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Mobility assisted data gathering with solar irradiance awareness in heterogeneous energy replenishable wireless sensor networks

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ABSTRACT

Wireless sensor networks adopting static data gathering may suffer from unbalanced energy consumption due to non-uniform packet relay. Although mobile data gathering provides a reasonable approach to solving this problem, it inevitably introduces longer data collection latency due to the use of mobile data collectors. In the meanwhile, energy harvesting has been considered as a promising solution to relieve energy limitation in wireless sensor networks. In this paper, we consider a joint design of these two schemes and propose a novel two layer heterogeneous architecture for wireless sensor networks, which consists of two types of nodes: sensor nodes which are static and powered by solar panels, and cluster heads that have limited mobility and can be wirelessly recharged by power transporters. Based on this network architecture, we present a data gathering scheme, called mobility assisted data gathering with solar irradiance awareness (MADG-SIA), where sensor nodes are clustered around cluster heads that adaptively change their positions according to solar irradiance, and the sensing data are forwarded to the data sink by these cluster heads working as data aggregation points. We evaluate the performance of the proposed scheme by extensive simulations and the results show that MADG-SIA provides significant improvement in terms of balancing energy consumption and the amount data gathered compared to previous work.

1. Introduction

Wireless sensor networks (WSNs) have been deployed for a variety of applications ranging from health, agriculture, industry to military. WSNs consist of a large number of randomly distributed sensor nodes that sense the environment and send the sensing data to the data collector in an ad hoc manner. These sensor nodes usually have limited energy supply, e.g., from batteries, which makes energy efficiency a critical issue in sensor network design and deployment. Much effort has been devoted to reduce energy consumption by employing power efficient hardware and software architectures, wireless communications and networking techniques [1–6]. Research shows that wireless communications is the dominant energy consumer on sensor nodes, thus how to gather data from sensor nodes is an important issue for energy consumption optimization in sensor networks.

One of the most important problems in data gathering in WSNs is to balance the energy consumption among sensor nodes. Unbalanced energy consumption caused by packet relay leads to energy holes in the network, which may disable the packet forwarding toward the data collector, and eventually results in degraded network performance, such as short network lifetime and low data throughput. In a conventional homogeneous wireless sensor network, a statically deployed data collector, referred to as *data sink*, is used to gather data from the network. Since data packets converge toward the data sink, the nodes that are closer to the data sink have to relay much more data than the nodes that are farther away from the data sink, and they consume energy much faster than other nodes. When these nodes deplete their energy, the data sink becomes unreachable to the rest of the nodes, thus the entire network can no longer operate.

Hierarchical WSNs have been proposed to relieve the unbalanced energy consumption problem, in which sensor nodes are organized into clusters [7–13]. Instead of sending all the data to the single data sink in a multi-hop manner, sensors upload data to the aggregation nodes of the cluster they belong to, which are referred to as *cluster heads*. These data are then relayed to the data sink by cluster heads which are built with stronger wireless communications capability and more energy supply. Such a hierarchical architecture can mitigate energy unbalance to some extent, however, since cluster heads are statically deployed, network lifetime is limited by the nodes around these cluster heads.

Mobility has been introduced into WSNs due to its benefits, such as guaranteeing network connectivity, reducing network cost, increasing reliability, and improving energy efficiency [14]. Mobile data

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gathering uses a mobile data collector to sojourn at different positions in a sensor network to gather data from surrounding sensor nodes. By moving the data aggregation points across the entire network, energy consumption tends to be balanced in the whole network [15,16]. However, a challenge of mobile data gathering is that such a scheme inevitably introduces long data collection latency because the mobile data collector has to visit all the selected positions before it can upload data to the data sink. The positions of data aggregation points also need to be carefully selected depending on multiple factors, such as network topology, energy levels of all the sensor nodes, and the amount of sensing data generated in each sensor node. The computation inevitably increases overhead and operational complexity of the network.

Energy harvesting techniques have been recently employed as a solution to prolong network operating time from another aspect. Such a scheme captures energy from the ambient environment, e.g., mechanical, thermal, photovoltaic or electromagnetic energy, to charge sensor nodes. However, the main drawback of energy harvesting techniques is the low efficiency of recharging, since the power output of energy harvesting devices is relatively low compared to the power consumption of the node for sensing and communications [17], especially for the sensor nodes around the data aggregation points.

In order to overcome the aforementioned problems, it is desirable to find a novel approach to balancing energy consumption to improve network performance in WSNs. By taking advantage of mobility and renewable energy while shortening data collection latency, we propose a **mobility assisted data gathering with solar irradiance awareness** scheme, abbreviated as **MADG-SIA**, to achieve balanced energy consumption in WSNs and prolong network lifetime. We construct an MADG-SIA enabled network with three types of devices: the static sensor nodes that are powered by solar panels, the mobile cluster heads that can be wirelessly recharged, and the power transporters (referred to as *PowCars*). Different from sensor nodes, the discharge rates of cluster heads are much higher than the charge rate provided by solar panels due to the large amount of data forwarding and movement. We use PowCars to charge cluster heads more efficiently when their energy levels are low. The network has a hierarchical architecture where sensor nodes are clustered and send data to their corresponding cluster heads. The cluster heads sojourn at different positions, referred to as *anchor points*, in each data gathering period, to collect data from surrounding sensor nodes in a one-hop or multi-hop manner. By carefully moving cluster heads to some positions for data gathering, the energy-consuming data forwarding tasks are shared among all the sensor nodes to balance their energy consumption. On the other hand, as the moving distance of cluster heads is limited, and they communicate with the data sink directly once settled down, the data collection latency in the proposed network is much shorter than that in mobile data gathering. Based on this network architecture, we will find optimal positions for anchor points and moving paths for cluster heads, and develop a clustering approach and determine the routes for sensor nodes to upload data to cluster heads.

The rest of the paper is organized as follows. The related work is discussed in Section 2. Section 3 describes the framework of the proposed scheme. In Section 4, the system model and the proposed algorithm are presented for WSNs with regular and random topologies. Section 5 evaluates the impact of various parameters on network performance. Finally, the paper is concluded in Section 6.

2. Related work

In this section, we briefly review some related work in the literature, which includes the work on data gathering with clustering and energy replenishment in WSNs.

2.1. Data gathering in clustered WSNs

An energy-efficient framework for clustering-based data collection in WSNs was proposed in [7]. By adaptively enabling/disabling prediction operations and updating clustering as well as accommodating in-network aggregation and the sleep/awake scheduling, the framework achieves energy efficiency when sensor data are spatially and temporally correlated. Clustering sensor nodes was also considered in [8]. By periodically selecting cluster heads according to the combination of residual energy and a secondary parameter, such as node proximity to its neighbors or node degree, this clustering method outperforms weighted clustering protocols in terms of several cluster characteristics. Heterogeneous ad hoc sensor networks were studied in [9] which focused on energy and link heterogeneity. The impact of the number and placement of heterogeneous resources on the performance of networks of different sizes and densities was evaluated. It was shown that it requires only a modest number of reliable, long-range backhaul links and line-powered nodes to have a significant impact. Employing mobile cluster heads in hybrid sensor networks was explored in [10]. A heuristic algorithm for positioning cluster heads and balancing traffic load in the network was proposed and shown to be able to increase network lifetime after only a few rounds of adjustments. An energy-balanced dominating set based clustering scheme was proposed in [12], where normal nodes broadcast the number of cluster head candidates around it. Each candidate calculates the median of such numbers received from its neighbors, and becomes a final cluster head with a probability inversely proportional to the median. Employment of distributed load balanced clustering (LBC) and MIMO uploading techniques in WSNs was studied in [13], in which the sensors are organized into clusters by executing a distributed LBC algorithm, which also generates multiple cluster heads in each cluster to balance the work load and facilitate MIMO data uploading.

The above schemes can greatly save energy by utilizing clustering compared to conventional relay routing in networks. However, since they are based on conventional sensor nodes and do not consider energy harvesting, the network lifetime is limited by the battery life. Alternatively, our work in this paper jointly considers energy replenishment and cluster head movement with the goal to extend operation time of WSNs.

2.2. Energy replenishment in WSNs

A general target coverage problem for a solar-powered active sensor network with a controllable sensing range was investigated in [18], where a near-optimal approximate solution was provided with a 60X improvement in speed at the cost of 8% reduction in the quality of coverage. A joint study of energy management and resource allocation problem for energy-harvesting sensors was presented in [19], in which the optimal sampling rate was explored based on the average energy replenishment rate, and a local algorithm was presented for each sensor to adapt the sampling rate according to short term fluctuations in recharging, with the objective of maintaining the battery at a target level. A dynamic energy-oriented scheduling method (DEOS) was proposed in [20] for multiple tasks allocation with a time-varying and limited energy constraint in energy harvesting WSNs. Simulation results indicated that DEOS is extremely lightweight and it effectively schedules tasks to utilize the dynamically available energy. RF radiation based energy replenishment for sensor networks was studied in [21], where a wireless charging system was developed and implemented so that sensor nodes get charged by a mobile charger. However, experiment reveals that energy replenishment with this technique is of low efficiency and difficult to be used in large scale WSNs with perpetual operation. The application of wireless energy replenishment through resonant magnetic coupling for WSNs has also been studied in literatures. A