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Static vs. mobile sink: The influence of basic parameters on energy efficiency in wireless sensor networks

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ABSTRACT

Over the last decade a large number of routing protocols has been designed for achieving energy efficiency in data collecting wireless sensor networks. The drawbacks of using a static sink are well known. It has been argued in the literature that a mobile sink may improve the energy dissipation compared to a static one. Some authors focus on minimizing *Emax*, the maximum energy dissipation of any single node in the network, while others aim at minimizing *Ebar*, the average energy dissipation over all nodes. In our paper we take a more holistic view, considering both *Emax* and *Ebar*.

The main contribution of this paper is to provide a simulation-based analysis of the energy efficiency of WSNs with static and mobile sinks. The focus is on two important configuration parameters: mobility path of the sink and duty cycling value of the nodes. On the one hand, it is well known that in the case of a mobile sink with fixed trajectory the choice of the mobility path influences energy efficiency. On the other hand, in some types of applications sensor nodes spend a rather large fraction of their total lifetime in idle mode, and therefore higher energy efficiency can be achieved by using the concept of reduced duty cycles. In particular, we quantitatively analyze the influence of duty cycling and the mobility radius of the sink as well as their interrelationship in terms of energy consumption for a well-defined model scenario. The analysis starts from general load considerations and is refined into a geometrical model. This model is validated by simulations which are more realistic in terms of duty cycling than previous work.

It is illustrated that over all possible configuration scenarios in terms of duty cycle and mobility radius of the sink the energy dissipation in the WSN can vary up to a factor of nine in terms of Emax and up to a factor of 17 in terms of Ebar. It turns out that in general the choice of the duty cycle value is more important for achieving energy efficiency than the choice of the mobility radius of the sink. Moreover, for small values of the duty cycle, a static sink turns out to be optimal in terms of both *Emax* and *Ebar*. For larger values of the duty cycle, a mobile sink has advantages over a static sink, especially in terms of *Emax*. These insights into the basic interrelationship between duty cycle value and mobility radius of a mobile sink are relevant for energy efficient operation of homogeneous WSNs beyond our model scenario.

1. Introduction

Recent advances in the development of low cost sensing devices and microminiaturization have further advanced the scope of applications of wireless sensor networks (WSNs). WSN based solutions have been designed and implemented in diverse areas, including environment and habitat monitoring, building automation, disaster and waste management, infrastructure monitoring, etc. [1]. Sensor nodes used in these applications are characterized by limited resources in terms of memory, computation power, and energy [2]. In particular, WSNs deployed for remote area monitoring usually comprise a large number of tiny static sensing devices, which are deployed in an ad hoc manner over a geographically wide area to sense parameters of interest. Such a random and uncontrolled deployment results in unknown network topology which, along with dynamic environment, low bandwidth, limited battery power and constrained storage capacity of the nodes, necessitates that each node always knows an energy efficient routing path to the sink with low congestion. Since ad hoc deployment of the nodes restricts programmers from pre-configuring routing tables at the sensor nodes, various techniques have been developed to maintain up-to-date routing paths to the sink. In the case of slowly changing topologies a proactive routing approach can provide an efficient solution where network topology discovery is based on the periodic broadcast of a beacon signal from the sink to the entire network [3]. In addition to maintaining energy

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efficient routing paths to the sink two other techniques often used for achieving energy efficiency are sink mobility [4,5] and duty cycling of the nodes [6].

In this paper we consider a WSN comprising homogeneous static sensor nodes. The sink can be static or mobile (for details see Section 2), and can be placed at different locations in the WSN. In the case of a static sink, nodes located in the vicinity of the sink deplete their energy (and die) much earlier compared to the nodes located farther away from the sink due to higher data relaying load. In order to address this issue, sink mobilization has been introduced, where the sink moves along a certain path through the network (see Section 2.2). It has also been shown that in most cases sink mobility helps in balancing the routing load and hence energy dissipation of the nodes [7,8].

Although it is clear that sink mobility improves load balancing among the nodes, it is an open question whether this also leads to improvements in the energy efficiency of a WSN. In order to address this question, we first need to define suitable metrics for quantitatively measuring energy efficiency.

One possible approach for comparing different sink mobility strategies is to compare the total energy consumption of the nodes in the WSN for the same total work(load) processed by the WSN. Consequently, our primary focus in this paper is on the *average energy dissipation per node Ebar*, i.e., the average over the accumulated energy dissipations of all nodes in the WSN during the observation period: $Ebar = \sum_{i=1}^{N} \frac{e_i}{N}$, where N denotes the total number of nodes in the WSN and e_i is the accumulated energy dissipation of node i during the observation period.

However, it is well known that in the case of a static sink the energy consumption of individual nodes varies strongly across the WSN, since the nodes close to the sink are much more heavily burdened due to relay operations than those farther away from the sink. For this reason, we additionally investigate the *maximum energy dissipation per node* $Emax = \max_{i=1,2,\ldots,N} e_i$.

For load balancing reasons, a static sink is usually located at the center of the WSN. If too many nodes in the area surrounding a static sink fail since they have used up their energy resources, the sink might become disconnected from the rest of the WSN. Therefore, *Emax* is definitely one of many possible relevant indicators for the *lifetime* of the WSN [27,31] in a generic abstract model for a WSN, which is the focus of this paper. Most of the existing work in the literature (see, e.g. [4,9,10]) discusses *either* the lifetime of a WSN *or* the average energy dissipation per node (either *Emax* or on *Ebar*). Contrary to that, in this paper we evaluate different protocols in terms of metrics for *both* of these aspects and pinpoint in which situations they yield different information. More importantly, in most cases the effects of *duty cycling* of the nodes, a very important feature in the practical application of modern WSNs, are not taken into account in quantitative evaluations.

In this paper, we quantitatively model and investigate the influence of duty cycling of static sensor nodes and of the mobility path of a mobile sink on the energy consumption in a simplified model scenario of a WSN. We quantitatively compare the energy efficiency of this model WSN with a static and a mobile sink in terms *Emax* and *Ebar*. We illustrate that for certain network configurations sink mobilization alone is not enough to improve *Emax* and *Ebar* compared to a static sink. We also show that for other configurations a mobile sink can significantly improve both *Emax* and *Ebar* by reducing data relaying load on the sensor nodes and congestion in the network. *Ebar* can vary up to a factor of 17 and *Emax* up to a factor of nine across all possible combinations of duty cycle value and mobility path of the sink. We explain the reasons for these observations on the basis of a geometrical model and validate this model by simulations. The basic understanding gained by the analysis presented in this paper can serve as a first step for the development of configuration guidelines for WSNs with homogeneous nodes which are valid beyond the simplified model setup analyzed in this paper.

The rest of the paper is organized as follows: Section 2 summarizes current state-of-the-art routing schemes for WSNs with a static or a mobile sink. Section 3 summarizes the considered mobility model, WSN model, energy model and the simulation methodology. Section 4 analyzes the effect of sink mobility and duty cycling on the energy efficiency of a WSN, and Section 5 concludes the paper.

2. Related work

In the following, we review state-of-the-art routing schemes for WSNs with static or mobile sinks.

2.1. WSNs with a static sink

In the early days, a typical WSN was composed of static sensor nodes and a static sink placed inside the observed region. In such a setup, the major energy consumer is the communication module of each node. In practice, multi-hop communication is required for sending data from sources to sink nodes. Consequently, the energy consumption depends on the communication distance. One way to reduce the communication distance is to deploy multiple static sinks [11] and to program each sensor node such that it routes data to the closest sink. This reduces the average path length from source to sink and hence results in smaller *Ebar* compared to the case of single static sink. On the other hand, reduction in *Emax* is also observed because routing load on the nodes located in the vicinity of a single sink also gets distributed among all the nodes located in the vicinity of multiple static sinks. The authors of [11,12] propose to deploy multiple static sinks. These static sinks partition the WSN into small sub-fields each with one static sink. By simulation it was shown that the proposed scheme leads to energy efficiency and better data delivery ratio compared to schemes based on a single sink.

However, a major problem with multiple static sinks is that one has to decide where to deploy them inside the monitored region so that the data relaying load can be balanced amongst the nodes. Vincze et al. consider this problem in [13] as an instance of the well-known "*facility location problem*" where for a given number of facilities and customers the optimal position for the placement of the facilities has to be identified so that all facilities are evenly burdened. If the positions of the static sinks are given, then the solution of this problem can be used for finding the optimal partitioning of the field. However, even if we assume location-optimal deployment of static sinks, the nodes close to a sink will deplete their energy rather rapidly. Adding some mobile sinks to a set of static sinks has been shown to improve the data delivery rate and to reduce energy dissipation of the sensor nodes [14].

2.1.1. Improvements for the static sink case

Some of the benefits of multiple static sinks for energy efficiency can also be realized with a single static sink by logically partitioning the sensor field at a single level or hierarchically. Such a partitioning can be either static or dynamic, and it can be predetermined or self-organized within the network. Besides the field partitioning, the selection of a cluster head in each partition is an important issue (see Fig. 1).

In order to avoid the "dying" of nodes close to the sink, partitioning of the field into subareas (clusters) has been investigated (e.g. [15,16]). Within each cluster, a cluster head is determined to which local nodes send their data. Cluster heads tend to have higher capacity than regular nodes and are responsible for forwarding collected data to the sink over single or multiple hops. Both the