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Compressive sensing and random walk based data collection in wireless sensor networks

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ABSTRACT

Data collection is one of the most important research topics in wireless sensor networks. Compressive sensing can break through the classical Shannon–Nyquist boundary and reduce the total energy consumption. Random walk technology has a significant advantage in the energy balance. Random walk based compressive sensing data collection mechanism is a combination of these two technologies, which reinforce complementary advantages. However, the traditional scheme faces two challenges, i.e., large transmission energy consumption caused by the overlong multi-hop transmission path and the low recovery accuracy caused by poorly designed compressive sensing measurement. In this paper, we propose a ring topology based compressive sensing data collection scheme (RTCS). The total number of hops is reduced by a ring topology based random walk. The recovery accuracy is improved by the dual compensation based compressive sensing measurement. The theoretical analysis, as well as the experimental evaluation obtained from two different network deployment environments, demonstrates that the proposed scheme can achieve the performance superior to the most closely related work.

1. Introduction

In recent years, wireless sensor networks (WSNs) are widely adopted in military, civil and commercial applications. An important function of WSNs is data collection, namely each node collects its sensor data, and transmits it to the sink in a multi-hop mode. In WSNs, nodes are usually equipped with batteries. Due to the complexity of the deployment environment, recharging is impractical (impossible or not worth it). As a result, how to achieve energy efficiency and prolong the network life cycle is one of the crucial research topics of data collection scheme.

Compressive sensing (CS) is a new technology, which integrates data acquisition and data compressive together. By exploiting the sparsity or compressibility of signal, it breaks through the boundary of the classical Shannon–Nyquist theory, and thus can achieve high precision of data recovery through fewer samples. In recent years, many CS-based data collection schemes have been put forward [1,2]. In these schemes, the sensor data is multiplied with some coefficients before transmitting to the sink through a specific routing path. The sink reconstructs the original data of each node by using these received measurement results, where the measurement matrix adopted in the recovery process is the same as that in the measurement process.

However, traditional CS-based data collection schemes have their own shortcomings. CS was originally developed for the efficient storage and compression of digital images. The condition under which CS performs well is not necessarily met in WSNs [3,4]. Wang et al. [5] and Sartipi and Fletcher [6] did not agree to apply CS on WSNs directly, because the inter-communications for generating each projection are too huge. For example, some schemes [7–9] use dense random matrix projection, which increases the communication overhead between nodes, and thus reduce the effectiveness of CS in WSNs. Some schemes [10,11] introduce sparse sample to reduce the amount of traffic, but in order to achieve a uniform and random measurement, they require accurate routing algorithm.

Random walk (RW) is an efficient routing method, which does not require global information. Each node on the RW path randomly selects its next hop node from its neighbors, without precise routing control. This random jump mechanism can achieve local load balancing effectively. Compared with traditional tree or cluster based structure, it can prolong the life cycle of networks [4].

Random walk based compressive sensing (RWCS) data collection schemes [3,4] integrate CS and RW to achieve complementary advantage, and effectively alleviate the shortage of traditional CS scheme. By linear combining sensor data of nodes along the RW path, it achieves

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efficiently sparse sampling measurement. Compared with traditional CS-based data collection scheme, RWCS data collection scheme can effectively reduce communication overhead. In the multi hop transmission process of random walk, each node randomly selects its next hop node from the candidate list which contains more than one node. It achieves local energy balance, and reduces the dependence on a few bottleneck nodes, so as to extend the network life cycle.

However, there are many problems in the traditional RWCS data collection schemes. For example, they usually have long multi hop measurement path and transmission path, which lead to excessive energy consumption. At the same time, the unbalanced energy distribution of the RW measurement matrix may decrease the recovery performance. More detail analysis of RWCS data collection scheme will be given in Section 3.

In order to solve the problems existing in the traditional RWCS data collection schemes, we propose a ring topology based compressive sensing data collection scheme (RTCS). In this scheme, a ring topology based random walk is proposed, which can provide direction guidance for RW when there is no location information (e.g., GPS) of nodes. Each hop randomly selects a node which is closer to the sink, and performs compressive sensing. The random walk based compressive sensing measurement and the measurement result transmission are integrated together, which can reduce the total transmission overhead. The proposed scheme improves the quality of the measurement matrix and then enhances the accuracy of data recovery by using a dual compensation scheme.

The main contributions of this paper are summarized as follows:

- We analyze the traditional RWCS data collection scheme and present the reasons for its high transmission cost problem and low recovery precision problem.
- We propose a ring topology based random walk. With the assistance of the ring topology, we can provide direction information for the random walk in the absence of location information of nodes, and thus effectively reduce the multi hop transmission overhead by controlling the random walk path length.
- We propose a compressive sensing data collection scheme based on random walk over ring topology. It integrates the random walk measurement with the measurement result transmission, and thus reduces measurement cost and transmission cost.
- We also present a dual compensation compressive sensing scheme. The scheme improves the quality of the measurement matrix by using energy compensation and non-uniformity compensation, so as to enhance the recovery performance of compressive sensing.

The remainder of this paper is organized as follows. Section 2 introduces the basic theory of compressive sensing and random walk. Section 3 analyzes the problems of the traditional RWCS data collection scheme. Section 4 presents the proposed scheme. Sections 5 and 6 are the theoretical analysis and experimental evaluation of the proposed scheme, respectively. Sections 7 and 8 are related work and conclusions.

2. Preliminaries

In this section, we present a brief overview of compressive sensing and random walk.

2.1. Compressive sensing

Compressive sensing consists of two parts: compressive sensing measurement and compressive sensing recovery.

The compressive sensing measurement of signal $x \in R^{N\times 1}$ can be expressed as $y = \phi x + e$, where $y \in R^{M\times 1}$ is the measurement result, $\phi \in R^{M\times N}$ is the measurement matrix, and $e \in R^{M\times 1}$ is measurement error. According to CS theory, signal x should be sparse represented on a specific basis, $x = \psi\theta$. General basis includes wavelet transform basis and Fourier transform basis. For sparse signals, it satisfies $||\theta||_0 \ll N$. For compressible signals, it satisfies $|\theta(i)| < Ci^{-\frac{1}{p}}$, where $p \le 1$, and $c < INF$. The measurement process of compressive sensing can be further expressed as $y = A\theta + e$, where $A = \phi\psi \in R^{M\times N}$ is the sensing matrix.

The compressive sensing recovery is equivalent to solving the following optimization problem:

$$\min \ ||\theta||_0 \quad s.\ t.\ \ ||A\theta - y||_2 \le \varepsilon,$$

where ε is the estimation of measurement error. However, this is a NP-hard problem. In practice, it is usually converted into the following optimization problem.

$$\min \ ||A\theta - y||_2 + \lambda||\theta||_p,$$

where $0 < p \le 1$ and $\lambda > 0$. When $p = 1$, it is a convex optimization problem, which is usually called the least absolute shrinkage and selection operator (LASSO). When $0 < p < 1$, it is a non-convex optimization problem, however, we can still get a good approximate solution.

2.2. Random walk

In the random walk process, each node of the path randomly selects its next hop from its neighbor node list. The random walk process can be modeled as a Markov chain [12,13]. The Random walk process randomly jumps from one node to another according to the transition probabilities matrix $P = [p_{ij}]_{N\times N}$, where p_{ij} represents the transition probability that from node i to node j. For a given graph $G = \{V, E\}$, where V is the vertex set, E is the edges set, p_{ij} can be defined as,

$$p_{ij} = P(s_{k+1} = j|s_k = i) = \begin{cases} \frac{1}{degree(i)} & (i, j) \in E \\ 0 & (i, j) \notin E \end{cases}$$

3. Problems of traditional RWCS data collection scheme

In this section, we will take the latest work [4] as an example to introduce the traditional RWCS data collection scheme. Two versions of RWCS data collection scheme are presented in [4], i.e., D-CSR and M-CSR. D-CSR assumes that all nodes can communicate directly with the sink, which is difficult to be satisfied in most ad-hoc networks. In addition, according to its analysis results, the communication cost of D-CSR is much greater than that of M-CSR. Therefore, in following sections, if there is no special explanation, the traditional RWCS data collection scheme represents M-CSR.

As shown in Fig. 1, the traditional random walk based compressive sensing measurement consists of two steps, one is the compressive sensing measurement alone the random walk (Fig. 1, solid line path), and the other is the upload process of measurement results along a

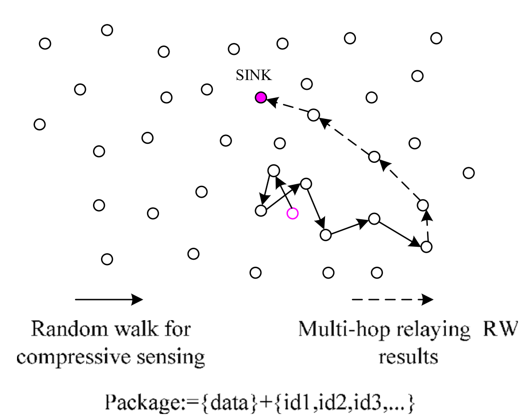

Fig. 1. Traditional RWCS data collection scheme (M-CSR).