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Toward cluster-based weighted compressive data aggregation in wireless sensor networks

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ABSTRACT

Conventional Compressive Sampling (CS)-based data aggregation methods require a large number of sensor nodes for each CS measurement leading to an inefficient energy consumption in Wireless Sensor Networks (WSNs). To solve this problem, we propose a new scheme in the network layer, called "Weighted Compressive Data Aggregation (WCDA)", which benefits from the advantage of the sparse random measurement matrix to reduce the energy consumption. The novelty of the WCDA algorithm lies in the power control ability in sensor nodes to form energy efficient routing trees with focus on the load-balancing issue. In the second part, we present another new data aggregation method namely "Cluster-based Weighted Compressive Data Aggregation (CWCDA)" to make a significant reduction in the energy consumption in our WSN model. The main idea behind this algorithm is to apply the WCDA algorithm to each cluster in order to reduce significantly the number of involved sensor nodes during each CS measurement. In this case, candidate nodes related to each collector node are selected among the nodes inside one cluster. This yields in the formation of collection trees with a smaller structure than that of the WCDA algorithm. The effectiveness of these new algorithms is evaluated from the energy consumption, load balancing and lifetime perspectives of the network. A comprehensive numerical evaluation is performed which shows that the performance of the proposed WCDA and CWCDA algorithms is significantly better than some existing data aggregation methods such as plain-CS, hybrid-CS and the Minimum Spanning Tree Projection (MSTP) schemes.

1. Introduction

1.1. Background

Wireless Sensor Networks (WSNs) are commonly recognized as a new technology consisting of a large number of independent wireless sensor nodes with a spatial distribution to support a wide variety of applications, including natural environment monitoring, medical services, surveillance and ocean pollution detection [1,2]. In a large-scale proactive WSN, each sensor node performs periodically some operations such as computing, sensing and self-organizing to transmit specific data to the sink node through multiple paths [3]. In such a configuration, sensors are typically powered by limited lifetime batteries, which are hard to be replaced or recharged. Other resource constraints in WSNs are short communication range, low bandwidth, limited processing/storage and in particular, the energy consumption. Energy consumption is mainly addressed in the following three stages: sensing, data processing, and data transmission. Generally, sensing and data processing have less energy consumptions than that of data transmission. Indeed,

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any reduction in the transmission cost can prolong the WSN's lifetime. Thus, minimizing the total energy consumption is of high importance in designing WSNs [4]. Numerous research works have addressed the energy efficiency challenge in WSNs from different perspectives, including energy conserving sleep scheduling [5], topology control [6], mobile data collectors [7], and data aggregation [8]. Central to this study is to deploy proper data aggregation and routing methods in a WSN to enhance both the energy consumption and the network's lifetime with taking the effect of load balancing into account.

With focus on the spatial correlation properties of sensed data in real WSNs, the number of data transmissions can be reduced by compression techniques to achieve a relatively high accuracy of recovery at the sink node. The spatial correlation of sensed data leads to an inherent sparsity of data in a proper basis such as Discrete Cosine Transform (DCT) domain or wavelet domain [9]. This means that a few number of data samples are nonzero or equivalently, a basis can be found in which the sensed data is sparse. To address the sparsity of such signals, Compressive Sensing (CS) theory [10,11] is employed as a newly emerged signal processing technique for efficiently compressing signals and accurately reconstructing of sparse and compressible signals. Unlike the Nyquist criterion, in CS theory, signals can be recovered using much fewer measurements than their original dimensions. More precisely, considering the inherent sparsity features and the spatial correlation of input signals in a correlated WSN, a CS-based data aggregation method forms a random measurement matrix via non-adaptive linear measurements to compress the corresponded data, and then reconstructs these signals through an optimization process [12].

1.2. Related work

In recent years, the attention of researchers has been devoted to utilizing CS-based data aggregation methods to increase the network's lifetime by reducing the amount of data transmissions and balancing the traffic load throughout the whole WSN (e.g. [13–17]). The first study on the decentralized CS-based data aggregation method in WSNs was framed in [13]. The technique in [13] simultaneously computes random measurements of the sensed data and broadcasts them throughout the network using a simple gossiping algorithm. This line of work was further expanded in [14] by incorporating an efficient Compressive Data Aggregation (CDA) method to improve both transmissions cost and the network's lifetime in large-scale WSNs. The authors in [14] analyze the network's capacity using the CDA method and prove that the capacity is proportional to the sparsity level of sensed data. In this method, the total data transmissions are decreased only when the number of required measured samples is small enough. Nevertheless, it is shown numerically in [14] that an increase in the number of measured samples leads to an increment in the number of network's transmissions when compared to the non-CS method. Reference [15] introduces an adaptive data aggregation method which applies CS on the local spatial correlation among data of neighboring sensor nodes. In [16], the authors propose a CS-based data aggregation scheme to reconstruct data at the sink node. The results show that the proposed data aggregation method depends on the network's structure, while the compression matrix design is related to the sensed data. However, the scheme in [16] cannot automatically match the features of complex spatio-temporal correlation data. Reference [17] introduces a hybrid-CS data aggregation algorithm to achieve a high throughput in a WSN. The authors in [17] claim that since the measurement matrix is not sparse enough, applying a plain-CS may not yield a significant improvement in the throughput, while, it can result in a high throughput in the hybrid-CS method.

So far, the interaction between routing and CS-based data aggregation has been a barrier toward the progress in the field of energy consumption in WSNs [18,19]. These techniques utilize both routing and CS-based data aggregation methods to reduce the data traffic. In [18], the authors present a CS-based scheme which considers both routing and compression methods to minimize the energy consumption required for data collection in a WSN. However, this study does not consider the minimization of the energy consumption for transmission of each CS measurement. Most recent data aggregation methods which rely on dense random measurements have not highlighted this fact that a large number of elements in the random measurement matrix may be zero. Reference [20] addresses this issue and proposes a distributed sparse random measurement by which the significant information of a compressible signal can be reconstructed. The authors in [20] claim that each CS measurement only needs a combination of some sensed data instead of using all of them. In addition, it is shown in [20] that using the sparse random measurement considerably reduces the energy consumption of WSNs. However, the transmission cost in the gathering process of measured samples in multi-hop WSNs is not considered in this study. Routing and CS are also jointly addressed in [21] in which the routing path is iteratively built through a greedy choice to minimize the coherence measurements error. Since, the proposed routing paths are not the shortest ones, additional transmission cost would be imposed on the network. It is shown in [22] that the data compression capability of sensor nodes and the routing strategy affect the transmission cost of the network. Since both schemes in [21,22] are based on sparse random measurements, they improve the energy consumption of WSNs. However, these methods suffer from the fact that the formation of routing trees in collecting of each CS measurement is not optimal, and this degrades the energy efficiency of WSNs. Reference [23] addresses this issue and proposes the Minimum Transmission data aggregation Tree (MTT) which forms a spanning tree based on the CS measurement matrix. Every node shares its sensed data for CS measurements only in a couple of times using the sparse random measurement matrix. The proposed algorithm in [23] forms the data aggregation tree based on the shortest path and the number of times that the nodes transmit their own data. Reference [24] proposes a tree-based energy efficient routing method to reduce the energy consumption of the WSN by considering the sensor transmission range and the probability of occurrence of non-zero elements in the measurement matrix. Following the same model as in [20], the authors in [25] introduce the Minimum Spanning Tree Projection (MSTP) which incorporates a compressive data aggregation method and the sparse random measurement to reduce the number of