Poster: On the Immortality of Wireless Sensor Networks by Wireless Energy Transfer — A Node Deployment Perspective

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Abstract

The lifetime of wireless sensor networks (WSNs) can be substantially extended by transferring energy wirelessly to the sensor nodes. In this poster, a wireless energy transfer (WET) enabled WSN is presented, where a base station transfers energy wirelessly to the sensor nodes that are deployed in several regions of interest, to supply them with energy to sense and to upload data. The WSN lifetime can be extended by deploying redundant sensor nodes, which allows the implementation of duty-cycling mechanisms to reduce nodes' energy consumption. In this context, a problem on sensor node deployment naturally arises, where one needs to determine how many sensor nodes to deploy in each region such that the total number of nodes is minimized, and the WSN is immortal. The problem is formulated as an integer optimization, whose solution is challenging due to the binary decision variables and a non-linear constraint. A greedy-based algorithm is proposed to achieve the optimal solution of such deployment problem. It is argued that such scheme can be used in monitoring systems in smart cities, such as smart buildings and water lines.

1 Introduction

Wireless sensor nodes are energy limited devices, which constraints the lifetime of the wireless sensor networks (WSNs). The objective to enable WSNs to work as long as possible has attracted much research interest. However, most of the approaches are based on the ideas either on providing addition energy [1], or on reducing energy consumptions [2].

To enable the WSNs to be immortal, we jointly consider providing additional energy source to the sensor nodes based on wireless energy transfer (WET) [3, 4], and also reducing energy consumption by deploying redundant nodes, which allows the nodes work in duty-cycle. Such an idea leads to a WET enabled WSN as shown in Figure 1, which consists

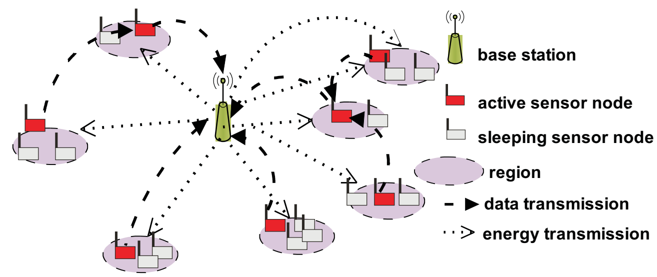

Figure 1. The wireless sensor network with wireless energy transfer considered in this poster

of a base station that is able for WET, and sensor nodes to monitor a set of regions. For each region, we are required to make measurements with a preset sampling rate to satisfy the monitoring requirements. Thus, we can deploy redundant sensor nodes in each region, where the nodes in the same region take turns to make measurements and to transmit data, such that the energy consumption of each node is reduced. On the other hand, the base station charges the sensor nodes wirelessly, and applies energy beamforming to increase the energy received at the nodes.

Based on such model, we will formulate a node deployment problem to minimize the total number of deployed node to make the WSN immortal. We will also propose an algorithm to find its optimal solution. In the best our knowledge, this is the first work that considers node deployment for the immortality of the WET enabled WSNs.

2 Node deployment problem and its solution

Suppose that there are N separated regions, $l_1,\dots,l_N$, to be monitored. The number of sensor nodes to be deployed in l_i is denoted by x_i, which needs to be determined.The base station uses an energy beam to transfer energy to the nodes in a region at a time, and it charges every region periodically. We denote the power transmitted by the base station to be P.

We assume that the sensor nodes in the same region are close to each other. Thus, for the nodes in the same region, their energy receiving rates are approximately the same, and it also holds for their energy consumption rates. It means that, for each region l_i, the nodes in it are homogeneous in terms of their energy consumption rates, c_i (which is determined by the required sampling rate, and the predetermined routing scheme), and the WET efficiency, α_i (which is determined by the circuits of the sensor node,

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the distances of the sensor nodes to the base station, and the wireless channels). Furthermore, we define total WET efficiency of a region with x_i nodes to be the ratio of the summation of the charged energy of these x_i nodes to the transferred energy from the base station toward the region. Notice that when several nodes are co-located at the same region, the WET efficiency of these nodes is sub-additive. We represent such sub-additiveness by a function $f(\cdot)$: if there are x_i sensor nodes in region l_i, then the total WET efficiency is $\alpha_i f(x_i)$, where $f(x_i)$ satisfies $f'(x_i) \geq 0, f''(x_i) \leq 0, f(1) = 1$.

The immortality considered in the paper is defined as that, for each region and for any time, there is at least one sensor node in that region has enough energy to make measurements and to transmit data. This can be translated into a requirement that, for every region l_i, the time-average consumed energy by all sensor nodes in the region, $E_i^{\text{out}} \triangleq c_i$, should be no larger than the time-average received energy in that region, E_i^{in}. Recall that the base station charge a region at a time, we denote β_i as the percentage of time that the base station charges l_i. Then, we have that $\sum_{i=1}^{N} \beta_i = 1$. Also, the immortality requirement gives us that $E_i^{\text{out}} \leq E_i^{\text{in}} = \alpha_i \beta_i f(x_i) P, \forall i$. These two requirements give us that $\sum_{i=1}^{N} c_i/(\alpha_i f(x_i) P) \leq \sum_{i=1}^{N} \beta_i = 1$. Thus, the optimal node deployment problem is formulated as follows:

$$\min_{\boldsymbol{x} \in \mathbb{Z}_+^N} \quad \sum_{i=1}^{N} x_i \tag{1a}$$

$$\text{s.t.} \quad \sum_{i=1}^{N} \frac{c_i}{\alpha_i P f(x_i)} \leq 1, \tag{1b}$$

where $\boldsymbol{x} = [x_1, \ldots, x_N]^T$ is the deployment of the nodes.

We can know that, the necessary and sufficient condition of the feasibility of Problem (1) (Problem (1) has feasible solution), is that $\lim_{x_i \to +\infty, \forall i} \sum_{i=1}^{N} c_i/(\alpha_i P f(x_i)) < 1$. When such requirement does not hold, the way to make the WSN immortal is either to increase the transmission power of energy at the base station, or to reduce the requirement of the sampling rates for some regions. When such condition holds, we should find the optimal solution for the problem, as we will discuss below.

Note that Problem (1) is a non-linear integer optimization, which is in general difficult to solve. However, due to the proposition of $f(x_i)$, i.e., non-decreasing and sub-additive, we develop a greedy algorithm to find the optimal solution for Problem 1. The idea is to initialize $x_i = 1, \forall i$. As long as $\boldsymbol{x} = [x_1, \ldots, x_N]^T$ does not satisfy Constraint (1b), we find the region with the largest benefit to deploy additional one node, i.e.,

$$l = \arg\max_i \left\{ \frac{c_i}{\alpha_i f(x_i)} - \frac{c_i}{\alpha_i f(x_i + 1)} \right\}. \tag{2}$$

and we update $x_l(t) \leftarrow x_l(t) + 1$. The algorithm is shown in Algorithm 1. We can show that such algorithm achieves the optimal solution for Problem (1) if the problem is feasible.

Algorithm 1: Greedy-based deployment (GBD)

```
Data: α_i, c_i, ∀i, f(·), P
Result: x
Set x_i = 1, ∀i;
while Σ_{i=1}^N c_i/(α_i P f(x_i)) > 1 do
    Find l ← according to (2);
    Update x_l ← x_l + 1;
end
```

3 Conclusion and Further Discussions

We have considered an optimization problem on node deployment for the immortality of sensor networks by wireless energy transfer, and provided an efficient algorithm to solve such a problem. Therefore, the considered WSN structure could be used in for the monitoring applications where battery replacement is not easy, such as structural health monitoring and water pipeline monitoring.

Although the optimal solution for Node deployment Problem (1) can be efficiently found, there are still some remaining works to make the WSNs become immortal. One reason is that Constraint (1b) is only the necessary condition for the immortality. To make the WSNs immortal, one should also optimize over the energy transmission schedules of the base station. The activation of the sensor nodes in a region should also be optimized, where the residual energy of the nodes should be considered. This is one of our future works. Another reason that hinders the immortality of such WSNs is that, in reality sensor nodes may fail due to various reasons. Thus, when one of the nodes fails, the functioning nodes may not satisfy Condition (1b). One solution is to deploy additional nodes to make the whole WSNs more robust against node failures. However, our work focuses on the theoretical bounds on the nodes to be deployed for the immortality of the WET enabled WSNs. The reliability issue can be a future work. Last, we should also mention that, although the base station in our model is a single static base station, the idea of placing redundant sensor nodes to increase the harvested energy and reduce energy consumption per node is also helpful for the cases with several base station or mobile charging base stations [4]. This could be another future work.

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5 References

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