denoted by $|S^*|$, satisfies $|S^*| = E_j(0)/f_j(\lambda_j) - 1$. Then, we can just let $S' = S^*$. Since only the charging schedule of node v_i and v_j is modified, we have that the length of S' depends on either sensor node v_j , or sensor node v_i , i.e., $|S'| = \min\{|S'_j|, |S'_i|\}$, where $|S'_j|$ is the case that determined by v_j and $|S'_i|$ is that determined by v_i . Notice that $B \rightarrow \infty$,

which means we do not need to consider the case of over charge, then if $|S'|$ depends on v_j , we have that

$$|S'_j| = \frac{E_j(0) + \alpha_j - f_j(\lambda_j)}{f_j(\lambda_j)} = \frac{E_j(0) + \alpha_j}{f_j(\lambda_j)} - 1. \quad (4)$$

On the other hand, if $|S'|$ depends on v_i , then we have $|S'_i| = T_i^* - \alpha_i/f_i(\lambda_i)$, where T_i^* is the maximum remaining lifetime of v_i from $t = 1$, if energy is transferred to v_i at $t = 0$. T_i^* satisfies

$$T_i^* \geq \frac{E_i(1)}{f_i(\lambda_i)} = \frac{E_i(0) + \alpha_i - f_i(\lambda_i)}{f_i(\lambda_i)} \geq \frac{E_j(0)}{f_j(\lambda_j)} + \frac{\alpha_i}{f_i(\lambda_i)} - 1.$$

Thus,

$$|S'_i| \geq \frac{E_j(0)}{f_j(\lambda_j)} - 1. \quad (5)$$

According to Eq. (4) and (5), we have that

$$\begin{aligned} |S'| &= \min\{|S'_j|, |S'_i|\} \\ &\geq \min\left\{\frac{E_j(0) + \alpha_j}{f_j(\lambda_j)} - 1, \frac{E_j(0)}{f_j(\lambda_j)} - 1\right\} \\ &= \frac{E_j(0)}{f_j(\lambda_j)} - 1 = |S^*|. \end{aligned}$$

Thus, for both Cases i) and ii), $|S_2| = 1 + |S'| \geq 1 + |S^*| = |S_1|$, which shows that there is a schedule $S_2 = \{j, S'\}$ that gives a lifetime no less than the one by S_1 .

Denote $F(\mathbf{E})$ the achievable maximum network lifetime given the initial energy to be $\mathbf{E}$, then we have

$$F(\mathbf{E}) = \begin{cases} 0, & \nexists i : \mathbf{E}' + \alpha_i \geq \mathbf{0}, \\ \max_{\{i: \mathbf{E}' + \alpha_i \geq \mathbf{0}\}} \{1 + F(\mathbf{E}' + \alpha_i)\}, & \text{o.w.}, \end{cases} \quad (6)$$

where $\mathbf{E}' = [E_1 - f_1(\lambda_1), \dots, E_N - f_N(\lambda_N)]^T$, and α_i is a vector with α_i on its i -th element and 0 for all the rest. Given any initial energy state, transferring energy to the sensor node i , which has the minimum residual lifetime, i.e., $i = \arg \min_k \{E_k/f_k(\lambda_k)\}$, is not worse than to transfer energy to other sensor nodes, we can achieve that the greedy transfer schedule by the GBC algorithm achieves the maximum network lifetime. ■

B. Solution for finite energy buffer

Notice that the GBC algorithm achieves an optimal WET schedule in terms of network lifetime if all the sensor nodes have infinite energy buffer, i.e., $B_i \rightarrow \infty, \forall i$. Based on this observation, we study the case where energy buffer is not infinite, and have the following corollary:

Corollary 1: Consider optimization Problem (2) with $\sum_{i=1}^N f_i(\lambda_i)/\alpha_i > 1$. Suppose that a WET schedule, $\mathbf{x}(t)$, with network lifetime T , is determined by the GBC algorithm. If the following condition is satisfied:

$$E_i(0) + \alpha_i \sum_{i=0}^m x_i(t) - m f_i(\lambda_i) \leq B_i, \quad \forall i, \forall 0 \leq m \leq T, \quad (7)$$

then the schedule $\mathbf{x}(t)$ is optimal in terms of network lifetime.

Proof: Due to the limited space, the proof is in the technical report [25]. ■

According to Corollary 1, a straightforward result can be achieved, as shown in the following corollary:

Corollary 2: Consider optimization Problem (2) that satisfies $\alpha_i \leq f_i(\lambda_i)$, $\forall i$, and $E_i(0) + \alpha_i \leq B_i$, $\forall i$. Suppose that a WET schedule, $\mathbf{x}(t)$, is determined by the GBC algorithm. Then $\mathbf{x}(t)$ is optimal in terms of network lifetime.

Proof: Due to the limited space, the proof is in the technical report [25]. ■

Similarly, we have the following corollary:

Corollary 3: Consider optimization Problem (2) that satisfies $\alpha_i \leq f_i(\lambda_i)$ and $E_i(0) = B_i, \forall i$. Suppose that a WET schedule, $\mathbf{x}(t)$, is determined by the GBC algorithm. Then $\mathbf{x}(t)$ is optimal in terms of network lifetime.

Proof: Due to the limited space, the proof is in the technical report [25]. ■

Remark 4: For the general cases where Condition (7) is not satisfied, one can solve the problem by combining the GBC algorithm with dynamic programming (6).

Next, we generalize the result of star topology networks to tree topology networks.

C. Extension to tree topology network

Consider a WSN, G , with tree topology and fixed routing. Since only the base station can transfer energy, all the sensor nodes receive energy from the base station, i.e., the WET topology is still a star topology. The sensor nodes that are not close to the base station have to transmit data in a multi-hop fashion. In this case, some sensor nodes also act as a relay. Therefore, the energy consumption of node v_i is $f_i(\lambda_i + \sum_{j \in \mathcal{S}(i)} \lambda_j)$, where $\mathcal{S}(i)$ is the set of sensor nodes in the sub-tree rooted at v_i . Then, we can transform the problem for G to a problem for another graph G^s , which has star topology, by keeping v_i, E_i, α_i, B_i unchanged and replacing λ_i by $\lambda_i^s = \lambda_i + \sum_{j \in \mathcal{S}(i)} \lambda_j$. Then, the GBC algorithm can be applied to find the WET schedule for G^s , which is also the WET schedule for G .

V. NUMERICAL RESULTS

In this section, we evaluate the network lifetime of WET enabled sensor network, and the performance of the proposed GBC algorithm. One base station and N sensor nodes constitute a WSN with star topology. The network parameters, which are similar to the setting in [9], are set as follows: the battery of sensor nodes is 10.8k Joule; the energy consumption of sending a packet of a sensor node is 0.05 Joule; the packet generation rates of the sensor nodes are λ_i per minutes, which vary from 1 to 15 in different cases; the energy transmission power at the base station is 3 Watts; the WET efficiencies of the sensor nodes, α_i , are randomly picked from $[0.005, 0.03]$. The dynamic of the nodal battery follows Eq. (1), where $x_i(t)$ is determined by the algorithm used in the base station.

To begin with, we evaluate the probability that the WSNs with different sizes are immortal by using WET according to Proposition 1. The size of the network, i.e., the number of

Fig. 2. The probability of wireless energy transfer enabled sensor networks to be immortal with different network size and packet rates

sensor nodes in the WSNs, N ranges from 1 to 30. The WET efficiencies of the sensor nodes, α_i , are uniform randomly picked from $[0.01, 0.03]$. The results are shown in Fig. 2. The horizontal axis represents the number of sensor nodes in the WSN. The vertical axis is the probability of the WSN to be immortal, whose criterion follows Proposition 1. The line with circles, squares, and diamonds represents packet generation rate λ to be uniform randomly determined from $[1, 6]$, $[1, 11]$, and $[5, 15]$ per minute respectively. When the WSN consists of 5 sensor nodes with $\lambda \sim U(5, 15)$, the WSN can be immortal with probability about 0.9. However, when we put 5 more sensor nodes into the network, the probability to be immortal is below 0.05. It follows that, even though WET can charge sensor nodes, the probability that the WSN is immortal drops dramatically with the increase of the network size and the packet generation rate, which relates to the sensing rates. It might be possible for small scale WSNs, such as body sensor networks, to be immortal, whereas for the large scale WSNs, the immortality seems to be impossible. Therefore, it is important to study the scheduling of WET to prolong the network lifetime.

Next, we evaluate the network lifetime achieved by the GBC algorithm. In this case, WET efficiencies, α_i , are chosen from $[0.005, 0.015]$ uniform randomly for sensor nodes. We compare the performance of the GBC algorithm to two other algorithms, and the case that WET is not used. In the Random algorithm, the base station picks a sensor node to transmit energy to with equal probability, whereas in the R-fairness algorithm, the base station randomly chooses the target sensor node according to the packet generation rates. The results are shown in Fig. 3 (a), (b), and (c), where the packet generation rates of sensor nodes are uniform randomly chosen from $[1, 11]$, $[5, 15]$, and $[10, 20]$. The horizontal axis is the network size, and the vertical axis is the average network lifetime. The results show that, compared to the case of no WET, the network lifetime achieved by the GBC algorithm is much longer, when the network size is small, e.g., tens of sensor nodes. It is about 1.5 to 2 times of the network lifetime with no WET when $N = 20$. However, the benefit of having WET in terms of network lifetime decreases with the increase of network size. It accords with Remark 2. Furthermore,

Fig. 3. Comparison of the network lifetime achieved by different algorithms with: (a) $\lambda \sim U[1, 11]$; (b) $\lambda \sim U[5, 15]$; (c) $\lambda \sim U[10, 20]$

the network lifetime achieved by the GBC algorithm is also larger than those achieved by the Random algorithm and the R-fairness algorithm, where WET is enabled. It shows the effectiveness of the proposed GBC algorithm, and the inefficiency of transmitting energy to sensor nodes arbitrarily.

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, we investigated the problem of scheduling the wireless energy transfer in wireless sensor networks to prolong network lifetime. We studied the requirement on energy transfer efficiency and the packet generation rate such that the network can be immortal. For larger network sizes or packet generation rates, we studied the lifetime maximization problem and proposed a solution algorithm. We showed that the algorithm achieves an optimal schedule, when the ratio of the received energy at a sensor node to the transmitted energy at the base station is low.

In the future, the study will be extended to some more general cases, e.g., there are multiple base stations in the network, and consider the randomness in the channel.

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