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Spanning tree based topology control for data collecting in predictable delay-tolerant networks

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ABSTRACT

In predictable delay tolerant networks (PDTNs), the network topology is known a priori or can be predicted over time such as vehicular networks based on public buses or trains and space planet network. Previous DTN research mainly focuses on routing and data access. However, data collecting are used widely in PDTNs and it is very important in practical application, how to maintain the dynamic topology of this type of PDTNs becomes crucial. In this paper, a spanning tree (ST) based topology control method for data collecting in PDTNs is proposed. The PDTN is modeled as layered space-time directed graph which includes spatial, temporal and energy cost information, which can be simplified as reduced aggregated directed graph. The topology control problem is defined as constructing a ST that the total energy cost of the ST is minimized and the time delay threshold is satisfied. We propose three heuristic algorithms based on layered space-time directed graph and reduced aggregated directed graph to solve the defined problem, and compare them in terms of energy cost and time delay. Extensive simulation experiments demonstrate that the proposed algorithms can guarantee data transmission effectively, reduce the network energy consumption significantly, and shorten the time delay of data transmission.

1. Introduction

Topology control has been studied widely in wireless ad hoc and sensor networks, which can maintain network connectivity while minimizing the energy consumption and reducing radio interference. A lot of methods have been proposed, for example, graph-based methods, hierarchical structure based methods, social network analysis based methods, probabilistic-based methods, and etc.

Recently, with the widely application of wireless devices in challenging environment, such as battlefield reconnaissance, search-and-rescue, and satellite communications, delay/disruption tolerant networks (DTNs) [1,2] emerge as a good complement to the traditional wireless ad hoc and sensor networks. Due to the harsh surrounding and the mobility of devices, DTNs are not always connected, and the data is delivered in a long delay. Therefore, how to ensure the data can be transmitted to the destination is very important. Many routing protocols for DTNs have been proposed to transmit data from the source to the destination by utilizing opportunistically existing and time varying routing paths. Most of them use some kinds of redundancy and exploit routing opportunity greedily, which may lead to unnecessary resource consumption.

In general, topology control can avoid extra resource consumption in data transmitting. It is also true in DTNs, especially for predictable DTNs [3], in which the network topology is known a priori or can be predicted over time. In PDTNs, a cyclic time Ct exists, and in each Ct, the network topology changes are identical. Pocket switched networks based on human mobility [4,5], vehicular networks based on public buses or taxi cabs [6,7], mobile social networks [8,9], disaster-relief networks, and space communication networks [10–12] are all PDTNs. Instead of trying to using all possible transmitting opportunities, topology control mechanism can select certain transmitting opportunities to delivery data in such network to satisfy the reliability/delay requirement with lower resource consumption, especially energy consumption.

However, using the existing topology control mechanisms to DTNs directly is not feasible because the topology of DTNs is time evolving and the routing paths intermittently exist. As far as we know, only Huang et al. [13–15,35] studied topology control in PDTNs. They took the temporal characteristic into consideration and model PDTN as a directed space-time graph which includes both spatial and temporal information. Two greedy-based methods were proposed to find a routing sub-graph from the directed

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space-time graph. The goal is to ensure each pair of nodes can communicate under certain reliability with the least energy consumption.

Data collecting are the dominant applications in most PDTNs, which means many to one are the most frequently used communication patterns. In this paper, we focus on the topology control issues in these kinds of network. A tree based topology control mechanism is proposed to satisfy the performance requirement while minimizing the energy consumption. Our major contributions are summarized as follows:

(1) The PDTNs for data collecting are modeled as layered space-time directed graph, and then re-formed as reduced aggregated directed graph. The topology control issue is defined as finding the spanning tree (ST) of such a graph.
(2) Heuristic algorithms are proposed to find the spanning tree.
(3) The constructed ST can minimize the energy consumption of data collection with the certain delay constraint.

The rest of this paper is organized as follows. In Section 2, we summarize related works in topology control and PDTNs. In Section 3, tree based topology control problem and model are defined. Section 4 describes the details of the heuristic algorithms proposed in this paper. Section 5 presents the simulation results of the proposed algorithms. Finally, Section 6 concludes the paper and points out future research directions.

2. Related works

2.1. Topology control in ad hoc and sensor networks

Topology control is very important in ad hoc and sensor networks, because it can save energy and reduce the interference of the network. It can effectively prolong the life time of the network and improve the success rate of data transmission. Among many methods proposed for topology control, constructing Minimum Spanning Tree (MST) to reduce the edges of original topology is a simple and effective method. Many researchers have drawn a significant amount of research interests on it recently.

In literature [16,17,20,21,23], they are all explore MST method for topology control. Sun et al. [16] and Li et al. [20] proposed the algorithms that each node builds its local minimum spanning tree (MST) respectively based on the energy-aware weighted graph and keeps on-tree nodes that are one-hop away as its neighbors in case the network topology adjusted. Chee-Wei and Chen-Khong [17] presented an algorithm, iMST, attempting to maximize average channel utilization by reducing interference. This algorithm not only generates k-edge-connected networks, but also guarantees minimum link bandwidth. Li et al. [21] proposed a family of structures, namely, k-localized minimum spanning tree (LMSTk) for topology control and broadcasting in wireless ad hoc networks. They give an efficient localized method to construct LMSTk using only O(n) messages under the local-broadcast communication model, i.e., the signal sent by each node will be received by all nodes within the node's transmission range. Chen et al. [23] proposed an improved variable-range transmission power control algorithm based on minimum spanning tree algorithm (MST) for mobile ad hoc network, and it support node's mobility and solve asymmetric graph problem.

In addition to the above, there is also has some other methods for topology control in terms of other aspects. For example, Xing et al. [18] proposed a new topology control formulation for lossy WSNs. Their formulation captures the stochastic nature of lossy links and quantifies the worst-case path quality in a network. They develop a novel localized scheme called configurable topology control (CTC). The key feature of CTC is its capability of flexibly configuring the topology of a lossy WSN to achieve desired path quality bounds in a localized fashion. Furthermore, CTC can incorporate different control strategies (per-node/ per-link) and optimization criteria. Qing and Jie [19] proposed three different algorithms, binary search, Prim's MST and its extension, to solve power conservation issue for ad hoc wireless networks, which can find the minimum uniform transmission power of an ad hoc wireless network where each node uses the same transmission power. And network connectivity is maintained. Zhang et al. [22] proposed DSPT, a more efficient topology control algorithm than traditional MST-based algorithms for WSN. A single destination shortest path tree rooted from sink node was build to minimize the power consumption. Tapiwa et al. [32] present a new distributed topology control technique that enhances energy efficiency and reduces radio interference in wireless sensor networks. Each node in the network makes local decisions about its transmission power and the culmination of these local decisions produces a network topology that preserves global connectivity. Central to this topology control technique is the novel Smart Boundary YaoGabriel Graph (SBYaoGG) and optimizations to ensure that all links in the network are symmetric and energy efficient. Fadoua et al. [36] explore the energy-aware topology control in wireless ad hoc networks by formulating and solving the corresponding optimization problem. They propose an ILP formulation that minimizes the total transmission power needed by nodes to construct a topology that can meet Quality of Service (QoS) requirements between source and destination node pairs with less computational effort. Hakki et al. [38] present a distributed fault-tolerant topology control algorithm, called the Disjoint Path Vector (DPV), for heterogeneous wireless sensor networks composed of a large number of sensor nodes with limited energy and computing capability and several super nodes with unlimited energy resource.

All of these topology control methods deal with topology in wireless sensor networks or ad hoc networks. For the topology changes in ad hoc networks, most algorithms explore re-perform algorithm method. Fortunately, many construction algorithms are localized or distributed algorithms, therefore the update cost is not expensive. However, all of the methods assume that the underlying communication graph is fully connected and they do not consider the time delay and the network changes with time evolving.

2.2. Routing in DTNs

Recently, many researches focus on DTN routing, most of the routing protocols belong to two categories: social-based and prediction-based. In social-based routing protocols, they usually use the social properties as the determinants for routing. Zhu et al. [24] summarized the social properties in DTNs, and provide a survey of recent social-based DTN routing approaches. And they classified social-based DTN routing approaches as positive and negative routing according to the social characteristics. Cao et al. [25] proposed a multi-dimensional routing protocol (MDimension) for the human associated delay-tolerant networks which uses local information derived from multiple dimensions to identify a mobile node more accurately.

Prediction-based routing protocol is based on the prediction of network according to the historical or other known information. Specifically, in PDTNs, this method is used widely. In literature [4,5], they use human mobility for forwarding in pocket switched networks. Cao et al. [26] proposed geographic routing in DTNs, which estimates the movement range of the destination using its historical geographic information, promotes message replication reaching the edge of this range using a Reach Phase and spreading within this range using a Spread Phase. Tournoux et al. [27] proposed an adaptive variant of the spray-and-wait algorithm DA-SW (Density-Aware Spray-and-Wait) to exploit the accordion phenomenon and tune the dissemination effort to respond adequately