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On the energy-delay trade-off in geographic forwarding in always-on wireless sensor networks: A multi-objective optimization problem

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ABSTRACT

The design and development of multi-hop wireless sensor networks are guided by the specific requirements of their corresponding sensing applications. These requirements can be associated with certain well-defined qualitative and/or quantitative performance metrics, which are application-dependent. The main function of this type of network is to monitor a field of interest using the sensing capability of the sensors, collect the corresponding sensed data, and forward it to a data gathering point, also known as *sink*. Thus, the longevity of wireless sensor networks requires that the load of data forwarding be balanced among all the sensor nodes so they deplete their battery power (or *energy*) slowly and uniformly. However, some sensing applications are time-critical in nature. Hence, they should satisfy strict delay constraints so the sink can receive the sensed data originated from the sensors within a specified time bound. Thus, to account for all of these various sensing applications, appropriate data forwarding protocols should be designed to achieve some or all of the following three major goals, namely minimum energy consumption, uniform battery power depletion, and minimum delay. To this end, it is necessary to jointly consider these three goals by formulating a multi-objective optimization problem and solving it. In this paper, we propose a data forwarding protocol that trades off these three goals via slicing the communication range of the sensors into *concentric circular bands*. In particular, we discuss an approach, called *weighted scale-uniform-unit sum*, which is used by the source sensors to solve this multi-objective optimization problem. Our proposed data forwarding protocol, called *Trade-off Energy with Delay* (TED), makes use of our solution to this multi-objective optimization problem in order to find a "best" trade-off of minimum energy consumption, uniform battery power depletion, and minimum delay. Then, we present and discuss several numerical results to show the effectiveness of TED. Moreover, we show how to relax several widely used assumptions in order to enhance the practicality of our TED protocol, and extend it to real-world network scenarios. Finally, we evaluate the performance of TED through extensive simulations. We find that TED is *near optimal* with respect to the *energy* $\times$ *delay* metric. This simulation study is an essential step to gain more insight into TED before implementing it using a sensor test-bed.

1. Introduction

Recent advances in sensor technology and wireless communications have enabled the design and development of inexpensive, large-scale wireless sensor networks,

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which are suitable for various civilian applications, such as health environments monitoring; natural applications, such as seism monitoring; and military applications, such as battlefields surveillance, to name a few. A wireless sensor network (WSN) is a collection of tiny, low-powered sensors that communicate with each other through multi-hop wireless links, and collaborate together to accomplish a common task. This type of network suffers from severe limitations of the sensors with respect to their battery power, computation, communication, and storage capabilities. It is worth mentioning that battery power (or *energy*) is the most crucial resource in WSNs. In fact, when the sensors are deployed in hostile environments, such battlefields, it is sometimes difficult or even impossible to recharge or replenish their battery. It is well known that the main function of WSNs is to monitor a field of interest using the sensing capability of the sensors, collect the corresponding sensed data, and forward it to a central data gathering point, called the *sink*. Thus, it is necessary to design energy-efficient data forwarding protocols for WSNs, which are an essential component and critical determinant of the effectiveness of the network design. These protocols should guarantee *uniform energy depletion* of the sensors in the network. This helps the sensors operate for longer periods of time, thus extending the network operational lifetime [31]. However, ensuring the longevity of WSNs becomes a challenging issue for sensing applications with strict source-to-sink delay (or simply *delay*) constraints [32], [33]. These delay constraints must be satisfied at the sink so it can make decisions in a timely fashion based on the collected sensed data (or simply *data*) regarding the observed phenomenon in the field of interest. A comprehensive survey on WSNs can be found in [2].

It is clear that the above-mentioned goals, namely minimum energy consumption, minimum delay, and uniform energy depletion, are conflicting goals. This conflict can be explained by the following three interpretations. First, the minimization of the energy consumption requires transmitting the data over short distances. Indeed, the energy (E_{tx}) spent in data transmission over a distance d between any pair of consecutive forwarders, is proportional to d, *i.e.*, $E_{tx} \propto d^{\alpha}$, with $2 \leqslant \alpha \leqslant 4$ being the path-loss exponent. Second, the minimization of the delay requires minimizing the number of intermediate forwarders between a source and the sink. This can be achieved by maximizing the distance between any pair of consecutive forwarders. It is worth noting that Haenggi [14] and Haenggi and Puccinelli [15] took an extreme position by arguing that long-hop routing is a very competitive strategy compared to short-hop routing. However, this sacrifices the very scarce energy resource of the sensors. Haenggi [14] provided twelve reasons explaining the advantages of long-range over short-range forwarding. We believe that a more balanced approach should be used to account for delay and energy uniformity. Third, usually, the search space of next candidate forwarders is a cone centered at the current sensor holding the data to be forwarded. A small cone yields an unbalanced distribution of the data forwarding load among the sensors. In fact, this causes a non-uniform depletion of the available energy of the sensors. Indeed, the candidate forwarders located in a small cone would suffer heavy depletion of their energy as they will be frequently selected as forwarders. In contrast, a large cone ensures a more balanced data forwarding load among the sensors and hence helps achieve uniform energy depletion of the sensors. Therefore, it is necessary to find a trade-off of these three goals, which are jointly considered.

1.1. Major contributions

Our major contributions in this paper are fourfold and can be summarized as follows:

- First, we propose an approach based on slicing the communication range of the sensors in order to trade-off three conflicting goals of sensing applications. More precisely, our approach aims to decompose the communication range of the sensors into *concentric circular bands* and classify them with a goal to satisfy the specific requirements of sensing applications in terms of energy consumption, delay, and energy depletion. For tractability, we assume that the communication ranges of the sensors are modeled by a disk. In addition, we suppose that all the sensors have the same radius of their communication range.
- Second, we formulate a trade-off of these three conflicting goals as a multi-objective optimization problem, which is solved using a *weighted scale-uniform-unit sum* (WES) approach [19]. Then, we propose a data forwarding protocol for WSNs, which exploits a solution to this multi-objective optimization problem to find an optimum trade-off of three conflicting goals, namely minimum energy consumption, minimum delay, and uniform energy depletion. To account for the third goal, we propose an approach to characterize the uniform energy depletion of the sensors based on the size of the cone that includes a subset of candidate forwarders. Although there are other methods, such as multi-objective optimization genetic algorithm (MOGA) [12], we find that the WES approach offers more flexibility to find solutions to an optimization problem with several weighted objective functions. We introduce these weighting coefficients to reflect the relative importance of the individual objective functions and address the problem of their different units and order of magnitude. Our theoretical results show that an optimum trade-off of the three goals exists. Moreover, this optimum trade-off depends on these weighting coefficients.
- Third, we relax several widely used assumptions in the design of WSNs and which we adopted in our study. Our ultimate goal is to enhance the practicality and effectiveness of our proposed TED protocol.
- Fourth, we evaluate the performance of TED through extensive simulations, and compare it with existing ones. We find that the performance of TED is *near optimal* with respect to the *energy* $\times$ *delay* metric. This simulation study seems to be an essential step to gain more insight into TED before implementing it on a sensor test-bed. To the best of our knowledge, although the design of energy-efficient data forwarding protocols for WSNs has received much attention, there is no