Theorem

# Silence is Golden with High Probability: Maintaining a Connected Backbone in Wireless Sensor Networks

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**Abstract.** Reducing node energy consumption to extend network lifetime is a vital requirement in wireless sensor networks. In this paper, we present and analyze the energy consumption of a class of cell-based energy conservation protocols. The goal of our protocols is to alternately turn off/on the transceivers of the nodes, while maintaining a connected backbone of active nodes. The protocols presented in this paper are shown to be optimal, in the sense that they extend the network lifetime by a factor which is proportional to the node density.

## 1 Introduction

Wireless sensor networks (WSN for short) are composed of battery-operated microsensors, each of which is integrated in a single package with low-power signal processing, computation, and a wireless transceiver. Sensor nodes collect the data of interest (e.g., temperature, pressure, soil makeup, and so on), and transmit them, possibly compressed and/or aggregated with those of neighboring nodes, to the other nodes. This way, every node in the network acquires a global view of the monitored area, which can be accessed by the external user connected to the WSN. Examples of scenarios where WSN can be used are described in [**?**,**?**,**?**,**?**].

Perhaps the most important cost in WSN is energy, since it determines battery use, and therefore the lifetime of the network. Since the major source of energy consumption in the sensor node is the wireless interface, considerable energy can be saved if the transceivers are completely shut down for a period of time. Of course, these sleeping times must be carefully scheduled, or network functionality could be compromised. A *cooperative strategy* is a distributed protocol that maintains a (minimal) connected backbone of active nodes, and turns into sleeping state the transceivers of non-backbone nodes. Periodically, the set of active nodes is changed to achieve a more uniform energy consumption in the network.

In this paper, we consider cell-based cooperative strategies for WSN. In the cell-based approach [**?**,**?**], the network deployment area is partitioned into identical non-overlapping cells. Each cell has an active representative. We focus on the process that for each cell updates its active representative.

We found and analyzed two interesting and simple strategies. The first assumes (possibly with unwarranted optimism) that all information about the nodes of the cell is available to the algorithm. The second is a probabilistic algorithm. If the number of nodes in each cell is known to the nodes within the cell, the algorithm is shown to elect a representative in constant expected time. The same behavior can be shown for the model in which the number is not known, but the nodes are assigned to cells uniformly and identically at random. The algorithms are energy-optimal, in the sense that they extend the network lifetime by a factor which is proportional to the node density. This is the best that any cell-based strategy can do [**?**]. We also find precise bounds for the running time of these algorithms.

Besides the potential usefulness of our algorithms, we believe that the ideas are interesting. They show how relatively inaccurate location information (the cell to which a node belongs) and loose synchronization can be exploited to elect leaders in a very simple and efficient way. Furthermore, we show how different amounts of "local" knowledge (deterministic vs. probabilistic knowledge of the number of nodes in a cell) result in different performance (worst-case vs. average case energy optimal). As discussed in Section **??**, the techniques presented in this paper techniques could be useful in other settings.

## 2 A WSN Application Scenario

A possible sensor networks application scenario in which the algorithms presented in this paper could be applied is the following.

A very large set of sensors is used to monitor a remote geographical region, for example to promptly detect fires in a vast forest. The (thermal) sensors are dispersed from a moving vehicle (e.g., an airplane or helicopter), hence their positions in the deployment region cannot be known in advance (but we have information about their probability distribution.) Once the sensors are deployed, their positions are mostly fixed.

The network should operate for a long period of time (e.g., the whole summer season), and should guarantee that, wherever the fire occurs, the alarm message generated by the sensor that detects the event quickly reaches the external supervisor, who is connected to some of the nodes in the network. Since the supervisor could be mobile (e.g., the supervisor is a ranger equipped with a PDA who wanders in the forest), the actual sensor nodes to which the supervisor is connected cannot be known in advance. This means that the alarm message should quickly propagate in the whole network, so that the supervisor can get the message independently of his physical location.

Since the batteries that power the sensors cannot be replaced once the unit is deployed, energy is a vital resource. With the current technology (see Section **??**), the sensor node component that consumes most energy is the radio interface, even when the radio is in idle mode. Hence, considerable energy savings can be achieved if the radio interface of sensors can be turned off most of the time. In principle, a sensor does not need to have its radio on while it is sensing: it could turn the radio on only when an event (fire) is detected, and the alarm message must be sent. However, some of the sensor nodes must keep their radio on also when they are sensing, so that the alarm message generated somewhere in the network could quickly reach the supervisor. I.e., *a connected backbone of awake nodes must exist at any time*.

The class of energy saving protocols presented in this paper aims at extending network lifetime by alternately turning on/off sensor transceivers, in such a way that a connected backbone of awake nodes always exists. The emphasis will be on minimizing the *coordination cost*, i.e., the cost due to the message exchange needed to assign roles (sleep/awake) to sensors.

## 3 Related Work

Several cooperative strategies aimed at extending network lifetime have been recently introduced in the literature. All of these strategies are related to some extent to the class of energy saving protocols presented in this paper.

In [?], Chen et al. present SPAN, a cooperative strategy aimed at reducing power consumption while preserving both the network capacity and connectivity. SPAN adaptively elects coordinators from all nodes in the network, which are left active, while non-coordinator nodes are shut down. The coordination algorithm is transparent to the routing protocol, and can be integrated into the IEEE 802.11 MAC layer. An inconvenient displayed by SPAN is that, contrary to what is expected, the energy savings achieved by the protocol do not scale with node density. This is due to the fact that the coordination cost with SPAN tends to "explode" with node density, and counterbalances the potential savings achieved by the increased density.

The CPC strategy presented in [?] is based on the construction of a connected dominating set: the nodes in the dominating set schedule the sleeping times of the other units. The authors show through simulation that CPC achieves energy savings with respect to the case where no cooperative strategy is used. However, the analysis of how CPC performance scales with node density is lacking.

The work that is most related to our are the papers by Xu et al. [?] and by Blough and Santi [?]. In [?], the authors introduce the GAF protocol for cell-based cooperation. The protocol is based on a subdivision of the deployment region into an appropriate number of non-overlapping square cells, with the property that if at least one node is awake for every cell, then the network is connected. Nodes in the same cell elect a representative, which is left active, while the transceivers of non-representative nodes are shut down. Periodically, the representative election phase is repeated to balance power consumption and to deal with mobility.

In [?], Blough and Santi investigates the best possible energy savings achievable by any cell-based cooperative strategy, i.e., the energy savings that are achievable under the assumption that the coordination cost is 0. They show that cell-based cooperative strategies have the potential to increase the network lifetime of a factor which is proportional to the node density. They also show that GAF achieves good energy savings, but that it leaves room for further improvement.

In this paper, we show that, if relatively inaccurate location information and loose synchronization are available, the theoretical limit of [?] can actually be achieved using very simple leader election algorithms. With respect to GAF, our algorithms are relatively more demanding (we require loose synchronization), but considerably simpler. Concerning the energy savings, our algorithms are proved to be optimal (in the worst case, or in expectation), while GAF is evaluated only through simulation.

A final comment concerns the synchronization assumption. In many WSN application scenarios, sensors must synchronized anyway (for instance, to report the events detected by the network in a consistent temporal order). So, we believe that our assumption is not particularly demanding.

## 4 The Energy Model

We assume that a sensor can be in the following states:

1. **sleeping**: node can sense and compute, but radio is switched off;
2. **idle**: radio is on, but not used;
3. **receiving**: node is receiving a radio message;
4. **transmitting**: node is transmitting a radio message.

The well known point is that while currents are minuscule in a chip, even a small radio requires energy levels that are orders of magnitude greater than those inside a processor. Measurements on a Medusa II sensor node [?] have shown sleep:idle:receiving:transmitting ratios of 0.25:1:1.006:1.244. It is also known that the energy cost of sensing is very small as compared to the energy consumption of the wireless transceiver, and is comparable to the cost of the radio interface in sleeping state [?].

As discussed above, we assume that nodes are able to determine the cell to which they belong through some form of location estimation. Similar assumptions were made in [?,?]. Furthermore, we assume that sensors are loosely synchronized. In the following we will assume that nodes are equipped with a GPS receiver. We remark that this assumption is done only for clarifying the presentation, and that any other localization and synchronization mechanisms could be used in practice. When the GPS receiver is used only to estimate node positions (at the beginning of the node operational time) and for loose synchronization purposes, its power consumption is about 0.033W [?], which is comparable to the 0.025W consumed by the wireless interface in sleep mode.

Given the discussion above, in this paper we use the following energy model:

- the energy consumption per time unit of a sensor with the radio on is modeled as a constant $C$, independently of the actual radio activity (idle, receiving, or sending);

– the energy consumption per time unit of a sensor with the radio off is modeled as a constant $c$, with $c \ll C$ (given the numbers above, we have $c \approx C/100$), independently of the actual sensor activity (sensing, or receiving the GPS clock).

## 5 Cell-Based Cooperative Strategies

We assume that the some initial information (such as node ID, node position, and so on) is available to the nodes by an initialization protocol. Since nodes are not coordinated in the initialization phase, conflicts to access the wireless channel could arise. These can be solved using traditional backoff-based techniques. The details of the initialization protocol implementation are not discussed in this paper. Rather, we are concerned with minimizing the energy consumed for node coordination *after* the initialization phase.

We assume that all the nodes are equipped with batteries with the same characteristics, i.e., that all the nodes have the same amount of energy $E_{init}$ available at the beginning of the network operational time, which for simplicity, we define as immediately after initialization[1].

Our goal is to turn the radio off as long as possible, while maintaining a connected backbone of active nodes. To further simplify the analysis, we assume here that $c = 0$, i.e., the energy consumed by a node for sensing and receiving the GPS signal with the radio off is negligible with respect to the energy consumed when the radio is on.

Observe that the energy consumption of a node in general is influenced by external factors, such as environmental conditions and, more notably, by "alarm" events (e.g., a fire in the WSN scenario of Section ??). During the alarm detection phase, energy consumption is no longer an issue: sensors must use all the energy that is needed to promptly propagate the alarm (e.g., the radio is turned on for a relatively long period of time). However, external factors are unpredictable by nature, and their influence on the nodes' energy consumption cannot be formally analyzed. For this reason, in the energy analysis of the protocols presented in this paper we will assume that there is no external influence on energy consumption during the network operational time. Thus, we will analyze the intrinsic energy cost of maintaining a connected backbone of active nodes (*the cost of silence*).

With the assumptions above, if no cooperative strategy is used to alternately turn the node transceivers on/off, the network operates for $T_b = E_{init}/C$ time units after initialization. At time $T_b$, all the nodes die simultaneously, and the network is no longer operative. Time $T_b$ is called the *baseline time*; the objective of our analysis will be to quantify the network lifetime extension yielded by our protocols with respect to this baseline time.

[1] This is likely not to be true even if nodes are equipped with batteries with the same characteristics, since the energy cost for initialization of a node is expected to be proportional to the number of nodes in its neighborhood. So after initialization different processors in different cells will not have the same charge. This does not affect our protocol, but would make the presentation more cumbersome.