Computer Communications 32 (2009) 1820–1828

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Topology control for delay-constraint data collection in wireless sensor networks

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ARTICLE INFO

Article history:
Received 29 October 2008
Received in revised form 1 July 2009
Accepted 2 July 2009
Available online 8 July 2009

Keywords:
Wireless sensor networks
Delay
Topology control
Energy efficient
Data collection

ABSTRACT

Data collection is one of the most important operations in wireless sensor networks. Many practical applications require the real-time data transmission, such as monitoring, tracking, etc. In this paper, we import and define the topology control problem for delay-constraint data collection (*TDDC*), and then formalize this problem into an integer programming problem. As NP-Hardness of this problem, we present a load-aware power-increased topology control algorithm (namely *LPTC*) to heuristically solve the problem. The theoretical analysis shows that this algorithm can reach O(1)-approximation ratio for the linear networks. And we also analyze the impact of the delay-constraint on the worst-case for the planar networks. Moreover, this paper designs two localized algorithms, called as *SDEL* and *DDEL*, based on the area division for *TDDC* problem. The experimental results show that *LPTC* algorithm can save at least 17% power consumptions compared with *HBH* algorithm in many situations.

1. Introduction

Wireless sensor networks (WSNs) are usually resource-constraint, such as power provision, computation capacity and bandwidth [1,2]. Thus, energy-efficient protocols or algorithms could help to prolong the lifetime of sensor networks. In general, wireless communication consumes much more power than other operations in sensor networks, such as sensing, signal processing and computation, etc. Thus, source nodes often transmit their data to the destination nodes through several short-range wireless links instead of a few longer ones to save the energy. The advantage of this strategy is that it can reduce the power consumption on data transmission greatly. However, this mechanism results in increasing of transmission delay through the data transferring.

Wireless sensor networks can be widely used in many fields. And a lot of practical applications require the packet to be delivered within a certain deadline, thus cannot tolerate the heavy communication delay. Consider an application of sensor network to monitor the nerve gas attacks in the battle-field [3]. As soon as a sensor node detects the presence of the poisonous gas, it should immediately report the relevant information, such as the gas concentration level and its geographical location, to the monitoring center. Topology control [4] is a feasible way to meet the trade-off between the power consumption and the real-time requirement in sensor networks. Intuitively, the nodes can transmit the data packet to the distant neighbor by increasing the transmission power. As a result, the data will be relayed to the base station or sink node in fewer hops incurring a lower delay, albeit at the higher energy cost. Therefore, this paper studies the trade-off between the total energy consumption and delay during the multi-hop data transmission.

In the monitoring network, each node will report the sensed data to the sink node periodically. There are usually two processing methods for this kind of *All-to-One* communication scheme. One is with the data aggregation, in which several packets can be combined into one packet with the same length through the fusion function. The other is without data aggregation, also called as data collection. Though data aggregation method can save the power consumption by reducing the number of transmitted packets, this scheme would be inapplicable in many practical applications. For example, in the safety monitoring network, each sensor node will send the data or multimedia information to the control center. In many applications of sensor networks, the historical information of each node should be capable of being retrieved by system managers and users. Obviously, this requirement can be easily realized under the data collection scheme. For its wide applications, we mainly study the energy-efficient real-time data collection for wireless sensor networks.

In this paper, we investigate the topology control for delay-constraint data collection problem in wireless sensor networks. For simplicity, transmission delay is measured by the hop-counts from the source node to the destination node [5,6]. Therefore, given a delay-constraint T of hops, the task of the problem is to assign each node a transmission power or a transmission distance, such that each node can construct a path to the sink node within T hops.

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doi:10.1016/j.comcom.2009.07.002

As we know, the traffic load and transmission power are two main factors that will affect the energy consumption on each node. Thus, we assume that each node generates the same amount of sensed data periodically, denoted as one unit. So, the objective of the algorithm is to minimize the total energy cost of all transmitting nodes under the delay-constraint.

Although some previous solutions focus on the heuristic algorithms for real-time routing [17,18] or real-time data aggregation problem [6,7], these algorithms do not fit well for the data collection problem. Because all the nodes will participate in the data collection and different sensor nodes have the various traffic loads. The main contribution of this paper is to define the topology control for delay-constraint data collection problem in wireless sensor networks, and formalize it into an integer programming problem. As NP-Hardness of this problem, we propose a load-aware power-increased topology control algorithm (namely *LPTC*). The theoretical analyses show that this algorithm can reach O(1)-approximation ratio for the linear networks. We also analyze that the power consumption of the proposed algorithm is about $O\left(\left(\frac{D}{T}\right)^{\alpha-1}\right)$ times as that of the optimal case without delay-constraint, where *D* is the depth of the spanning tree for the arbitrary graph using Dijkstra algorithm, *T* is the constraint hop-count, and is a constant determined by the hardware and environments. Moreover, two localized algorithms, *SDEL* and *DDEL*, are designed based on the area division for *TDDC* problem. The experimental results show that the proposed algorithms can acquire the effective performance of power consumption under the delay-constraint. For example, *LPTC* algorithm reduces about 17% energy cost by comparing with *HBH* algorithm under the same network configuration and constraint conditions.

The rest of the paper is organized as follows. In Section 2, we discuss the related works and place our work in their contexts. In Section 3, we introduce the network model, define *TDDC* problem, and formalize it into integer programming. And the NP-Hardness of *TDDC* problem is proved in Section 4. Section 5 proposes a heuristic algorithm to solve *TDDC* problem, and analyzes the approximation performance for the linear networks and planar networks, respectively. In Section 6, we design two localized algorithms for *TDDC* problem. Section 7 evaluates the performance through simulations under the various network configurations. We conclude the paper with a brief discussion on the future work in Section 8.

2. Related works

In recent years, topology control problem becomes an important topic in wireless ad hoc and sensor networks, for it can greatly decrease the power consumption while preserving some significant properties. Most of the works have been focused on the construction and maintenance of a network topology under the different requirements by the minimum power assignment. Lieyed et al. [8] gave a summary of the related work for topology control problem. They used a 3-tuple $< \mathrm{M}, \mathrm{P}, \mathrm{O} >$ to represent the topology control problem formally, where M, P, and O denoted the network graph model, the required topology properties and the objectives, respectively. The NP-Completeness of this problem was proved, and several algorithms were also proposed. Ramanathan [9] presented two centralized optimal algorithms to generate the connected network while minimizing the maximum transmission power of all nodes. Additionally, two distributed algorithms were designed for adaptively adjusting the node's transmission power to maintain a connected topology in response to the topological changes. But, these methods could not guarantee the connectivity of the network. Thus, Li et al. [10] proposed a *MST*-based algorithm that could assure the connectivity with minimal power consumption. A distributed cone-based method was developed in [11]. Basically, each node gradually increased its transmission power until it found a neighboring node in every cone of its communication area. As a result, the global connectivity was ensured with minimal power for each node. Marsan et al. [12] presented a method to optimize the topology of Bluetooth, which aimed to minimizing the maximum traffic load of nodes. Though the topology control methods can save the energy greatly, the delay will be rapidly cumulated in the multi-hop transmission.

For the delay requirement, there are some researches on real-time routing for wireless ad hoc networks. He [18] proposed a delay-minimum energy-aware routing protocol (*DERP*) for real-time communication. As this protocol was based on the *DFS* tree, the maximal hop number from each sensor node to the sink was minimized. Akkaya and Younis [21] suggested an energy-aware routing protocol to deliver the data within a bounded delay in the WSNs. The proposed mechanism built up the energy-aware multi-hop paths with a certain *end-to-end* delay-constraint. Also, a Weighted Fair Queuing (*WFQ*) packet scheduling technique was employed for online forwarding. Chipara et al. [20] designed the *RPAR* protocol, which consisted of four components: a dynamic velocity assignment policy, a delay estimator, a forwarding policy, and a neighborhood manager. The *RPAR* method mainly used the velocity assignment policy to map a packet's deadline to a required velocity. Habib et al. [19] presented an approach that characterizes the trade-off between energy and delay. The authors divided the transmission range of sensors into concentric circular bands (*CCBs*). And this provided a classification of the *CCBs* that helped a sensor express its degree of interest in minimizing two conflicting metrics, namely energy consumption and delay.

The real-time routing problem mainly focuses on the delay-constraint point-to-point communication, while the most related works with *TDDC* problem is real-time data aggregation (*RTDA*), which is just Hop-bounded Minimum Spanning Tree (*HBMST*) problem. Alfandari et al. [13] proved that this problem was NP-Hard even when the edge weight was Euclidean distance and the hop constraint was 2. Ernst et al. [14] proposed an algorithm to compute a feasible-Hop spanning tree with expected cost $O \log n$ times of the optimal case, where was the number of the vertex in the graph. Jia et al. [15] defined the Qos-aware topology control problem which toke the bandwidth and delay-constraints into consideration. This problem was formalized into an integer programming problem, but the authors did not provide an efficient method for this problem. Cheng et al. [6] studied the delay-degree-bounded data aggregation problem, and presented three heuristic algorithms to solve this problem. Xu et al. [3] presented a heuristic algorithm for delay-constraint data aggregation problem, and analyze the impact of the delay-constraint for the worst performance. Yu et al. [7] presented a packet scheduling for *RTDA* problem. But this algorithm was based on the different delay assumption from others [5,6,13–15].

We observe that the previous works scarcely focus on the *TDDC* problem. Though the related works for the real-time data aggregation can also be used to solve the *TDDC* problem, these algorithms cannot obtain the satisfied performance for *TDDC* problem. That is because the previous works do not care for the different traffic loads on all nodes. Moreover, it also lacks of the theoretical analyses for the *TDDC* problem.

3. Preliminaries

3.1. Network model

The sensor network usually consists of a sink node and a set of sensor nodes. We assume that all sensor nodes are static and power-constraint. Moreover, each sensor node can communicate