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Compressive data gathering using random projection for energy efficient wireless sensor networks

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This paper proposes a novel data gathering method using Compressive Sensing (CS) and random projection to improve the lifetime of large Wireless Sensor Networks (WSNs). To increase the network lifetime, one needs to decrease the overall network energy consumption and distribute the energy load more evenly throughout the network. By using compressive sensing in data aggregation, referred to as Compressive Data Gathering (CDG), one can dramatically improve the energy efficiency, and this is particularly attributed to the benefits obtained from data compression. Random projection, together with compressive data gathering, helps further in balancing the energy consumption load throughout the network. In this paper, we propose a new compressive data gathering method called Minimum Spanning Tree Projection (MSTP). MSTP creates a number of Minimum-Spanning-Trees (MSTs), each rooted at a randomly selected projection node, which in turn aggregates sensed data from sensors using compressive sensing. We compare through simulations our method with the existing data gathering schemes. We further extend our method and introduce eMSTP, which joins the sink node to each MST and makes the sink node as the root for each tree. Our simulation results show that MSTP and eMSTP outperform the existing data gathering schemes in decreasing the communication cost and distributing the energy consumption loads and hence improving the overall lifetime of the network.

1. Introduction

Increasing the lifetime of a wireless sensor network depends directly on minimizing the energy consumption at sensor nodes. In a WSN, most of the power is consumed in data transmission and forwarding. Therefore, to maximize the network lifetime, one has to address the following two challenges: (1) reducing the global network communication cost, and (2) dealing with the unbalance of energy consumption throughout the network. In a large-scale network, when individual sensors transmit their data to the sink, it is expected that a single data could be transmitted several times through multi-hop routing, which causes a large number of redundant transmissions in the network, therefore increasing the overall network communication cost. Furthermore, nodes which are closer to the sink do more forwarding tasks than other nodes. Therefore, these bottleneck nodes (i.e., neighbor nodes to the sink) consume more power and consequently run out of energy quickly, which shorten the lifetime of the network. Different methods have been proposed by researchers to maximize the lifetime of WSNs, such as, adjusting sensing ranges [1], sleep scheduling [2], clustering routing protocol [3], cross-layer network formulation [4] and data aggregation [5]. Data aggregation, unlike the other approaches, aims at reducing the amount of data to be transported, and hence significantly helps in overall energy consumption load.

In this paper, to minimize the network communication cost and achieve better balanced consumption throughout

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the network, we propose a method based on data aggregation using Compressive Sensing (CS) [6,7]. The CS technique first has been presented by David L. Donoho in [8] for signal processing; this technique promises to successfully deliver and recover the signals with far fewer rates than the Nyquist rate [9], as long as the signals are compressible or transferable to a sparse domain (such as wavelet). Bajwa et. al. in [10] introduced CS into wireless network for a single-hop star network. In [11], the authors gave a conceptual understanding of CS in a wireless sensor network. They showed that original data reading vector of sensors could be recovered at the sink with far fewer sample measurements using the same technique of CS in [8] for signals. Note that, with this technique, it appears as if the original sensors reading vector has been compressed. Hence, instead of transmitting the original data in the network, the compressed data is rather sent and thus a reduction in the traffic transmission loads in the network is expected. The authors of [12] considered a large number of sensor nodes densely deployed where sensor readings are spatially correlated and proposed a compressive data gathering (CDG) to reduce global scale communication cost without introducing intensive computation or complicated control. They proposed that the sink node, instead of receiving each sensor's reading by one packet in multi-hop route, may, based on CS technique, receive only few weighted sums also called projections (each projection in one packet) from all the nodes in the network by gathering the weighted nodes readings on their routes path from the leaf nodes to the sink. Therefore, each node in the network sends exactly the same number of few packets. That is, nodes near the sink send the same number of packets as those nodes far away from the sink. Consequently, the energy consumption throughout the network is balanced. We will explain the CS technique and CDG in more details in Section 4.

By comparing CDG with basic data collection (non-CS), we observe that, nodes closer to the sink in CDG transmit fewer packets in comparison to the non-CS scheme. However, nodes far away from the sink in CDG transmit more packets when compared to non-CS. Therefore, clearly using CS for all nodes is not very attractive, but most importantly, CDG resolved the problem of bottleneck nodes. J. Lue et al. in [13] introduced plain-CS and hybrid-CS, where the former (plain-CS) uses CS encoding for all nodes in the network (same as the CDG scheme) and the latter (hybrid-CS) applies CS only to relay nodes that are overloaded. Hybrid-CS resolved the drawback of CDG with respect to the number of packet transmission and hence reduced the global network communication cost.

As one can observe from the hybrid-CS, all nodes in the network participate in data gathering for each projection, resulting in a waste of energy resources. Wang et al. in [14] presented a novel distributed algorithm based on sparse random projections, which requires no global coordination or knowledge. The algorithm selects different nodes at random to do the projection and accordingly, each projection node gathers a weighted sum from sparse number of nodes in the network. The algorithm used in [14] cannot guarantee that all the nodes always will participate in projections, because sparse nodes are selected at random for each projection node. Further, the algorithm cannot minimize the global network communication cost since for each random projection, the algorithm requires a large number of multi-hop transmissions to collect the data from individual sparse nodes and no data gathering is used in the routing paths to projection nodes.

In this paper, we propose a new data gathering method by combining the Compressive Data Gathering (CDG) presented in [12] with sparse random projection presented in [14] to reduce further the overall number of transmissions and most importantly to distribute the energy consumption load more evenly throughout the network to increase the lifetime of wireless sensor network. Our method (the Minimum Spanning Tree Projection (MSTP)), same as [14] selects different nodes at random to do projection. Where in [14] each projection node after collecting the native data from set of nodes sends the projected data to the sink. But MSTP unlike [14] uses CDG [12] for each projection node to collect and gathers one weighted sum by constructing independent forwarding tree which ensures fewer transmissions. MSTP gathers a weighted sum from nodes step by step starting from leaf nodes following the routing paths towards the projection node. Finally, each projection node sends the gathered data in one packet through a shortest path to the sink. The novelty of our approach lies in utilizing independent forwarding trees, where each forwarding tree carries one weighted sum (compressed data rather than native) to the sink. These forwarding trees are constructed to ensure fewer number of transmissions as well as evenly distribute the transmission load across the network. We present our method (MSTP) in more details in Section 5 and then we modify our method and present the extended version (eMSTP) that improves our first method by letting the sink node to gather weighted sums directly from nodes instead of projection nodes; in this way we eliminate the traffic resulting from transmitting the corresponding projection packets from projection nodes to the sink. We present MSTP before eMSTP to show how progressively we improve the lifetime of the network. Later, we compare our method with non-CS, plain-CS and hybrid-CS. Simulation results show that our method MSTP and extended one eMSTP outperform the existing methods in respect to network global communication cost and load balancing.

The rest of the paper is organized as follows. The literature survey on compressive data gathering is presented in Section 2. In Section 3, we characterize our system model. The background of CS, CDG, hybrid-CS and Data Gathering with Sparse Random Projections are presented in Section 4. In Section 5, we describe our methodology follow by numerical results in Section 6. Finally, we conclude the paper in Section 7.

2. Related work

Compressive data gathering (CDG) in wireless sensor networks is both challenging and interesting topic and has been receiving some increased attention in recent littearture. In [12], the authors proposed a compressive sensing technique independent from the routing algorithm. In this method, a routing tree from nodes to the sink