Utilizing Renewable Energy in Cluster-based Sensor Networks

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Abstract

Energy conservation plays a crucial in wireless sensor networks since such networks are designed to be placed in hostile and non-accessible areas. While battery-driven sensors will run out of battery sooner or later, the use of renewable energy sources such as solar power or gravitation may extend the lifetime of a sensor. We propose to utilize solar power in wireless sensor networks and extend LEACH a well-known cluster-based protocol for sensor networks to become solar-aware. The presented simulation results show that making LEACH solar-aware significantly extends the lifetime of sensor networks.

1 Introduction

Wireless sensor networks have to take into account the very limited resources of the nodes. While many researchers assume that all nodes in a sensor network are battery-driven [1, 2] nodes can also be powered by renewable energy sources such as gravitation or solar power. Nodes powered by such a source can process data, receive and transmit packets as well as perform other tasks without consuming battery energy. We call protocols considering such energy resources solar-aware. One problem in that context is that the energy source is not permanent, i.e. sometimes a node may be powered by solar energy while it needs to run on battery another time.

In the lab at FU Berlin, we developed sensor boards equipped with solar cells and in previous work we have presented a solar-aware routing protocol [6] similar to directed diffusion [4]. Although this approach leads to significant energy savings, we believe that in many scenarios cluster-based protocols are more adequate when some sensor nodes have "unlimited" energy resources. First, cluster heads perform the most energy-intensive tasks and thus nodes with "unlimited" resources are natural candidates for becoming cluster heads. Second, cluster-based protocols inherently avoid a problem experienced by Willig et al. who consider nodes with permanent power supply [7]. They experienced that nodes close to those nodes with "unlimited" resources experience an increased traffic load and therefore potentially run out of battery early.

For these reasons we investigate if preferably choosing solar-powered nodes as cluster heads is feasible and can provide energy savings. We extend LEACH (low-energy adaptive clustering hierarchy) [2, 3], the best-known cluster-based protocol, to become solar-aware. In LEACH, the cluster heads selected by the base station remain cluster heads for a certain time called round. We develop a solar-aware extension of LEACH and present simulation results comparing the increased sensor network lifetime with the standard LEACH protocol. The solar-aware extension provides significant benefits in many scenarios. We also present a handover mechanism that allows a cluster head to choose another, solar-powered node as a new cluster head. We show that this handover provides additional benefits.

2 Sensor Board Hardware

The hardware used in the lab at FU Berlin consists of a Texas Instruments MSP430 controller as core and associated sensor hardware such as light, passive infrared, temperature sensors. The sensors communicate via an RF module in the 868 MHz band. The sensor board can be operated in three different power modes. The energy needed even in the most power-intensive mode (ca. 40 mA) can be provided by a solar cell. Figure 1 shows the sensor board and an attached solar cell. Note that much smaller solar cells could be used that provide enough power in the daylight, but these are more expensive. The first generation of the sensor board has the size

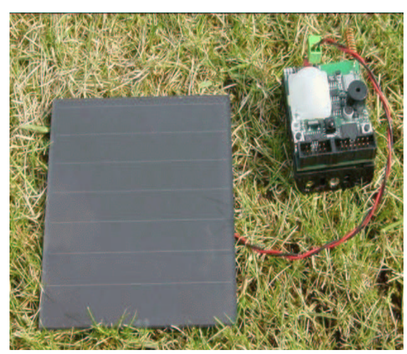

Figure 1. Sensor board with attached solar cell

*This work was performed at FU Berlin while Thiemo Voigt was a post-doctoral researcher there.

of three AAA batteries. Thus the hardware demonstrates that an operation mode we further call solar-powered is possible.

3 LEACH

LEACH makes some assumptions about both the sender nodes and the underlying network. Some of these assumptions are very strong, but it is not the purpose of this paper to judge these assumptions. LEACH assumes that all sensor nodes can adapt their transmission range. Furthermore, energy consumption during transmission scales exactly with the distance and every sensor node is able to reach a base station (BS). Moreover, nodes support several MAC layers and perform signal processing functions.

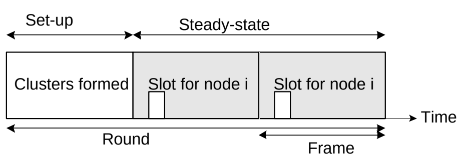

Figure 2. LEACH operations

In LEACH, sensor nodes form clusters with one node being the cluster head. Nodes transmit data to the cluster head that aggregates the data and sends it to the BS. Therefore being a cluster head is an energy-consuming task.

The operation of LEACH is divided into *rounds*. As shown in Figure 2, each round starts with a set-up phase followed by a steady-state phase. In the set-up phase [3], the BS uses a central control algorithm to choose the cluster heads. Each node sends information about its energy status and its position to the BS. Since the problem of finding the *k* optimal cluster-heads is NP-hard, Heinzelman et al. [3] use simulated annealing to find cluster heads. The BS station broadcasts a message containing the cluster head ID for each node. The cluster heads then determine a TDMA scheme for the nodes belonging to their cluster, broadcast the scheme and the steady-state phase starts.

During the steady-state phase, each node transmits data to the cluster head during its allocated slot. The transmission uses the minimal amount of energy necessary to reach the cluster head. At the end of each frame when the cluster head has received data from all associated sensor nodes, it aggregates the data and sends it to the base station. The cluster heads send this data using a fixed spreading code with CSMA.

4 Solar-aware LEACH

The aim of solar-aware LEACH (sLEACH) is to extend the life-time of the sensor network by preferably choosing solar-powered nodes to perform the energy intensive task of being a cluster head[1].

[1]Our simulations have shown that being a cluster head is about 10-15 times more energy-consuming than not being a cluster head.

The authors of LEACH do not present the detailed algorithm the BS uses to choose *k* cluster heads. We have decided to use simple heuristics that have shown good results in test cases: In step 1, we choose the *k+3* nodes with the highest remaining energy. In step 2, we remove the potential cluster head with the minimal sum of the distances to all other potential cluster heads. In step 3, we remove one of the two potential cluster heads that have the closest distance to each other. If one of these two nodes is close to the border of the area the sensor networks spans (the sensor area), we remove this node. Otherwise we remove the node closer to the center of the sensor area. When removing the third node, we minimize the total sum of the square distance between non-cluster heads and their potential cluster head. Note that this approach is probably simpler and thus not as close to the optimal solution as the simulated annealing approach by Heinzelman et al. However, in our simulation both sLEACH and the original LEACH use this algorithm. Since both protocols are affected in the same manner we believe not to discriminate any of the protocols.

In sLEACH, besides the remaining energy and the position, nodes also transmit their solar status[2] to the base station. In step 1, each node is assigned an energy value corresponding to its energy level. From this energy value we subtract *e*, the assumed energy consumption for the next round assuming the node was a cluster head. If a node is solar-powered, we assume it remains solar-powered for half of the round and thus subtract only $e/2$. The *k+3* nodes with the highest energy value are chosen. This scheme assures that solar-driven nodes that have a high remaining energy level have a high chance of becoming cluster head. In step 2, we do not remove a solar-powered node if possible. In step 3, if one of the nodes with the closest distance to each other is solar-powered we do not remove that node. The last step does not change.

5 Experiments

We have implemented the algorithms described in Section 3 and Section 4 in the OMNet++ discrete event simulator [5]. We have used the same radio model and, whenever possible, the same parameter settings as Heinzelman et al. [2]. For the simulation we need a way to determine when a node is solar-powered or when it is running on battery. We specify two random variables, namely the average number of nodes that are solar-powered (*sunNodes*) and for how long a node is solar-powered (*sunDuration*) after the "sun starts shining on it" (*sunStart*). After the *sunStart*, a node is solar-powered for *sunDuration* time units. $(numberofNodes/sunNodes) * sunDuration$ after a *sunStart*, nodes become solar-powered again. As a metric we use the number of rounds until the first node is running out of battery and the number of rounds until half of the nodes have run out of battery.

[2]The solar status denotes if a node is powered by solar energy or by battery.

Results In the first experiments we set *sunDuration* to 1200 and the number of frames in each round to ten. The duration of a frame is less than 30 time units on average. Hence, with ten frames in each round one rounds takes about 300 time units. Figure 3 shows the improvement of sLEACH over the standard LEACH protocol (in %). On the x-axis we see the average number of nodes that are solar-powered (*sunNodes*). *F* stands for number of rounds until first node runs out of battery and *H* denotes the number of rounds until half of the nodes have run out of battery. For example, when *sunNodes* is set to five, sLEACH runs 22,5% more rounds until the first node dies than standard LEACH.

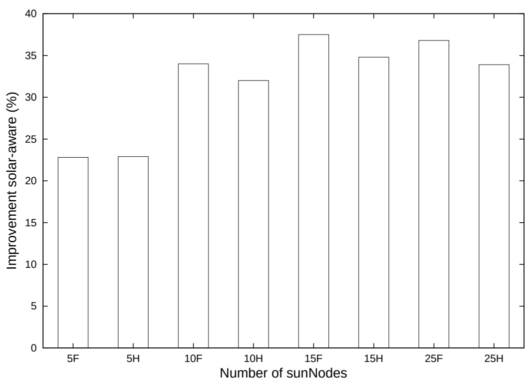

Figure 3. Improvement over standard LEACH

The improvements of sLEACH stem mainly from the fact that, as expected, solar-powered nodes become cluster heads with higher probability than with standard LEACH. With 10 *sunNodes*, using standard LEACH a node is cluster head 7.7 times on average. On average, a node is cluster head while it is solar-powered only 2.8 times. Using sLEACH, a node is cluster head 10.8 times on average, thereof 8.5 times while it is solar-powered.

For longer *sunDurations*, the improvement of sLEACH is larger than with shorter *sunDurations*, in particular for a small number of *sunNodes*. With more *sunNodes*, also the standard LEACH protocol has a longer network lifetime, since the probability to select a solar-powered node as cluster head increases. Once a solar-powered node is clusterhead, it usually remains cluster head until its solar status changes to battery-driven.

Handover As mentined above, sLEACH does not perform that well when the *sunDuration* is small. One possible improvement is that we perform a handover, i.e. a new cluster head is chosen during the steady-state phase in a round. Therefore, whenever a node sends data to the cluster head, a flag denoting if the node's solar state has changed to solar-powered is added. If the cluster head runs on battery and a node sends a data message with this flag set, this node may become the new cluster head.

To enable handovers, we have modified the protocol in two ways. First, nodes set their transmission range to the distance to the cluster head plus an additional distance *d*. Second, within a round, a node can only become the new cluster head if it is within the distance *d* from the current cluster head. For simplicity, we allow only one change of cluster head per round in our current version.

Table 1. Improvement of sLEACH with handover

Protocol	5F	10F	15F	25F
sLEACH	2.7	6.8	4.8	1.8
sLEACH with handover	18.7	31.1	44.9	51.8

The results in Table 1 (*sunDuration* 200) show that the handover significantly increases the lifetime of a LEACH sensor network. The average improvement over all eight scenarios (5F to 25H) is less than 5% for LEACH and more than 35% for LEACH augmented with the handover capability.

Summary of the results and conclusions Our simulations have shown that making LEACH solar-aware increases the lifetime of a sensor network substantially in typical scenarios. We have also presented a handover scheme that allows changes of cluster heads during the steady-state phase of the LEACH protocol. The handover can provide additional benefits in certain scenarios.

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