Utilizing Solar Power in Wireless Sensor Networks

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Abstract

Sensor networks are designed especially for deployment in adverse and non-accessible areas without a fixed infrastructure. Therefore, energy conservation plays a crucial role for these networks. We propose to utilize solar power in wireless sensor networks, establishing a topology where – changing over time – some nodes can receive and transmit packets without consuming the limited battery resources. We propose and evaluate two protocols that perform solar-aware routing. The presented simulation results show that both protocols provide significant energy savings when utilizing solar power. The paper shows that incorporating the solar status of nodes in the routing decision is feasible and results in reduced overall battery consumption.

1 Introduction

Routing in wireless sensor networks has 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] [5] [7] [9], nodes can also be powered by other energy sources such as gravitation or solar power. Nodes powered by such a source can receive and transmit packets without consuming battery energy. Therefore, routing packets via such nodes is appealing. It is, however, complicated by the fact, that the energy source is not permanent. In our lab, we have developed sensor boards which we will soon equip with solar cells. This motivated us to investigate if preferably routing via solar-powered nodes is feasible and can provide energy savings.

We present simulation results using two protocols that perform what we call solar-aware routing, i.e. they preferable route via solar-powered nodes. One protocol is a simplified version of directed diffusion [2], based mainly on local interactions between adjacent nodes, the other one is an extension of directed diffusion. Our simulation results show that the first protocol is more suited for small sensor networks while the second protocol performs better on larger networks. In all cases, solar-aware routing can provide significant energy savings. From the results we conclude that it is worthwhile to make routing protocols for wireless sensor networks solar-aware, i.e. the fact that one could route via solar-powered nodes should be incorporated into the routing decision.

The key contribution of this paper is the design and evaluation of routing protocols that preferably route via solar-powered nodes. To the best of our knowledge the idea of utilizing solar power in wireless sensor networks to perform energy-efficient routing has not been published yet.

The rest of the paper is outlined as follows: In Section 2 we present some background on directed diffusion and our hardware. In the following section we present two solar-aware routing protocols. We describe our simulation and the results in Section 4. After discussing related work in Section 5 we conclude with conclusions and future work.

2 Background

As the solar-aware routing we present in this paper is strongly related to directed diffusion, we first sketch the basics of this energy-efficient paradigm for wireless sensor networks. In this section, we also present our sensor board hardware that we are building in parallel with the simulations we present.

2.1 Directed Diffusion

Directed diffusion as a scheme for data dissemination in sensor networks was presented in [10] and [2]. It deals with the propagation of interests and the establishment of paths through the network.

In the terminology of directed diffusion, a *sink* is a node that is interested in some data a sensor in the network might be able to deliver, i.e. the node has a certain *interest*. A sensor node being able to deliver the desired information is called a *source*. Sinks express their interest by sending an *interest message* into the network. The requested data is named as an attribute-value pair. While interest messages are diffused in the network towards a potential source, nodes set up *gradients*. A gradient denotes state information about the sensor data the sink desires and about the direction an interest message came from. In the simplest case, the diffusion of interest messages from sink to source is done by broadcasting the messages. All nodes in transmission range of each other thus establish a gradient towards each other.

The sensor data (events) generated at the source are sent to the sink using these gradients. These events are called *exploratory* (and the gradients *exploratory* gradients), as they will be used to set up a path in the next step. To *positively reinforce* a path (to set it up for long-term use), the sink resends the original interest message, but requests a higher data rate. As opposed to the first, exploratory phase, this interest is not broadcasted to all neighbours, but sent to normally only one neighbour. A node may reinforce one neighbour based on the earliest response, the lowest loss rate etc. Further data messages from the source will only be sent on this reinforced path. The directed diffusion scheme also incorporates a *negative reinforcement* that is used to remove loops inside the network.

Directed diffusion also performs in-network data processing. While this provides energy savings we do not utilize this feature of directed diffusion in our protocols. It is, however, orthogonal and straightforward to incorporate.

2.2 Sensor Board Hardware

The hardware used in our labs consists of a Texas Instruments MSP430 controller as core and a set of associated sensor hardware. These sensors are:

- A light sensor for the detection of visible light
- A passive infrared sensor for detection of movement
- A temperature sensor
- A gravitation sensor for the detection of movement of the sensor board
- A microphone for determination of the ambient noise level

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 of three AAA batteries.

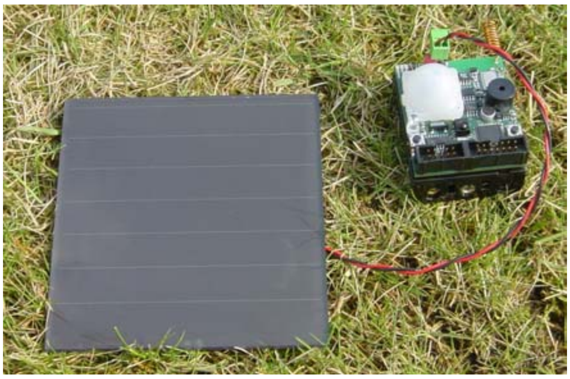

Figure 1: Sensor board with attached solar cell

Thus the hardware demonstrates that an operation mode we further call *solar-powered* is possible. We are currently building large quantities of the sensor boards (see `www.scatterweb.net`) and will compare the simulative results with real-world scenarios.

3 Protocol Description

In this section we describe our two solar-aware routing protocols.

3.1 Solar-aware Protocol Based on Local Interaction

Our first protocol is a solar-aware, simplified version of directed diffusion. As in directed diffusion, data propagation in this version of our protocol is based on localized interactions, i.e., interactions with neighbouring nodes. In our protocol, gradients also contain information about the *solar state* of the neighbours that denotes if a node is battery-driven or if it is running on solar power. As in directed diffusion, our protocol assumes that at least adjacent nodes can be distinguished by identifiers.

3.1.1 Interest Propagation

Interest messages are generated by a sink and are simply flooded through the network. Note that other methods such as directional flooding based on location or previously cached data are more efficient and could be used as well [2]. Interest messages contain the attribute value pair, source and destination identifier, an interval that states the rate at which the sink wants to receive sensor data as well as a hop counter and the solar state of the sender. Nodes establish gradients to all other nodes from which they receive interest messages. A gradient to a neighbour is updated when an interest message for the same interest is received with a smaller hop count.

For every interest, nodes rebroadcast the first interest message they receive as well as following interests with a lower hop count. In most of the cases, however, the first interest message should have the lowest hop count.

3.1.2 Data Propagation

When a source receives an interest, it senses the environment at the specified rate and sends a data message towards the sink. A data message contains the attribute-value pair that allows the intermediate nodes to identify the gradients and the next hop towards the sink. When choosing the next hop, care must be taken to avoid loops. Propagating data along the shortest path is one method to avoid a loop. However, if there is exactly one shortest path we will not be able to preferably route via solar-powered nodes. Therefore, we allow the source and exactly one intermediate node to choose a next hop different from the one closest to the sink. The latter nodes are those neighbours from which a node has received the smallest hop counter in the interest message.

A flag in the data message indicates if a node already has utilized the option to route via an intermediate node not on the shortest path to the sink. If this is not the case, an intermediate node can choose to forward the data to another node, that is solar-powered rather than a node on the shortest path. In our current implementation, the first node having a solar-powered neighbour uses the option to send to the solar-powered neighbour instead of sending to the next node on the shortest path. Once the flag is set an intermediate node must forward the message to one of the nodes on the shortest path. If one of those is solar-powered, the intermediate nodes forward it to the solar-powered node.

3.1.3 Status Updates

When a node changes its solar status, it should inform the upstream nodes (nodes closer to the source) about its new status. Then the upstream nodes can route via the now solar-powered node. If the new status of the node is battery-powered the upstream nodes can route via a solar-

Source	Dest	Proto	Attr	Value	SeqNr	Bcount	Scount	ExpPd

Figure 2: Interest Message

Source	Dest	Proto	Attr	Value	SeqNr	Bcount	Scount

Figure 3: Exploratory Data Message

powered node instead.

There are two design options here. One is that a node simply broadcasts its new status; the other option is that it waits until it hears some communication going on or itself receives a data packet. The advantage of the first option is that a more energy-efficient route can be found at once while using the second option some data messages might still be routed via a less energy efficient route. The advantage of the second option is that it avoids unnecessary broadcasts, meaning broadcasts that do not lead to more energy-efficient routes.

3.2 Solar-aware Directed Diffusion

Solar-aware directed diffusion extends the standard directed diffusion protocol as described in Section 2.1 by adding several fields to the standard directed diffusion headers. While the original directed diffusion scheme does not prevent loops to occur but has means to detect and remove them, we have aimed at designing a scheme that prevents loops in the first place.

3.2.1 Interest Messages

The interest message format is shown in Figure 2. We have added four fields in addition to some of the fields that regular directed diffusion interest messages contain and which we used in our simulation. Regular directed diffusion contains a timestamps while we have chosen to use sequence numbers. We have added two counters called *bcount* (battery counter) and *scount* (solar counter). Each node increases one of the counters depending on its solar state, for example a solar-driven node would increase *scount.* The *ExpPd* (exploratory period) field specifies at which rate the source is supposed to send exploratory data that may help to find new paths via a lower number of battery-powered nodes. As in the local protocol, nodes set up gradient to their downstream (towards the sink) neighbours but in this case, gradients contain the *bcount* and *scount* as well.

3.2.2 Exploratory Data Messages

When the interest messages have reached the source it sends out exploratory data messages (see Figure 3). These are forwarded by intermediate nodes towards the sink. They form several paths from which the sink may choose one, for example the one that arrives first or the one on which the messages traverse the minimum number of battery-driven nodes. We call the latter path “least battery path”. The fields *bcount* and *scount* fulfil the same function as described above and help to find the shortest (minimum sum of *bcount* and *scount*) path and the least battery path. An important decision that each node has to take is to which neighbours it forwards the exploratory data messages. If these messages are forwarded to all adjacent nodes, the network is flooded again. If they are forwarded to a small number of nodes only, the best paths, for example the least battery path may not be found. If not mentioned otherwise, an intermediate nodes searches in its gradients for the neighbours on the shortest path and the least battery path. If these are the same, the node on the second shortest path is chosen. Note that the information about the

Source	Dest	Proto	Attr	Value	SeqNr	Period	Strategy

Figure 4: Reinforcement Message

Source	Dest	Proto	Attr	Value	Bcount	Scount	Data

Figure 5: Data Message

least battery path can only be assumed to be correct for a short time after the interest message has been sent. When handling exploratory data messages, nodes set up upstream gradients towards the source so they know where to forward reinforcement messages.

3.2.3 Reinforcement Messages

After having collected exploratory data messages, the sink reinforces one data path on which is wants to receive data by sending a reinforcement message (see Figure 4). More exact, it chooses the next hop, and in our extension it also specifies a strategy that tells the intermediate nodes which next hop to choose: Either the least battery path or the shortest path. When receiving a reinforcement message from a node *n*, intermediate nodes know that they must forward data messages to node *n*.
We have also added a third strategy option called *send exploratory*. This option is used to tell the source that it should send exploratory data again. This is useful when the number of forwarding nodes on the least battery path suddenly has increased. Note that there are a number of parameters that determine when it is wise to send such a message, for example, the time that is left until the source will send exploratory data again.
The *period* denotes the rate at which the sink wants to receive data messages.

3.2.4 Data Messages

Data messages are shown in Figure 5. Besides the actual data, they include a *bcount* and *scount* field. These fields are again updated by every intermediate node and allow the sink to determine if the number of solar-powered nodes on the least battery path has changed.

4 Experiments

We have conducted simulation studies using the OMNet++ discrete event simulator [3]. The aim of the study was to investigate if solar-aware routing provides energy savings by preferably routing via solar-powered nodes.

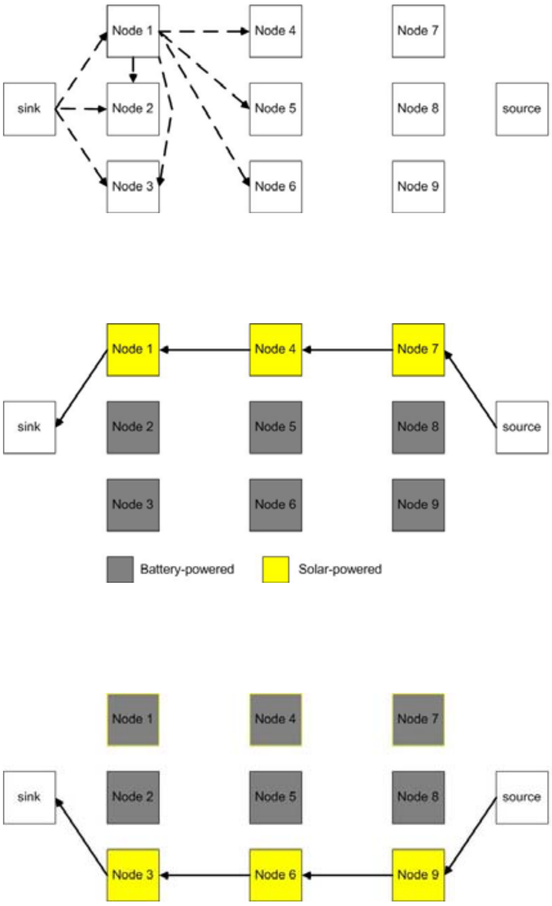

Figure 6: First Experiment

4.1 Experiment with a Simple Topology

The setup for the first experiment is shown in Figure 6. In this experiment, we show how the first protocol described in Section 3.1 can be used in such a scenario. In this scenario, each node is in the transmission range of the nodes in the same column and the neighbouring columns. For example, the sink is in the transmission range of the nodes 1 to 3 and vice versa. Node 7 is in the transmission range of the nodes 4-6, 8-9 and the source. In the experiment the sun is moving from North to South, i.e. in the beginning node 1, 4 and 7 are solar-powered.

When the interest messages are flooded from the sink to the source as depicted in the top part of the figure, each node learns which adjacent nodes are solar-powered. The same is true for the source that therefore transmits the first data message to node 7. Since node 8 and 9 are also in the transmission range, they receive this data message as well, but do not forward it. We have not yet designed a sleeping protocol which would enable nodes 8 and 9 to sleep.

It is obvious that assuming there is at least one solar-powered node in each column, solar-aware routing is able to find a path using solar-powered nodes only. The middle part of Figure 6 shows the data flow when nodes 1, 4 and 7 are solar-powered, the bottom part shows the data flow when nodes 3, 6 and 9 are solar-powered.

4.2 Experiments with Random Topologies

In the next experiments, we generated random topologies with the nodes distributed randomly across a certain area *a* with 20, 64 and 96 nodes. We generated 20 topologies for each number of nodes. The sink and source are placed in the middle of the eastern and western boundary of this area *a*. The area *a* is 800x600 for 20 nodes (it is not quadratic since it was almost impossible to get useful networks, i.e. networks with several distinctive paths, with 20 nodes only) and 1200x1200 for the networks with 64 and 90 nodes. The transmission range is fixed to 250 with 20 nodes, to 270 with 64 nodes and to 190 with 96 nodes. The transmission range is chosen in order to place between six and seven nodes in the range of an intermediate node on average. For 64 and 96 nodes, we split the area into eight sections and made sure that the same number of intermediate nodes was in each section.

In our scenarios we let the sun move across the area from North to South, covering an area which is about a third (for 20 nodes) and a sixth (for 64 and 96 nodes) of the area *a*.

4.2.1 Results with the Solar-aware Protocol Based on Local Interaction

We also compare this protocol with *shortest-path routing*, i.e. a route that would be found by native directed diffusion. For comparison we use a simple metric, namely the number of messages that must be transmitted using battery power. We do not include the interest messages in our comparison since they do not differ between solar-aware routing and shortest path routing. However, we include the extra status messages generated by the solar-aware routing in our comparison.

Number of nodes	20	64	96
Improvement (%)	26,8	15,1	12,1

Table 1: Improvement with Local Algorithm

As shown in Table 1, with 20 nodes, the average improvement of solar-aware routing over shortest-path routing is 26.8 %. For several scenarios, the improvement was more than 40%, while for other scenarios the improvements were only marginal. The latter scenarios often contained one bottleneck “link” each packet had to pass and thus solar-aware routing was not able to deviate from the shortest path for more than a few hops.

With 64 nodes, solar-aware routing was 15.1 % better than shortest-path routing. Also here, the improvement depended on the random scenario. We saw improvements larger than 30% but also only marginal improvements. However, solar-aware routing was only in very rare cases (and in these negligibly) worse than shortest path routing. With 96 nodes, solar-aware routing was only 12.1 % better than shortest-path routing.

The improvement for 64 and 96 nodes is less than with 20 nodes, because solar-aware routing based on localized interactions cannot take advantage of paths containing solar-driven nodes in the northern or southern areas.

4.2.2 Results with Solar-aware Directed Diffusion

We repeated the experiments with solar-aware directed diffusion (see Section 3.2). Also here, we compare the protocol with shortest-path routing, i.e. with a path that directed diffusion would find. We use the same simple metric as in the experiments in the previous section, namely the number of messages that must be transmitted using battery power. We do not include interest messages. Since directed diffusion also sends exploratory and reinforcement messages, we include only the extra messages generated by the solar-aware extension of the protocol, i.e. the ones that are generated when the sink forces the transmission of extra exploratory data by sending a reinforcement message with the option *send exploratory* as described in Section 3.2.3.

Number of nodes	20	64	96
Improvement (%)	0	10,7-20,5	5-20

Table 2: Improvement with Extended Directed Diffusion

With 20 nodes, there was almost no improvement, in many cases, solar-aware directed diffusion was worse than shortest-path routing. This was due to the overhead of sending additional reinforcement and exploratory data messages.

With 64 and 96 nodes, the results improved. However, they depend on many parameters. The results depend on the rate with that the source sends exploratory data and how well this rate corresponds to the movement of the sun as well as the fanout of the exploratory data. With a larger fanout, the number of exploratory data messages transmitted increases substantially but on the other hand, the chance that the best paths are found increases.

When we increased the number of exploratory data messages that each intermediate node transmits from two to three, the number of exploratory data messages increased by a factor of four. However, we implemented a very naïve strategy where a node forwards an exploratory message as soon as it arrives. If later another exploratory message on a path with, for example, less hops via battery-driven nodes arrives, the message has to be forwarded again. By waiting for other messages we could decrease the number of exploratory messages but the delay would increase. It would be very interesting to investigate if topology information would give us the possibility to cover more relevant parts (parts not leading to deadlock etc.) of the network with less exploratory data messages.

4.2.3 Summary of the Results

The results suggest that our first protocol is more suited for small networks since it is has less overhead in term of extra messages but it is not able find paths that are more than one hop away from the shortest path. Our second protocol, on the other hand, is more suitable for larger networks, but its efficiency depends on many parameters. We believe that the rate at which the source sends exploratory data could be dynamically adapted. Furthermore, location awareness could assist intermediate nodes in the decision on where to forward exploratory data messages. In summary, our results suggest that making routing protocols solar-aware can lead to significant energy savings in wireless sensor networks.

5 Related Work

Our routing protocols are modifications of directed diffusion [2].[10], an energy efficient paradigm for sensor network protocols.

Willig et al. have extended an energy-efficient routing protocol called Energy aware routing [6] to consider nodes with permanent power supply [4] while our protocols assume that the set of nodes having “unlimited” solar energy resources changes over time. Therefore, they perform the search for an energy-efficient path (by sending out interest messages) only once, while we need to explore at least parts of the network several times. One advantage of performing this search several times is that the load is balanced better across the nodes and therefore can prevent that some nodes are drained rapidly. This load balancing also helps to diminish another problem Willig et al. experience, namely that the nodes behind nodes with unlimited energy also experience an increased forward load and potentially get depleted early.

Heinzelman et al. have developed LEACH, an energy-efficient protocol that establishes an adaptive clustering hierarchy [7]. In LEACH, nodes organize themselves into local clusters thereby choosing a node for the high-energy cluster-head position. It would be interesting to investigate how their scheme would benefit from choosing solar-powered nodes as cluster-heads.

Our protocols are also similar to reactive protocols for ad-hoc routing such as AODV. A brief overview on energy management in ad hoc networks is presented by Feeney [8]. Braginsky and Estrin discuss the tradeoffs between flooding queries (reactive routing) and proactively creating paths to a source by flooding event notifications [11]. A prospective adoption of this idea to solar-aware routing might be that solar-powered nodes set up paths proactively.

Topology discovery and its application to route optimization and energy conservation are discussed in [12] and [13]. These approaches could help us to perform more efficient exploratory data delivery.

6 Conclusions and Future Work

We have presented two protocols for solar-aware routing. Solar-aware routing preferably routes traffic via nodes powered by solar energy. Our simulations of two solar-aware protocols show that they can provide significant energy savings in many scenarios. The results suggest that utilizing solar power in wireless sensor networks is efficient and feasible.

We have explored solar-awareness for protocols that are related to resp. are an extension to directed diffusion, a protocol based on local interactions between. We believe that cluster-based routing protocols as well as routing protocols that are partly proactive are also good candidates that can benefit from solar-awareness.

We will also conduct real live experiments when we have finalized all necessary hardware and the protocols are implemented on the sensor boards.

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