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Clustering algorithms for maximizing the lifetime of wireless sensor networks with energy-harvesting sensors

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ABSTRACT

Motivated by recent developments in wireless sensor networks (WSNs), we present several efficient clustering algorithms for maximizing the lifetime of WSNs, i.e., the duration till a certain percentage of the nodes die. Specifically, an optimization algorithm is proposed for maximizing the lifetime of a single-cluster network, followed by an extension to handle multi-cluster networks. Then we study the joint problem of prolonging network lifetime by introducing energy-harvesting (EH) nodes. An algorithm is proposed for maximizing the network lifetime where EH nodes serve as dedicated relay nodes for cluster heads (CHs). Theoretical analysis and extensive simulation results show that the proposed algorithms can achieve optimal or suboptimal solutions efficiently, and therefore help provide useful benchmarks for various centralized and distributed clustering scheme designs.

1. Introduction

With the developments of low-power and multi-functional sensors, wireless sensor networks (WSNs) [44,4,36,2] composed of sensor nodes with abilities of data sensing/processing and wireless communication have paved the way for a wide variety of practical applications in monitoring, tracking, control, etc.

Since batteries in sensors have finite stored energy and it is generally not convenient to replace or recharge these batteries, a critical issue in WSNs is to achieve high energy efficiency in order to prolong the lifetime of the networks. Extensive researches have been carried out to tackle the problem and many solutions have been proposed, among which include *clustering*-based approaches [2,26]. A clustered WSN is typically composed of a base station (BS) and a certain number of clusters. Each cluster is composed of a cluster head (CH) and some non-cluster head (NCH) nodes. The CH is responsible for receiving data from NCHs, processing the data and then forwarding the information to the BS, either directly, via other CHs or via one or multiple *relay* nodes. Relay nodes are responsible for forwarding data received from other nodes and may not necessarily be responsible for local sensing. In clustered WSNs, transmitting to a CH nearby rather than to a possibly far away BS helps reduce the energy consumption of NCHs. However, CHs may be heavily burdened since they need to process and transmit the data for the whole cluster. This may shorten the lifespan of CHs, especially in the absence of relay nodes between CHs and BS. Lowering the energy consumption of CHs therefore usually plays a critical role in prolonging the lifetime of clustered WSNs. Since the communication distance largely determines the energy consumption of data transmission, finding a good location for each CH is of critical importance for prolonging network lifetime: an inappropriate CH location may force the CH node to communicate with BS over a long distance and consequently uses up its stored energy quickly.

Clustered WSNs have been extensively studied in recent years [1]. Existing works include energy-efficient schemes and algorithms [21,47,50,51,23,35], enhancement of cluster stability in various network topologies [46,22], MAC

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layer design [48,42,50] and many more. The work on energy-efficient schemes typically adopts two different objectives, namely minimizing the overall energy consumptions [21,47] and maximizing the network lifetime [24,5] respectively. These two parts of work are closely related to but different from each other: the former one works on a minimization problem while the latter one usually works on a min–max problem since the lifetime of a network is usually decided, or at least strongly affected (depending on the definitions of lifetime, as we will discuss in more detail in Section 5 later), by those nodes with shortest lifespan. We term such nodes as the *bottleneck* nodes. In clustered WSNs, as mentioned earlier, the bottleneck nodes are usually, though not always, CHs. In this paper, we focus on designing clustering algorithms to maximize network lifetime.

Existing results on lifetime maximization problem can be largely classified into two categories: centralized methods [33,24,11,5,13,14,49,16,37,40,7,34,18,6] and distributed methods [50,31,28,21,47,9]. Centralized methods typically require knowledge of the sensors' locations to achieve global optimization with respect to certain performance metrics. Distributed methods, on the other hand, make decisions based on local information exchanged between neighboring sensors, thus achieving better scalability. We focus on studying centralized methods in this paper as they can provide a good reference for network pre-planning and serve as a useful benchmark for evaluating the performance of distributed methods.

Parallel to the significantly improved network clustering techniques, another important recent progress is the development of energy harvesting (EH) sensors [41,17,38,19,8]. EH sensors can harvest energy (e.g., solar, kinetic, thermal, etc.) from their environment, converting this energy into electrical energy which is then stored in devices with large numbers of recharge cycles (such as super-capacitors) [41] to achieve virtually infinite lifetime. While the deployment of large-scale WSNs composed solely of EH sensors remain impractical in the near future due to high costs and low achievable duty cycles, an arguably more practical approach is to adopt EH sensor nodes sparsely in WSNs [25,32].

Clustering methods and energy-harvesting techniques come as a natural combination for prolonging the network lifetime: a proper formation of clusters liberates most sensors (especially NCHs) from high energy consumptions, while a carefully planned sparse deployment of EH sensors helps prolong the lifespan of the bottleneck nodes. Since energy harvesting rates are sensitive to the environment [8], it may not be practical to let EH nodes serve as function-critical nodes such as CHs. In this paper, we consider a simple case where EH sensors serve as relay nodes for CHs. By communicating with EH nodes over a shorter distance rather than sending data to BS directly, CHs can have lowered energy consumptions for at least a certain fraction of time. This simple case can provide some useful insights into where EH sensors should be located to maximize network lifetime.

To summarize, in this paper we propose algorithms for maximizing the lifetime of clustered WSNs, with or without EH nodes. Specifically, we assume that a given number of sensors are distributed in a certain area with arbitrary distribution. These sensors can be formed into a given number of clusters under centralized control. Each cluster contains a single CH and a certain number of NCHs. NCHs forward data to their CH. Each CH is responsible for aggregating data from NCHs and forwarding the information to BS, either directly or via a dedicated EH relay node. The EH nodes only serve as relay nodes; they do not collect/process environmental information themselves. Furthermore, we assume that each sensor is equipped with same amount of energy at the beginning and BS is equipped with infinite energy, e.g., through mains power.

The main contributions of this paper are twofold: (i) we propose efficient algorithms for maximizing the network lifetime of both single-and multi-cluster WSNs. Analytical and extensive simulation results demonstrate the fast convergence of our proposed algorithms to optimal or suboptimal solutions and (ii) based on the assumption that the locations of the EH nodes can be adjusted in order to maximize network lifetime, we extend the proposed algorithms to handle the case where EH sensors serve as relay nodes for CHs. Extensive simulation results quantify how much EH nodes may help prolong the network lifetime. Finally, we also briefly discuss on the revision of the proposed algorithms under different definitions of network lifetime.

The rest of the paper is organized as follows: a brief survey of some closely related work is provided in Section 2. In Section 3, we propose algorithms for calculating the optimal locations of CH nodes in single-and multi-cluster networks. Both single-and multi-cluster algorithms are extended to handle the case where EH sensors serve as relay nodes of CHs in Section 4. Brief discussions on the extension of the proposed algorithms under different lifetime definitions are presented in Section 5. In Section 6, extensive simulation results and discussions are presented for verifying the performances of the proposed algorithms and the effects of EH sensors on prolonging network lifetime. Finally, Section 7 concludes the paper and presents several directions for future research.

2. Literature survey

Numerous centralized clustering algorithms for WSNs have been proposed [33,24,11,29,5], typically aiming to reduce the power consumption of CHs to prolong network lifetime. Ning et al. proposed an algorithm which adopted the sequential location-allocation decomposition method to minimize the communication power and achieve high reliability for a large-scale network [33]. Irani et al. proposed heuristic approaches for the CH deployment problem and also studied the effects of the number of clusters [24]. An incremental algorithm was proposed in [11] for efficient placement of CH nodes. Li et al. proposed a clustering scheme based on uncapacitated facility location in which the network lifetime is extended by adding a layer of Super-Cluster-Head nodes to ease the transmission load of the CHs and to balance the load distribution within the network [29]. Aslam et al. proposed a weighted cost function based on the residual energy levels of cluster heads for the