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Fast track article

Impact of source counter on routing performance in resource constrained DTNs

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ABSTRACT

We study routing schemes for Disruption Tolerant Networks (DTNs) where transmission bandwidth is scarce. In such a setting, a key issue is how to schedule the transmission of packets under limited bandwidth to optimize performance. Such a scheduling consists of source control (i.e., source nodes choosing a routing scheme) and the local transmission scheduling performed by each node. Existing works typically focus on transmission scheduling and buffer management aspects, but due to theoretical and practical difficulties, only heuristics have been proposed. In this work, we explore an alternative way to improve DTN routing performance via source control. We first show through simulation that for spray-and-wait routing scheme where the source node specifies the maximum allowed number of copies of a packet in the network, there exists an optimal counter value that achieves the minimum network-wide average packet delivery delay. Then as a first step towards understanding multi-hop multi-copy DTN routing schemes such as spray-and-wait scheme, we perform modeling study of two-hop single-copy scheme and two-hop multi-copy scheme under various transmission scheduling schemes, via queuing network analysis and continuous time Markov chain model analysis. Our modeling analysis provides insights into the impact of source counter on routing performance and further suggests the existence of an optimal counter value. Relying on the insights gained via simulations and modeling studies, we propose an adaptive scheme where nodes adjust their counter values to achieve minimum packet delivery delay, in a distributed and asynchronous fashion. Simulations demonstrate the effectiveness of our scheme and suggest the potential of exploring this rich area for improving DTN routing performance.

1. Introduction

For Disruption Tolerant Networks, i.e., sparse and/or highly mobile networks in which there may not be a contemporaneous path from source to destination, routing protocols typically adopt a "store-carry-forward" paradigm, where each node in the network *stores* a copy of the data packet that it generates or that has been forwarded or duplicated to it by other nodes, *carries* the packet while it moves around in the network, and *forwards* or *duplicates* the packet to other nodes or the destination node when they come within the transmission range of each other [1,2].

DTN routing consists of two components: the overall packet routing scheme chosen by the source node; and the transmission scheduling scheme adopted by each node for the data packets in its local buffer. The routing scheme chosen by the

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source node mainly decides the number of replicates allowed for each packet in the network and the number of hops that a packet is allowed to travel in the network. The transmission scheduling scheme adopted by a node decides which packets in its local buffer are to be forwarded when it encounters another node.

Most of the previously proposed DTN routing schemes assumed that there was no resource constraint in the network, and therefore focused mainly on the routing scheme aspect. Routing schemes can be classified into single-copy or multi-copy schemes. Under a single-copy scheme, at any time, there is at most one copy of each packet in the network. In other words, each packet is *forwarded* along a single path from source to destination. Under a multi-copy scheme, multiple copies of a packet are allowed to concurrently travel in the network; a packet can be *copied (i.e., duplicated)* to other nodes, allowing simultaneous use of multiple paths to the destination. For example, epidemic routing [1] scheme allows a node carrying a copy of a particular packet to duplicate it to every other node it encounters (if the other node does not have a copy yet). Variations of epidemic-like routing schemes include spray-and-wait [3–5], K-hop and probabilistic forwarding [6]. Compared to single-copy schemes, multi-copy schemes enjoy a better delivery performance (i.e., lower delivery delay and higher delivery probability), at the expense of higher transmission overhead and buffer occupancy. For a classification of DTN routing schemes, interested readers are referred to [7].

More recently, several works (such as [8,7,9]) addressed the routing in DTNs that are subject to resource constraints. In practice, the transmission bandwidth in DTNs is often limited due to the low data rates of wireless radio and the short duration of node-to-node encounters. Applications such as mobile sensor networks often deploy small battery-powered nodes, hence energy and memory capacity are also scarce resources. Research in [8,7,9] addressed the transmission scheduling (and buffer management, if the storage is constrained) problems for resource constrained DTNs, assuming that the routing scheme chosen by source nodes are fixed (e.g., epidemic routing is often employed). And they (e.g., [7,9]) mainly rely on heuristics for improving routing performance which impose lots of control traffic for information exchange, as Balasubramanian et al. [7] shows that finding an optimal schedule for DTN routing is NP-hard.

In this paper, we study how to optimize the routing performance in DTNs where the transmission bandwidth is scarce resource but power and storage are not constrained (e.g., vehicle based DTNs [8,10,11]). Since bandwidth is limited, it is critical to schedule the routing and transmission of packets optimally for achieving optimal routing performance. In contrast to existing works, we explore an alternative way to improve DTN routing performance via data source control, assuming the transmission scheduling of local buffer of each node is given and fixed. By data source control, we mean that a source node (at the application or transport layer) decides to choose a particular routing scheme such as epidemic routing, or a spray-and-wait scheme with certain counter number for each packet. Here we assume that all nodes in a network are fully cooperative in carrying out the routing scheme chosen by the source node. We study the spray-and-wait counter-based routing scheme, with a focus on the 2-hop multi-copy scheme. The central question we address in this paper is: can source nodes improve their routing performance by adjusting the duplication factor for each packet?

Our main contributions are summarized as follows. First, we observe via simulations that there exists an optimal counter value that achieves the minimum average network-wide packet delivery delay. Then as a first step towards understanding multi-hop multi-copy DTN routing schemes, we model a two-hop multi-copy DTN routing via a continuous time Markov chain. This modeling analysis provides insights into the impact of counter on routing performance and further suggests the existence of an optimal counter value. In this process, we study the capacity region of DTN routing, and accurately analyze the average packet delivery delay under the two-hop single-copy relaying scheme. Relying on the insights gained via simulations and modeling, we design an adaptive scheme that allow nodes to adaptively adjust their counter values (in search for an optimal counter value) to achieve minimum packet delivery delay. Our simulation studies demonstrate the effectiveness of our scheme and suggest the great potential of exploring this approach to improve DTN routing performance.

This paper extends and improves upon our earlier workshop paper [12] in the following ways. We extend the analysis of the two-hop single-copy scheme. We have generalized the equal allocation scheme to the proportional allocation scheduling scheme. We have also performed an in-depth analysis of both proportional allocation and priority scheduling scheme where we discuss the conditions for the schemes to be stable and provide an explanation to the modeling errors observed for the priority scheduling scheme. For the two-hop multi-copy scheme, we have clarified the modeling of IMMUNE recovery scheme in the model, and presented more technical details for the numerical solution of the model. We have also performed a comparison of all routing schemes considered in this paper through simulation and modeling studies.

The remainder of this paper is organized as follows. In Section 2, we discuss related work. Section 3 presents the network and traffic model considered in this work, and discusses the maximum network throughput. Then in Section 4 we present our simulation results that show the existence of an optimal counter for the spray-and-wait routing scheme. In Section 5, we present a queuing system analysis of the two-hop single-copy routing scheme, considering both proportional allocation and priority scheduling. In Section 6, we propose a Markov chain model for two-hop K-copy routing, and present the modeling studies and simulation studies that explore the impact of the protocol parameters and compare the performance of different routing schemes. In Section 7, we demonstrate the effectiveness of counter-adaptation routing control based on our modeling results. Finally, we conclude our paper in Section 8.

2. Related work

For DTNs without resource constraint, there exists a fundamental trade-off between the routing performance (in terms of delivery delay and delivery ratio) and overhead [13]. Various research works explored this trade-off in their studies of DTN