Ad Hoc Networks 24 (2015) 147–159

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Topology control for predictable delay-tolerant networks based on probability

Hongsheng Chen [a,b], Ke Shi [a,*]

[a] College of Computer Science and Technology, Huazhong University of Science and Technology, Wuhan 430074, China
[b] College of Computer Science and Technology, Hubei University of Science and Technology, Xianning 437005, China

ARTICLE INFO

Article history:
Received 25 July 2013
Received in revised form 8 August 2014
Accepted 22 August 2014
Available online 30 August 2014

Keywords:
Predictable delay tolerant networks
Connection probability
Topology control

ABSTRACT

In wireless networks, topology control can improve energy effectiveness and increase the communication capacity. In predictable delay tolerant networks (PDTNs), intermittent connectivity, network partitioning, and long delays make most of the researchers focus on routing protocol, and the research on topology control is in the very early stage. Most existing topology control approaches for PDTN assume the underlying connections are deterministic, which excludes a large amount of probabilistic connections existing in the challenged environments. In this paper, probabilistic connections are taking into consideration. The predictable delay tolerant networks are modeled as a three dimensional space–time weighted directed graph which includes spatial, temporal and connection probability information. The topology control problem is formulated as finding a sub graph to balance the energy cost and data transferring reliability. This problem is proved to be NP-complete, and two heuristic algorithms are proposed to solve the problem. The first one is to find a sub graph that assures the maximum connection probability between each pair of nodes. The other one is to find the sub graph in which the connection probabilities between each pair of nodes satisfy the given threshold with the minimum energy cost. Extensive simulation experiments demonstrate that the proposed topology control algorithms can achieve our goal.

1. Introduction

In recent years, Delay/Disruption Tolerant Networks (DTNs) [1] have attracted more and more researchers' attention [2]. Predictable Delay/Disruption Tolerant Networks (PDTNs) is a kind of DTNs whose topology is known a priori or can be predicted over time, such as pocket switched networks based on human mobility, vehicular networks based on public buses or taxi cabs, and space satellite networks.

Due to the characteristics such as intermittent connectivity, partitioned network, long delays and node mobility, the DTNs/PDTNs are not fully connected and the topology dynamically changes over time. How to transmit data between each pair of nodes successfully is a challenging problem, which makes many researchers focus on routing protocols [3–9].

Topology control has been studied widely in wireless ad hoc and sensor networks, which can maintain network connectivity while reducing the energy cost and radio interference. In general, topology control can avoid extra resource consumption of data transmitting. It is also true in DTNs, especially PDTNs. Instead of trying to using all possible transmitting opportunities, topology control mechanism can select certain transmitting opportunities

---

[*] Corresponding author. Tel.: +86 27 87558592.
E-mail addresses: chenhs1981@163.com (H. Chen), keshi@mail.hust.edu.cn (K. Shi).
URL: http://cs.hust.edu.cn (K. Shi).

http://dx.doi.org/10.1016/j.adhoc.2014.08.014
1570-8705/

to delivery data in such network to satisfy the reliability requirement with lower resource consumption.

However, using the existing topology control methods to PDTNs directly is not feasible because the topology of PDTNs is time evolving and the routing paths intermittently exist. Some researches on routing protocol mentioned above considered dynamic topology and intermittent connectivity to make better routing decision to maximize the data delivery while maintain a reasonable resource cost.

Temporal characteristic is not considered in all these solutions. Huang et al. [10] takes the temporal characteristic into consideration and model PDTNs as a directed space–time graph including spatial and temporal information. The topology control problem is formulated as finding a sub graph. However, they assume the underlying connections are deterministic.

In practical wireless environments, transitional region phenomenon exists [11,12]. Beyond the ”always connected” region, there is a transitional region where a pair of nodes may probabilistically connect. The links between such pairs of nodes is called lossy links. The lossy links provide probabilistic data transmission, which means the nodes connected by them are not fully connected but reachable. It has been reported that in the wireless network, especially DTN, the number of lossy links are much more than the number of fully connected links. It has been proved that utilizing lossy links appropriately can reduce the energy cost and improve the data delivery chance [13,18,19,21].

If the underlying links are deterministic, the connection between a pair of nodes either exists or not. However, considering lossy links will make the connection between a pair of nodes exists probabilistically. The quality of connection needs to be evaluated to get better transferring paths. The Quality of Connectivity (QoC) is used to evaluate the quality. It measures how easily and reliably a packet can be sent between a pair of nodes in a network. It complements the use of capacity to measure the quality of a network in saturated traffic scenarios and provides a native measure of the quality of end-to-end network connections. The QoC is calculated as the connection probability between a pair of nodes in the network. An example is shown Fig. 1, obviously its value depends on the topology and underlying link qualities. In Fig. 1, the number beside the direct edge represents the corresponding link probability, the connection probability of each pair of nodes can be calculated by inclusion–exclusion principle of probability theory. For example, the QoC indicating the quality of connection between V_0 and V_3 in case (a) is $\mathrm{QoC}_a = 0.9 * 0.8 * 0.95 = 0.684$ since there is only a serial three hop connection. The connection probability is simply the product of underlying link probabilities. In case (b), there are two parallel connections between V_1 and V_3, either of these connections can be used to transfer, which leads to higher QoC value, $\mathrm{QoC}_b = 0.9 * (1 - (1 - 0.8 * 0.95) * (1 - 0.9)) = 0.8784$. In case (c), there are two parallel connections between V_0 and V_2. Similar with case b, either of these connections can be used to transfer, which leads to higher QoC value, $\mathrm{QoC}_c = (1 - (1 - 0.8) * (1 - 0.9 * 0.8)) * 0.95 = 0.8968$. Obviously, case (b) and (c) are better than (a) since multiple paths exist (see Fig. 1).

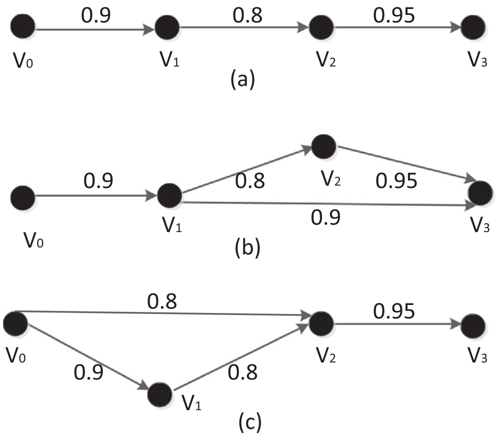

Fig. 1. An example of calculating the QoC.

Our approach optimizes the tradeoff between the energy cost and connection quality by making use of lossy links. The goal is to ensure the connection probability of each pair of nodes is maximized or reach a certain threshold with the minimum energy cost. Our major contributions are summarized as follows:

(1) We model PDTNs as a three dimensional space–time weighted directed graph, which include lossy links. The topology control problem is defined as constructing a sub graph(minimum cost sparse structure) from the original three dimensional space–time graph such that: maximizing connection probability of each pair of nodes, or satisfying the given connection probability threshold with lower energy cost. We also prove this problem is NP-complete.

(2) We propose two heuristic topology control algorithms. The first one is to find a sub graph that assures the maximum connection probability between each pair of nodes. The other one is to find the sub graph in which the connection probabilities between each pair of nodes satisfy the given threshold with the lower energy cost.

(3) Extensive simulation experiments demonstrate that the proposed algorithms can provide a certain data transferring reliability with lower energy cost.

The remainder of the paper is organized as follows. Section 2 reviews related work. In Section 3, we describe the three dimensional space–time weighted directed graph model and define the topology control problem. In Section 4, two heuristic algorithms proposed in this paper are described. Section 5 discusses the simulation results. Finally, Section 6 concludes the paper and discusses the future directions.

2. Related work

Topology control has been studied widely in ad hoc and sensor networks. The aim of topology control is to maintain network connectivity with the least energy cost. Most