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 resource. 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 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.

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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

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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 have 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 transmission range [24, 13].

DTN routing consists of two fundamental 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 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 to forward when it encounters another node.

Most of the early proposed DTN routing schemes assumed that there was no resource limitation 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 [24] 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 [23, 21, 22], K-hop and probabilistic forwarding [11]. Compared to single-copy schemes, multi-copy schemes enjoy 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 [2].

More recently, several works (such as [3, 2, 16]) addressed routing in DTNs that are subject to resource constraints. In practice, 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 [3, 2, 16] 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., [2, 16]) mainly rely on heuristics for improving routing performance which imposes lots of control traffic for information exchange, as Balasubramanian *et al* [2] 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 transmission bandwidth is scarce resource but power and storage are not constrained (e.g., vehicle based DTNs [3, 26, 7]). Since bandwidth is limited, thus 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 a source node. We study the spray-and-wait counter-based routing scheme, with 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 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 [28] 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.

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 [27]. Various research works explored this trade-off in their studies of DTN routing schemes. For example, [19, 1] proposed the optimal probabilistic routing schemes with the goal of achieve optimal tradeoff between delay and power, or achieve optimal delivery probability while satisfying certain power constraint. For mobile sensor networks, [25] proposed data delivery schemes that achieve the desired data delivery ratio with minimum overhead (i.e., power consumption).

DTNs with bandwidth and/or buffer constraints have drawn more attention from researchers in recent years. [2, 16] have taken resource constraints into consideration when designing routing schemes. While these works focused on the design of the local transmission scheduling and buffer management policy adopted by the network nodes in order to optimize system wide performance such as average packet delivery delay, we focus on a different aspect of DTN routing control, i.e., the choice of duplication factor at the source node. A common assumption made by [2, 16] and our paper is that all network nodes are cooperative in optimizing network wide performance. In [20, 5], incentive mechanisms for fostering cooperation in DTNs with selfish nodes were proposed.

As to the performance modeling of DTN routing schemes, the majority of existing work (e.g.,[9, 27, 12]) assume there is no bandwidth constraint, i.e., when two nodes meet, they can transfer an unlimited number of packets. To the best of our knowledge, [14] is the only modeling work taking into account bandwidth constraint. [14] studies delivery delay under epidemic routing and spray-and-wait routing when purely randomized scheduling scheme is adopted by the network relay nodes. We however focus on the two-hop, single-copy and multi-copy routing scheme, and take into considerations more sophisticated scheduling schemes. In particular, we study proportional allocation of bandwidth between source-to-relay and relay-to-destination transmission, and prioritized scheduling scheme where the relay-destination transmission is given strictly higher priority than the source-relay transmission, For packets of same type of transmission, we study First-Come-First-Serve (FCFS) scheduling (for single-copy scheme) and randomized scheduling scheme (for multiple-copy scheme). As [2, 16] pointed out and our simulation studies confirmed, prioritized scheduling outperforms purely randomized scheduling scheme.

[17] characterized the scaling properties (i.e., asymptotic behavior) of the throughput and delay of DTNs under the two-hop relay scheme proposed by Grossglauser and Tse [10]. Based on a different DTN model, we have performed an accurate analysis on the delivery delay under the two-hop relay scheme (with considerations for more transmission scheduling schemes), and demonstrated that this scheme achieves the network capacity for DTNs with even number of nodes and circular traffic pattern.

3. System Model

In this section, we first present the network and traffic model considered in this paper. We then discuss the maximum per-flow throughput that can be supported by the network. Finally, we introduce the spray-and-wait scheme and the two-hop single-copy/multi-copy scheme, together with the different transmission scheduling schemes studied in this paper.

Notation	Description
N	number of nodes in the network
β	pair-wise inter-meeting rate
B	number of packets that can be exchanged during a contact
λ	per flow packet generating rate
K	packet duplication factor used in two-hop K-copy scheme
P_{SR}	fraction of bandwidth used for source-relay transmission
P_{RD}	fraction of bandwidth used for relay-destination transmission
T_d	packet delivery delay
T_p	packet propagation duration
$E[C_r]$	average number of relay nodes carrying a copy of a packet
c_{min}	the minimal spray-and-wait counter to use
c_{inc}	the increment step when adapting spray-and-wait counter
c_{dec}	the decrement step when adapting spray-and-wait counter

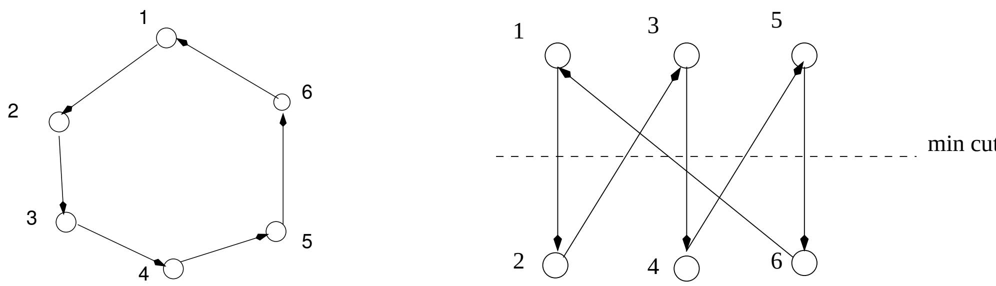
Table 1: Summary of Notations

3.1. Network and Traffic Model

Consider a network of N mobile nodes moving within a closed region. Each node has a limited transmission range such that the network is sparse and disconnected. Let *inter-meeting time* between a pair of nodes denote the duration of time from the time when the two nodes move out of transmission range of each other to the next time they come into range of each other. We assume in this paper that the inter-meeting time between each pair of nodes follows an exponential distribution with rate β, an assumption made by most previous modeling work in DTNs (e.g.,[9, 27, 12]). This assumption is motivated by the findings in [9] which showed that under random waypoint and random direction models, the pair-wise inter-meeting time follows an exponential distribution when node velocity is relatively high compared to the region size and the transmission range is relatively small. Furthermore, [4, 15] show that under a large class of mobility scenarios, the inter-meeting time follows a power-law up to a point, and then exhibits an exponential decay. As far as we know, [17] is the only analytic work that is based on such two-phase distributed inter-meeting time model where only asymptotic results for the two-hop single-copy scheme are obtained.

We consider bandwidth constraint by assuming a total of B packets can be exchanged between two nodes during their encounter. Note that the unit of bandwidth B can be interpreted in many different ways: $B = 2$ can represent that two packets or messages or files are exchanged per nodal contact. Without loss of generality, we will use packets per contact as B's unit.

We consider the following traffic model commonly adopted in DTN and MANET literature ([10, 27, 17]). There are N unicast flows in the network, with packets arriving at each source node (and flow) according to a Poisson process with rate λ. Each node is the source of only one flow, and the destination of another (and only one) flow. Let f_i denote the unicast flow originated from node i ($1 \leq i \leq N$), and $d(f_i)$ denote the destination node of flow f_i. We have $d(f_i) \in \{1, 2, ..., N\} - \{i\}$ and $d(f_i) \neq d(f_j)$ for $i \neq j$, $1 \leq i, j \leq N$. Under this traffic model, an equal amount of traffic is



(a) A circular traffic pattern for $N = 6$ case. This figure only shows the traffic flows.

(b) Min cut for the network shown in (a). This figure only shows the traffic flows. There are 9 edges cross the cut.

Figure 1: Example of a network with even number of nodes and circular traffic pattern

originated at and destined to each node in the network. As each node is the source of one flow (the destination of another flow), under the two-hop routing schemes, there is no inter-flow scheduling issue, i.e., selecting from multiple flows during the source-to-relay transmissions (relay-to-destination transmissions). Such homogeneous traffic model is a reasonable assumption for modeling studies, given the lack of application traffic models that are derived from real DTN traces.

As we focus on DTN scenarios where the nodes are not power constrained, the performance metric of interest is the delivery performance, more specifically, the *packet delivery delay*, defined as the time duration from when a packet is generated at the source node to the time when the packet is first delivered to the destination. Our system-wide optimization goal is to minimize the average delivery delay of all packets from all flows.

The simulations reported in the paper were carried out using a discrete event DTN simulator that we developed. We simulated the node mobility by drawing the pair-wise inter-meeting time from an exponential distribution with rate β. For each simulation run, the N unicast flows are configured randomly as follows: for each node, we choose a node uniformly at random (from all nodes that have no flow destined to it yet) to be the destination of its generated packets. Simulation setting can be described as a 4-tuple (N, β, B, λ). N, β, B, and λ, together with other notations used in the paper, are summarized in Table 1. Throughout the paper, we report average packet delivery delay for packets generated after the system has entered a steady state. The confidence interval of the average delivery delay is not reported as the interval is very small due to the large sample size (i.e., a large number of delivery delay samples) used.

3.2. Maximum Network Throughput

Before presenting DTN routing schemes studied in this paper, we first consider the following question: for a network setting given by a 3-tuple (N, β, B), what is the maximum per-flow traffic rate that can be supported[1]? The maximum per-flow

[1] that is, there exists a routing scheme that can sustain the per-flow traffic rate.

traffic rate is an important reference point for both the modeling analysis and simulation studies.

When evaluating the maximum network throughput, a DTN can be viewed as a static undirected network where every node is connected with every other node in the network, and the long-term average bandwidth of each link is $B\beta$. The maximum achievable per-flow throughput can be found by solving a classical *maximum concurrent multi-commodity flow problem*, which in general can be solved as a Linear Programming problem [6]. Nevertheless, as demonstrated in Section 5.1, the two-hop single copy schemes can support a per-flow throughput of $\lambda^* = NB\beta/4$, therefore providing a lower bound on the maximum achievable per-flow throughput.

For the special case where the network has an even number of nodes and a circular traffic pattern (e.g., Fig 1.(a)), we obtain an upper bound on the maximum achievable per-flow throughput as follows. In [18], it has been shown that the *min-cut* (i.e., *sparsest cut*) of a (undirected) multi-commodity flow problem is an upper bound of the max-flow, where the min-cut is defined to be the cut with the minimum ratio (among all cuts) of the cut capacity over the demand over the cut. Fig 1.(b) illustrates the min-cut for the multi-commodity flow problem shown in Fig 1.(a). For all such networks, i.e., with an even number of nodes and a circular traffic pattern, we form the min-cut by dividing the set of N nodes, V, into two sets U and $V-U$, each with $N/2$ nodes, such that for each of the N unicast flows, its source node is in one set and its destination is in another set. The capacity of the cut is $N/2 \times N/2 \times B\beta$, obtained by multiplying the number of links crossing the cut with the link bandwidth. The demand of the cut, i.e., the number of unicast sessions flowing through the cut, is N. The value of this cut is therefore $NB\beta/4$, and one can easily show that this cut is the min-cut. We therefore conclude that the maximum per-flow throughput of the network is upper-bounded by $\lambda^* = NB\beta/4$. Furthermore, as the two-hop single-copy schemes (shown in Section 5.1) can support a per-flow throughput of λ^*, we conclude that for this particular network setting, i.e., a DTN with an even number of nodes forming a circular traffic pattern, the maximum per-flow throughput is λ^*.

3.3. DTN Routing Schemes

In this section, we present the routing schemes studied in this paper. We start with the spray-and-wait scheme which is an multi-hop multi-copy routing scheme. We then describe the two-hop single-copy scheme and two-hop multi-copy schemes, together with the transmission scheduling schemes considered in this paper.

3.3.1. Spray-and-Wait Scheme

Under binary spray-and-wait [23, 21, 22] scheme with a counter value of L, the source node assigns a token value of L to the source packets it generates. When a node u carrying the packet with $n (n > 1)$ tokens meets a relay node v that does not carry a copy, node u copies the packet to node v and split the n tokens in half with node v. When a node has one token left, it only delivers the packet to the destination (i.e., no more replication). It has been shown that under an independent and identically distributed mobility model, binary spray-and-wait scheme minimizes the expected time to distribute all L copies [22], and therefore minimizes the packet delivery delay.

3.3.2. Two-Hop Single-Copy Scheme

In their seminal work [10] that demonstrated the positive effect of mobility on throughput, Grossglauser and Tse proposed a two-hop single-copy scheme that leverage the mobility of nodes in a mobile ad hoc network to deliver packets via a one-hop or two-hop path. Under this scheme, the source node either directly transmits its source packet to the the destination when they come into transmission range of each other, or forwards the packet to one of the $N - 2$ non-destination nodes (*relay* nodes) which stores the packet and delivers the packet to the destination when they encounter each other.

In particular, when node i and j encounter each other, the total bandwidth B are equally allocated to packet transmission in the two directions (from node i to j, and from node j to i), i.e., $B/2$ packets can be transferred in each direction. We now consider the packet transmission from node i to j (the packet transmission from node j to i is similar). If node j is the destination node of flow f_i, i.e., $j = d(f_i)$, then the only possible type of transmission from node i to j is the *direct source-destination transmission* to which all bandwidth ($B/2$ packets per contact) is allocated. If node j is not the destination node of flow f_i, then j acts as a relay node for flow f_i, and node i acts as a relay node for the flow destined to j. [10] considered an equal allocation scheme, where the total available (one-way) bandwidth, $B/2$, is allocated as follows, i.e., $B/4$ packets for *source-relay transmission* from source node i to relay node j, and $B/4$ packets for *relay-destination transmission* from relay node i to destination node j. Packets of same transmission type are served (i.e., transmitted) in the First-Come-First-Serve order.

In this paper, we not only generalize the equal allocation to *proportional allocation*, but also consider priority scheduling schemes. Under the proportional allocation, the total one-way bandwidth ($B/2$ packets per contact) is allocated to the relay-to-destination transmission and the source-to-relay transmission in proportion, e.g., $P_{RD}(0 < P_{RD} < 1)$ fraction of the bandwidth is allocated to relay-to-destination transmission, while P_{SR} (which equals to $1 - P_{RD}$) fraction of the bandwidth is allocated to source-to-relay transmission. Motivated by those works that give higher priority to packets that are destined to the receiver node [2, 16], the *priority scheduling* scheme gives strictly higher priority to relay-to-destination transmission over source-to-relay transmission. More specifically, for the transmission from node i to j, where $j \neq d(f_i)$, node i first transmits all relay packets that are destined to node j, and then transmits its own source packets to node j (which acts as a relay) if there is remaining bandwidth.

3.3.3. Two-Hop K-Copy Scheme

Under the two-hop K-copy scheme, the source node replicates a source packet to up to K ($K \leq 1$) relay nodes; each of the relay nodes can only forward the packet to the destination. At any point of time, there might be multiple copies of a packet in the network, including the copy carried by the source node and up to K copies in the relay nodes. The packet is first delivered to the destination when a node carrying a copy of the packet encounters the destination that does not have the packet and chooses to forward the packet. Note that under the two-hop 1-copy (i.e., $K = 1$) scheme, the source node *duplicates* the packet to 1 relay node, resulting in up to 2 copies of each packet in the network at any time. This distinguishes it from the two-hop single-copy scheme introduced in the previous section.

The modeling study of the performance of two-hop K-copy scheme is much more challenging than the single-copy scheme, and we focus on the *proportional allocation with randomized scheduling* scheme for tractability. As before, when two nodes, i and j, encounter each other, the total bandwidth B is equally allocated to transmission in the two opposite directions. The packet transmission from node i to j proceeds as follows. If node j is the destination of flow f_i, all available bandwidth ($B/2$) is allocated to source-destination transmission. Otherwise, node i schedules source-relay transmission with probability P_{SR}, and schedules relay-destination transmission with probability $P_{RD}(= 1 - P_{SR})$. For each type of transmission, purely randomized scheduling is used to pick a packet from all eligible packets to transmit.

Being a multi-copy scheme, the two-hop K-copy scheme employs control signaling to avoid transmitting a packet to a node multiple times. When two nodes, i and j, encounter each other, they first exchange signaling messages which contain the IDs of of the packets that they carry, and then choose packets (based on the transmission scheduling scheme) from all packets of which the other node does not have a copy.

For multi-copy schemes, *recovery* schemes [11, 27] have been proposed to save energy consumption. Different recovery schemes differ in the incurred signaling overhead and resource savings. For example, under the IMMUNE recovery scheme, when a node first delivers a packet to the destination, an *anti-packet* for the packet is generated and stored by the node and the destination. Subsequently, when the destination encounters other nodes carrying a copy of the packet, it transmits the anti-packet to those nodes which consequently discard their copies of the packet and store the anti-packet to avoid being "re-infected" by the packet in the future. More aggressive recovery schemes such as VACCINE scheme, where anti-packets are propagated by network nodes (not only the destination), improves routing performance at the expense of control signaling. We focus on IMMUNE recovery in this paper as the modeling of VACCINE recovery scheme increases the complexity of the model substantially.

Although relatively simple compared to the spray-and-wait scheme with more complex scheduling scheme, the two-hop K-copy scheme has the following two important aspects of a DTN routing scheme and therefore understanding it is an important first step towards understanding more complexed DTN routing schemes. First, the choice of P_{SR} (and P_{RD}) of a node reflects its level of cooperativeness. A node with a larger P_{SR} is more selfish as it allocates more bandwidth to disseminate its own source packets, and less bandwidth to relay packets for other nodes. Second, a source node can adjust its intended usage of network bandwidth by adjusting the maximum number of copies to disseminate for each packet, i.e., K.

4. Impact of Counter on Routing Performance

As we stated earlier, under limited link bandwidth, a key research issue is how to schedule the transmission of packets to optimize performance. Such a scheduling can be done by data source nodes and/or each node's transmission scheduling scheme. Existing routing schemes typically focus on individual nodes' transmission scheduling and buffer management, assuming that the routing scheme chosen by source nodes are

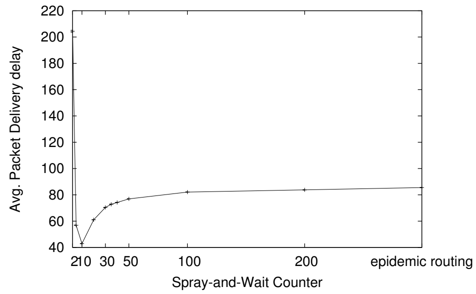


Figure 2: Average packet delivery delay under spray-and-wait scheme with varying counter, network setting: $(N = 101, \beta = 0.0049, B = 2, \lambda = 0.05)$. All nodes use same spray-and-wait counter.

fixed. As there are theoretical and practical difficulties with the above approach, we pursue an alternative way in this paper to improve routing performance via routing control from source nodes. Specifically, we assume that the transmission scheduling of each node is given, and we explore whether source nodes can vary their counter values for packet replication such that the routing performance can be improved.

To pursue this direction, we conduct a set of simulations of *binary spray-and-wait* scheme and epidemic routing scheme under the network setting given by $N = 101, \beta = 0.0049, B = 2, \lambda = 0.05$. All nodes adopts same local transmission scheduling. Our simulation results plotted in Fig 2 shows that there exists an optimal counter value, denoted as L^*, which minimizes the average packet delivery delay. Using larger and smaller counter leads to larger delivery delay. Note that L^* depends on the system parameters. When the network load is very low, L^* can be very large and the spray-and-wait scheme approaches to epidemic routing.

The above results motivate us to explore the potential of routing control by source nodes. We attempt to understand why the counter-based routing schemes have optimal counter values, and how to design simple yet effective algorithms to allow source nodes to improve their routing performance by adjusting packet replicating counters. Next, we start off with formally analyzing counter-based routing schemes. To keep our analysis tractable, we focus on two-hop routing schemes. We first analyze the two-hop single-copy scheme (Section 5), then we model the two-hop K-copy scheme using a continuous time Markov Chain (Section 6).

5. Two-Hop Single-Copy Schemes

In this section, we study the two-hop single-copy schemes, analyzing the average packet delivery delay achieved under different transmission scheduling schemes.

We assume that the bandwidth of each nodal contact is $B = 2$. This bandwidth is equally shared by transmissions in the two opposite directions, i.e., one packet can be transmitted in each direction during each contact.

Each node has a queue for its own source packets, referred to as *source queue*, and $N - 2$ queues, referred to as *relay queues*, each for a flow for which this node is a relay.

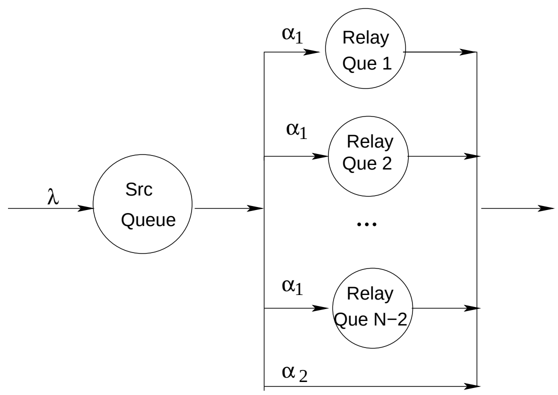


Figure 3: Queuing network model for Two-Hop Single-Copy schemes

Note that this node is also the destination node of one flow in the network. Under the two-hop single-copy scheme, each packet is either delivered to the destination directly, or forwarded to a relay node which then delivers the packet to the destination. As illustrated in Fig 3, when a source packet is first generated at the source node, it is first queued in the source node's *source queue*. After a certain queuing delay, the packet is either directly delivered to the destination (with probability α_2), or forwarded (not duplicated) to a relay node (with probability α_1) where the packet is queued at the relay node's *relay queue* and forwarded to the destination later. We have $(N-2)\alpha_1+\alpha_2 = 1$.

The arrival and service rates of the source queue and relay queue, and the values of α_1 and α_2 depend on the transmission scheduling scheme employed. We assume that when a node meets the destination node of its source flow, all of the one-way bandwidth ($B/2 = 1$ packet per contact) is allocated to deliver packets in its source queue to the destination[2]. If a node meets another node that is not the destination of its flow, we consider the following two scheduling schemes:

- *proportional allocation scheduling* where the total one-way bandwidth ($B/2 = 1$ packet per contact) is allocated so that the source-to-relay and relay-to-destination transmission is allocated P_{SR} and P_{RD} of the bandwidth, where $P_{SR}+P_{RD} = 1$, $P_{SR} > 0$ and $P_{RD} > 0$.
- *priority scheduling*, where relay-to-destination transmission is given strictly higher priority over source-to-relay transmission.

We next present a queuing network analysis of the two-hop single-copy schemes with the above two scheduling schemes.

5.1. Proportional Allocation Scheduling

We first consider the proportional allocation scheme.

[2]Under the traffic pattern considered in this paper, there is no other type of transmission.

The *source queue* can be modeled as a $M/M/1$ queue. The arrival rate is per-flow packet arrival rate, λ. Each source packet is either directly delivered to the destination (when the source meets the destination) with a rate of β, or forwarded to a relay node when the source node meets one of the $N-2$ relay nodes. For a meeting between a pair of nodes that are not source-destination pair, P_{SR} fraction of the bandwidth is allocated to the source-to-relay transmission, therefore the rate that a source packet is forwarded to some relay node is $(N-2)\beta P_{SR}$. The service rate of the source queue is therefore $\beta + (N-2)\beta P_{SR}$. The source queue is ergodic if and only if the arrival rate is smaller than the service rate, i.e.,

$$\lambda < \beta + (N-2)\beta P_{SR}, \tag{1}$$

and has an average sojourn time (the total time a packet spent in the queue) of $T_s = \frac{1}{\beta+(N-2)\beta P_{SR}-\lambda}$. The probability that the source queue is empty, denoted as p_0, is given by $p_0 = 1 - \frac{\lambda}{\beta+(N-2)\beta P_{SR}}$.

When a packet leaves the source queue, with probability $\alpha_2 = \frac{1}{1+(N-2)P_{SR}}$, the packet is delivered to the destination, i.e., no further delay; with probability $1-\alpha_2$ the packet is forwarded to one of the $N-2$ relay nodes. The probability that the packet is forwarded to any particular relay node is $\alpha_1 = \frac{1-\alpha_2}{N-2} = \frac{P_{SR}}{1+(N-2)P_{SR}}$.

Each *relay queue* at a node can also be modeled as an $M/M/1$ queue. Packet arrives whenever the relay node meets the source of the flow with a non-empty source queue and source-to-relay transmission is scheduled. The arrival rate to the relay queue is then $(1-p_0)\beta P_{SR}$ (only P_{SR} fraction of the meetings are used for source-to-relay transmission). The service rate of the queue is βP_{RD}, considering that P_{RD} fraction of the meetings between the relay to destination node are used for relay-to-destination transmission. The relay queue is ergodic if and only if

$$(1-p_0)\beta P_{SR} < \beta P_{RD}, \tag{2}$$

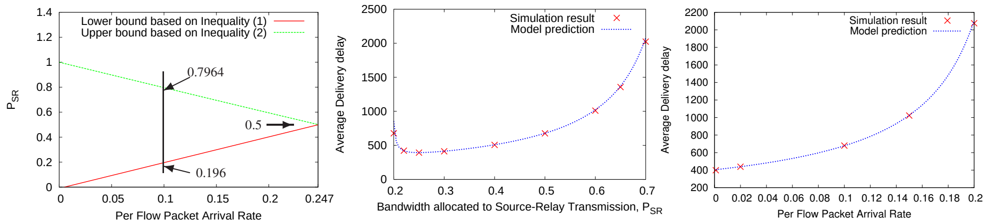
and the sojourn time is $T_r = \frac{1}{\beta P_{RD} - \beta P_{SR} + p_o \beta P_{SR}}$.

In summary, the average packet delivery delay under the two-hop single-copy scheme with proportional allocation is:

$$T_d = T_s + \frac{(N-2)P_{SR}}{1+(N-2)P_{SR}} T_r. \tag{3}$$

For a given network setting specified by the tuple $(N, \beta, \lambda, B = 2)$, the value chosen for P_{SR} decides whether the scheme can support the offered traffic rate so that the network is stable[3]. We solve inequalities (1) and (2) to obtain the range of values that P_{SR} can take in order for the scheme to be stable. Fig 5.(a) plots the value ranges for the P_{SR} under varying per packet arrival rate, λ. We observe that when λ is small, P_{SR} can take a larger range of value; and when λ approaches λ^*, the upper bound and lower bound intersect at the value of 0.5.

[3]In the sense that all queues in the network have bounded time average backlog [8].



(a) Constraints on P_{SR}

(b) Delivery delay under varying $P_{SR}, \lambda = 0.1$

(c) Equal Allocation ($P_{SR} = 0.5$) under varying λ

Figure 4: Two-hop single-copy relay scheme with proportional allocation, $N = 101, \beta = 0.0049, B = 2, \lambda^* = \frac{NB\beta}{2} = 0.24745$

Furthermore, within the above identified value range for P_{SR}, the value chosen for P_{SR} has a significant impact on the system wide packet delivery delay. Fig 5.(b) plots the average packet delivery delay (both model prediction and simulation result) under varying P_{SR} for the case with $\lambda = 0.1$, where the value range for P_{SR} is $[0.196, 0.7964]$ according to Fig 5.(a). We observed a perfect match between the model prediction and simulation result. We also observe that as P_{SR} increases, the average packet delivery delay first decreases, and then increases. This is because as Eq. (3) shows, the average packet delivery delay consists of two parts, the queuing delay at the source queue, T_s, and the queuing delay at the relay queue, T_r. As P_{SR} increases, T_s decreases, T_r increases and the probability of experiencing relay queue delay increases too, leading to the observed behavior of packet delivery delay. For a given network setting, there is a value for P_{SR} that minimizes the average packet delivery delay, denoted as $P^*_{SR} = \text{argmin}_{P_{SR}} T_d$. We can obtain P^*_{SR} by solving the following equation:

$$\frac{dT_d}{dP_{SR}} = 0,$$

for P_{SR}.

From Fig 5.(a), we also observe that when $P_{SR} = 0.5$, as long as $\lambda < \lambda^*$, both inequalities (1) and (2) are satisfied and therefore the scheme is stable. This scheme, i.e., with $P_{SR} = 0.5$, is exactly the two-hop single-copy scheme proposed in [10]. Interestingly, under such equal allocation, the source queue and relay queue have same utilization factor ($\rho = \frac{2\lambda}{N\beta}$) and average queue length. Both queues are stable as long as $\lambda < \frac{N\beta}{2} = \lambda^*$, therefore the scheme can support a per-flow throughput of λ^*[4]. The following closed form expression for average packet delivery delay can be obtained from Eq. (3):

$$T_d = T_s + (1 - 2/N)T_r = \frac{2N - 2}{N\beta - 2\lambda}.$$

Fig 5(c) plots the average packet delivery delay under varying per-flow traffic rate, comparing the simulation results against the model prediction. The model proposed

[4] This result can be extended to the case where $B > 2$.

in this section accurately predicts the average packet delivery delay for the two-hop single-copy scheme under proportional scheduling scheme.

5.2. Priority Scheduling

The proportional allocation scheme considered in the previous section is more tractable for analysis, as the fixed proportional allocation allows us to obtain the arrival and service rates of the source queue and relay queue. However, as [2, 16] have demonstrated, higher priority should be given to delivery traffic (including source-destination and relay-destination). In this section, we analyze the two-hop single-copy scheme with priority scheduling where relay-to-destination transmission is given strictly higher priority than source-to-relay transmission.

Recall that a queuing network model as depicted in Fig 3 can be used to model a two-hop single-copy scheme. For a node in the network, we denote by N_S the number of packets in its source queue and N_R the number of packets in each relay queue (there are $N-2$ relay queues in each node), and let $r_0 = Pr\{N_R = 0\}$ and $s_0 = Pr\{N_S = 0\}$.

We first consider the arrival and service rate of the source queue. Source packets arrive to the source queue with packet arrival rate, λ. A source packet leaves the queue when the source directly delivers the packet to the destination (with rate $B\beta/2 = \beta$), or when the source forwards it to a relay node. Recall that source-to-relay transmission has lower priority than relay-to-destination traffic: only when the source node has no relay packet destined to the receiver, will the source packet be forwarded. Therefore, the source node forwards a source packet to a relay node with rate βr_0, and the rate that a source packet is forwarded to one of the $N-2$ relay nodes is: $(N-2)\beta r_0$. The total service rate of source queue is therefore $\beta + (N-2)\beta r_0$. The condition for the source queue to be stable is:

$$\lambda < (N-2)\beta r_0. \tag{4}$$

We also have

$$s_0 = Pr\{N_S = 0\} = 1 - \frac{\lambda}{\beta + (N-2)\beta r_0}, \tag{5}$$

and the average sojourn time of the source queue is

$$T_s = \frac{1}{\beta + (N-2)\beta r_0 - \lambda}.$$

After a source packet leaves the source queue, with probability $\frac{(N-2)\beta r_0}{\beta+(N-2)\beta r_0}$, the packet enters some relay queue, where it experiences another delay before being forwarded to the destination, i.e., $\alpha_1 = \frac{\beta r_0}{\beta+(N-2)\beta r_0}$, and $\alpha_2 = \frac{\beta}{\beta+(N-2)\beta r_0}$.

For the relay queue, a packet arrives when the relay node meets the source with a non-empty source queue, and the source carries no relay packet that is destined to the relay node. Therefore the packet arrival rate to the relay queue is

$$\beta Pr\{N_S \neq 0 \&\& N_R = 0\} \approx \beta Pr\{N_S \neq 0\} Pr\{N_R = 0\} = \beta(1 - s_0) r_0, \tag{6}$$

assuming that $N_S \neq 0$ (i.e., the node has a non-empty source queue) is independent from $N_R = 0$ (i.e., the node has an empty relay queue for the node it meets). The service rate of the relay queue is β, as the relay-to-destination traffic has strictly higher priority over source-to-relay traffic. No matter what is the value of λ, the relay queue is always stable as its arrival rate is always smaller than the service rate. For this $M/M/1$ queue, we have

$$r_0 = Pr\{N_R = 0\} = 1 - \frac{\beta(1-s_0)r_0}{\beta},$$

which yields

$$r_0 = 1/(2 - s_0). \tag{7}$$

The sojourn time of the relay queue is then given by

$$T_r = \frac{1}{\beta - \beta(1-s_0)r_0}.$$

In summary, the average packet delivery delay is:

$$T_d = T_s + \frac{(N-2)\beta r_0}{\beta + (N-2)\beta r_0} T_r, \tag{8}$$

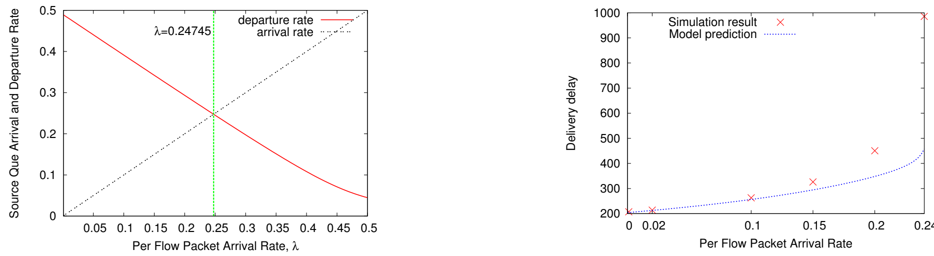
where r_0 and s_0 can be calculated by solving the equations Eq.(5) and Eq.(7). We plug the value of r_0 to inequality (4) and find the maximum per packet flow rate that can be supported by this scheme. In Fig 5.(a), the arrival and service rate of the source queue under varying per-flow packet arrival rate is plotted, and we observe that as long as the per packet arrival rate is smaller than $\lambda^* = 0.24745$, the source queues are stable, and so is the scheme.

Fig 5.(b) compares the model predicted average delay with the simulation result which shows a very good match for $\lambda < 0.15$, and an underestimation of delivery delay for heavier traffic rate. This is due to the approximation in Eq (6) based on the assumption of the independence between the events of a non-empty source queue and an empty relay queue during a source-relay encounter. Our simulation studies indeed show a mismatch between $Pr\{N_S \neq 0 \&\& N_R = 0\}$ and $Pr\{N_S \neq 0\}Pr\{N_R = 0\}$, especially for heavy load case.

6. Modeling Studies of Two-Hop K-Copy Scheme

When the per-flow traffic rate is low, the available network bandwidth is not fully utilized by the two-hop single-copy schemes. To reduce packet delivery delay, a packet can be replicated in the network and therefore multiple copies of the packet are propagated simultaneously through multiple paths.

In this section, we analyze the two-hop K-copy scheme for the homogeneous case where all nodes use the same P_{SR}. We propose a continuous time Markov Chain (MC) to model a packet's lifetime in the network, and then numerically solve the MC, coupled with queuing analysis of the source queue and relay queue, to obtain average packet delivery delay.



(a) Arrival & departure rate of source queue

(b) Average Packet Delivery Delay Comparison

Figure 5: Two-hop Single-copy scheme under priority scheduling, $N = 101, \beta = 0.0049, B = 2$

6.1. Markov Chain Model of A Packet's Life Time

In this section, we present a Markov Chain that models the propagation and delivery of a typical packet in the network. For ease of explanation, we denote this packet as P. Suppose that packet P is generated at the source node at time $t = 0$, and the two-hop K-copy ($K \leq 1$) scheme is used to propagate the packet in the network where all nodes employ *proportional allocation with randomized scheduling* with same value for P_{RD}.

Fig 6 depicts the state diagram of the MC. Each state of the MC is denoted as (S_I, R_I, R), where S_I denotes whether the source node has a copy of the packet (with value 1) or not (with value 0), R_I denotes the number of infected or recovered relay nodes, and takes integer values ranging from 0 to K, and R denotes whether the packet has been delivered (with value 1) or not (with value 0). The initial state is $(1, 0, 0)$, where only the source node carries a copy of the packet. The propagation of the packet stops when the source node "recovers" from the packet, i.e., it delivers the packet to the destination or meets the destination node that already received the packet[5]. We hence use a single state $(0, *, 1)$ to represent all states where the source has recovered from the packet and there are different numbers of infected or recovered relay nodes. This MC is reducible and transient, where the state $(0, *, 1)$ is an absorbing state and the initial state $(1, 0, 0)$ cannot be reached from any other state.

There are five types of transitions in the MC, labeled as *S-R*, *S-D*, *R-D* and *D-S* respectively in the diagram. The *S-D transition* occurs when the source node meets the destination which has not received packet P yet, and from all eligible source-to-destination packets, packet P is chosen to be transmitted. The *S-R transition* occurs when the source meets a susceptible relay node that does not carry a copy of packet P, and from all eligible source-relay packets, packet P is chosen to be transmitted. The *R-D transition* occurs when a relay node that carries packet P meets the destination that has not received the packet yet, and the relay node chooses packet P from the set of all eligible relay-destination packets. Finally, the *D-S transition* occurs when the destination that has already received packet P meets the source, and transmits the anti-

[5]Remaining copies of the packet carried by relay nodes will be eventually deleted when the relay nodes meet the destination.

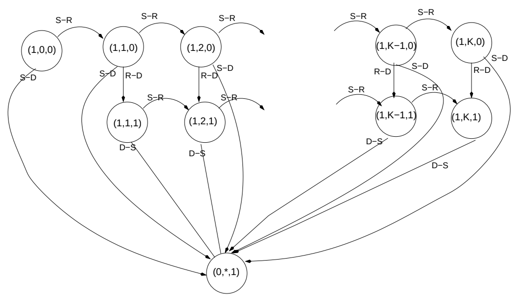


Figure 6: MC model of a packet's lifetime under two-hop K-copy scheme

packet to the source. The source subsequently deletes its copy and stops propagating the packet. Note that under IMMUNE recovery, when the destination that has already received packet P meets one of the infected relay nodes, it transmits an anti-packet to the relay node allowing the relay node to become recovered (i.e., delete its copy). However, this does not result in a change in the MC state, due to the fact that the MC states record the sum of the number of infected and recovered relay nodes.

Similar Markovian models of multi-copy DTN routing schemes such as epidemic routing and 2-hop routing have been proposed and studied in previous modeling studies [9, 11, 27, 14]. However, except [14], most works assume there are no resource constraint, and therefore each packet propagates in the network independently from other packets, allowing one to express the various transition rates more easily. To account for bandwidth constraint, we need to take into account the fact that when two nodes meet, there are multiple packets competing for the transmission opportunity. For the purely random scheduling, the probability that the packet P is chosen to be transmitted is equal to the reciprocal of the number of packets competing for the transmission opportunity.

We now introduce three random variables that denote the number of packets competing for each of the three types of transmissions, i.e., source-to-destination, source-to-relay, and relay-to-destination respectively. We will discuss how to evaluate them in Section 6.3. Let N_{SD} denote the number of eligible source packets to be transmitted to the destination, when the source meets the destination, and $E[N_{SD}]$ denote its expected value. And let N_{SR} denote the number of source packets in the source that are eligible to be transmitted to a relay node when the two nodes meet, and $E[N_{SR}]$ denote its expected value. Finally let N_{RD} denote the number of relay packets that are eligible to be transmitted to the destination node when the two nodes meet, and $E[N_{RD}]$ denote its expected value. We assume that these three quantities have a stationary distribution, which is true if the scheme stabilizes.

With the expected values of the above three variables, we now analyze the transition rates of the MC:

- The *S-D transition* rate, i.e., the rate that the source node meets the destination which has not received packet P yet, and delivers packet P, is β/N_{SD}, and can be approximated by $\beta/E[N_{SD}]$. Note that the source meets the destination node with a rate of β, and during such encounter, the source uniformly randomly

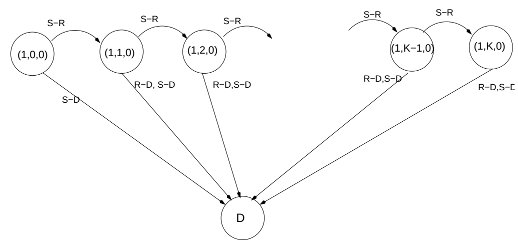


Figure 7: MC model of a packet's lifetime *until delivery*

chooses a packet from the set of all eligible source packets (there are N_{SD} such packets) to transmit, therefore the probability that packet P is chosen is $1/N_{SD}$, which is approximated by $1/E[N_{SD}]$.

- That *S-R transition* rate, i.e., the rate that the source meets a susceptible relay nodes (i.e., relay nodes that do not carry a copy of or an anti-packet for packet P), and transmits packet P to the latter, is state dependent. If there are currently R_I relay nodes that either carries a copy of packet P or carries an anti-packet for packet P, then the S-R transition rate is $(N-2-R_I)P_{SR}\beta/E[N_{SR}]$. This is because the source meets a susceptible relay node with rate $(N-2-R_I)\beta$ (note that there are $N-2-R_I$ susceptible relay nodes in the network), with probability P_{SR}/N_{SR} (which we approximate by $P_{SR}/E[N_{SR}]$), the source performs source-to-relay transmission and chooses packet P to transmit to the relay node encountered.

- The *R-D transition* rate is the total rate that one of the relay nodes that carry packet P meets the destination that has not received the packet yet, and deliver packet P to the destination. The total encountering rate between infected relay nodes and the destination is $R_I\beta$ (given that the destination has not received the packet yet, the number of infected relay nodes is R_I, i.e., there is no recovered relay node.). With probability P_{RD}, the encountering performs relay-destination transmission. The probability that packet P is chosen to transmit, under uniformly random scheduling, is $1/N_{RD}$. Therefore, the R-D transition rate can be approximated by $R_I\beta P_{RD}/E[N_{RD}]$.

- The *D-S transition* rate is the rate that the destination which has already received packet P meets the source. As we assume there is no bandwidth constraint for control signaling, the D-S transition rate is β, the rate that the source and the destination encounter each other.

6.2. Packet Delivery Delay, Propagation Duration and Number of Copies in Network

We now derive *average packet delivery delay* ($E[T_d]$), *average packet propagation duration* ($E[T_p]$), and *average number of copies in the network* ($E[C_r]$) from the MC model. The packet delivery delay is of interests in its own right, where the other two metrics are needed for estimating $E[N_{SD}]$, $E[N_{SR}]$ and $E[N_{RD}]$ as the next section details.

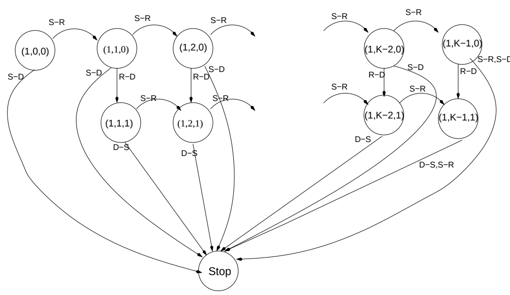


Figure 8: MC model of a packet's *propagation*: for calculating average number of relay copies

Let T_d denote *packet delivery delay* and $E[T_d]$ its average value. To calculate $E[T_d]$, the MC model in Fig 6 is simplified by merging all states where the destination node has received the packet (i.e., $R = 1$) to a single state "D". The resulting MC is depicted in Fig 7. T_d is then the time it takes for the system, starting from the initial state $(1, 0, 0)$ to enter the state D. $E[T_d]$ can be calculated via the following recursive numerical solution.

Let $S(s)$ denote the expected sojourn time of state s (which equals to the reciprocal of the total transition rates coming out of sate s), $T(s_1, s_2)$ denote the *expected* time it takes for the system to enter state s_2 starting from s_1, and $P(s_1, s_2)$ denote the probability that the system currently in state s_1 enters state s_2 next. We have the following equations:

$$\begin{aligned}
T((1,0,0),D) &= S((1,0,0)) + P((1,0,0),(1,1,0))T((1,1,0),D) \\
T((1,1,0),D) &= S((1,1,0)) + P((1,1,0),(1,2,0))T((1,2,0),D) \\
&\;\;... \\
T((1,K,0),D) &= S((1,K,0))
\end{aligned}$$

The above equations are solved recursively to obtain $T((1, 0, 0), D)$, i.e., $E[T_d]$.

Let T_p denote *packet propagation duration*, i.e., the duration of time from when a packet is generated by the source node, to the time when the source node stops propagating the packet to relay nodes. The source node stops propagating the packet, either after K copies of the packet have been sent or after meeting the destination node that has already received the packet. To calculate $E[T_p]$, we simplify the MC model in Fig 6 by merging all states where the source node has stopped propagating the packet (i.e., $(1, K, 0)$, $(1, K, 1)$, and $(0, *, 1)$) together to a single state *stop* as shown in Fig 8. T_p is the duration of time for the system to enter state *stop*, starting from initial state $(1, 0, 0)$. We numerically evaluate $E[T_p]$, similar to the case of $E[T_d]$.

Another useful metric is the *average number of infected or recovered relay nodes* for packet P in the network during the time duration from the time it is generated to the time that the source node stops propagating the packet. We denote this random variable as C_r, and its expected value as $E[C_r]$. Based on the MC in Fig 8, we have:

$$E[C_r] = \sum_{\text{all state s}} S(s)C(s)/E[T_p],$$

where $S(s)$ denotes the expected sojourn time in state s, and $C(s)$ denotes the number of infected or recovered relay nodes for packet P in the network in state s, i.e., $C((S_I, R_I, R)) = R_I$.

6.3. Evaluating $E[N_{SD}]$, $E[N_{SR}]$, and $E[N_{RD}]$

In the previous section, we demonstrate how to derive interesting metrics such as $E[T_d]$, $E[T_p]$, and $E[C_r]$ from the MC models. However, the transition rates in the MC models involve three quantities $E[N_{SD}]$, $E[N_{SR}]$ and $E[N_{RD}]$ which we analyze in this section.

Recall that $E[N_{SD}]$ represents the average number of eligible source packets to be transmitted to the destination node, when a source node meets the destination node. Source packets arrive to the source node with rate λ, and the duration of time that a packet remains eligible to be transmitted to the destination is the time duration from the packet generation time to the time the packet is delivered, i.e., the packet delivery delay T_d. Little's Law yields $E[N_{SD}] = \lambda E[T_d]$.

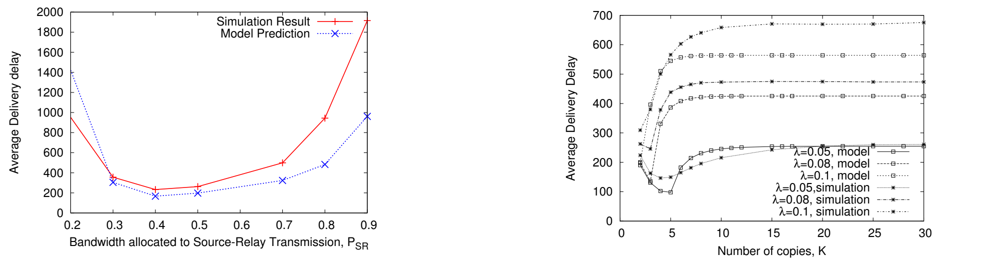
We now estimate $E[N_{SR}]$, the average number of source packets that are eligible to be transmitted to a particular relay node (denoted as r), when the source node encounters the said relay node. Source packets arrive to the source node with a rate of λ, and the duration of time that a source packet remains eligible to be transmitted to relay nodes is the *packet propagation duration* T_p. Therefore the source node has in average $\lambda E[T_p]$ source packets that are eligible to be transmitted to relay nodes, based on Little's Law. However, relay node r might already carry a copy for some of these packets and therefore not all of these packets are eligible to be transmitted to node r.

Recall that $E[C_r]$ represents the average number of infected or recovered relay nodes, i.e., relay nodes carrying a copy or an anti-packet, in the network during the packet's lifetime. As each of the $N-2$ relay nodes has equal probability of carrying a copy or an anti-packet of a particular packet (due to the homogeneous mobility model), relay node r has probability $\frac{E[C_r]}{N-2}$ of carrying a copy or an anti-packet of the packet. The number of packets that relay node r already has a copy or has an anti-packet of follows a binomial distribution, $B(\lambda E[T_p], \frac{E[C_r]}{N-2})$, with mean $\lambda E[T_p]\frac{E[C_r]}{N-2}$. Consequently, among the $\lambda E[T_p]$ source-relay packets that the source node carries, relay node r in average has a copy or an anti-packet of $\lambda E[T_p]\frac{E[C_r]}{N-2}$ packets. So the number of source packets that are eligible to be transmitted to relay node r (i.e., r does not carries a copy of) is:

$$E[N_{SR}] = \lambda E[T_p] - \lambda E[T_p]\frac{E[C_r]}{N-2} = \lambda E[T_p](1 - \frac{E[C_r]}{N-2}).$$

We estimate $E[N_{RD}]$, the average number of (relay) packets that are eligible to be transmitted from the relay node to the destination when the two nodes meet, as follows. Packet arrives to the relay node whenever the relay node meets the source node which has some eligible packets to copy, i.e., the arrival rate is $\beta P_{SR}\mathbf{1}\{N_{SR} > 0\}$ (where $\mathbf{1}\{\}$ denotes the indicator function), which we approximate by its expected value $\beta P_{SR} Pr\{N_{SR} > 0\}$. As N_{SR} can be approximated as a binomial distributed random variable, we have:

$$Pr\{N_{SR} > 0\} \approx 1 - (1 - \frac{E[C_r]}{N-2})^{\lambda E[T_p]}.$$



(a) $N = 101, \lambda = 0.08, \beta = 0.0049, K = 2$ (b) $N = 101, \beta = 0.0049, P_{RD} = 0.5$, varying K

Figure 9: Comparison of model predicted delivery delay and simulation results for 2-hop K-copies schemes

The duration of time that a relay packet remains eligible to be transmitted to the destination is the remaining time to deliver the packet[6], which varies with the current number of copies of the packet in the network, and is upper bounded by the packet delivery delay. We use its upper bound T_d's expected value to approximate it, and obtain the following estimation using Little's Law:

$$E[N_{RD}] \approx \beta P_{SR} Pr\{N_{SR} > 0\} E[T_d].$$

6.4. Iterative Solution of the Model

We note that the transition rates in the MC model involve quantities such as $E[T_d]$, $E[T_p]$ and $E[C_r]$, which are derived from the same MC model. This suggests the following iterative approach to find a fixed point solution.

We first assign randomly chosen initial values to $E[T_d]$,$E[T_p]$, $E[C_r]$, then enter a loop where in each iteration *i)* the transition rates of the MC models are updated based on the values of the above three quantities, *ii)* the MC models are then solved to obtain new values for the three quantities. The loop stops when the values of $E[T_d]$, $E[T_p]$ and $E[C_r]$ have converged.

For each network setting and the value of P_{SR} and K, we run the above iterative algorithm for 100 runs with each run initialized with randomly chosen values for $E[T_d], E[T_p], E[C_r]$. $E[C_r]$ is generated from a uniform random distribution with value range $[1, K]$, while $E[T_d]$ and $E[T_p]$ are generated from a uniform random distribution with value range $[100, 2000]$, as we observed from simulations that the delay under two-hop K-copy schemes for the network setting we considered falling within this range.

6.5. Model Verification and Discussions

In order to evaluate the accuracy of the proposed model for 2-hop K-copies scheme, we perform simulation studies using our custom built simulator. Recall that nodes mobility is modeled by pair-wise exponential inter-meeting times. Network traffic load, λ, is varied between $[0, \lambda^*]$, where λ^* is identified in Section 3. We also examine the

[6]If the packet has been delivered, this relay node deletes the packet upon encountering the destination.

impact of the important parameters of the schemes, and compare the performance of different routing schemes studied in this paper.

6.5.1. Impact of Bandwidth Allocation, P_{SR}

We first examine the impact of bandwidth allocation on the average delivery delay. Fig 9(a) plots the average delivery delay under two-hop 2-copy scheme under various P_{SR}, with per-flow packet arrival rate of $\lambda = 0.08$. The figure shows that the model provides best prediction when P_{SR} takes value in the range of $[0.3, 0.5]$. There is significant modeling error for large P_{SR} and small P_{SR} cases, which is understandable given the various approximations involved in the model. The model predicts the optimal value of P_{SR} accurately.

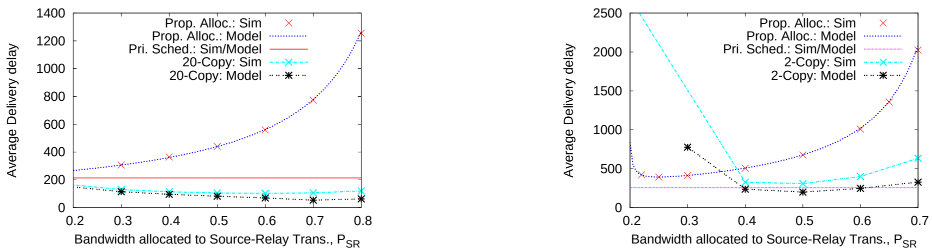
We observe that as P_{SR} (the proportion of bandwidth allocated to source-relay transmission) increases, the average delivery delay first decreases and then increases. When P_{SR} increases, it has two opposite effects on delivery delay. On the one hand, it allows more bandwidth to be allocated for source-relay transmission and enables faster propagation of source packets to relay nodes. On the other hand, it leaves less bandwidth for relay-destination transmission and slows down packet delivery. When P_{SR} is small, the former effect outweighs the latter, leading to reduced delivery delay when P_{SR} is increased; when P_{SR} reaches a certain value, the latter effect outweighs the former, and the delivery delay increases when P_{SR} is increased.

Note that the impact of P_{SR} on this two-hop K-copy scheme is similar to that observed for the two-hop single-copy scheme (Fig 5(b)). The optimal P_{SR} value varies for different K and network setting. We are not able to obtain closed form solution for the optimal P_{SR} due to the fact that the MC model needs to be solved numerically.

6.5.2. Impact of Duplication Factor, K

We next examine the effect of varying K on the average delivery delay. Fig 9(b) plots the average delivery delay under two-hop K-copy scheme with various K under three different per-flow traffic rates, comparing the model predicted delivery delay with the simulation result. Both simulation results and model results demonstrate that there exists an optimal K value under which the average delivery delay is smallest. We observe that there exists certain discrepancy between the model prediction and simulation result, however the model prediction not only captures the trend of the curve, but also predicts the optimal K value accurately.

This optimal value of K varies for different per-flow traffic rate, λ. In particular, the optimal K value is larger when λ is small. Intuitively, under a light traffic load, there are more free bandwidth available in the network for two-hop K-copies scheme to take advantage of. We also observe that when K takes a value larger than the optimal value, the delivery delay first increases sharply and then levels off. This is because when a large K is used, there are more source-relay packets competing for the source-relay transmission opportunities. The imperfect scheduling (randomized scheduling within same traffic) allows packets that have been duplicated more times (or have been delivered) in the network to compete with packets that just start propagating in the network, leading to degraded performance. However, the increase in delay diminishes as K increases further, as the source stops propagating a packet upon encountering



(a) Under relative light load $\lambda = 0.02$

(b) Under relative high load $\lambda = 0.1$

Figure 10: Comparison of different 2-hop routing schemes $(N = 101, \beta = 0.0049, B = 2)$

the destination that has received the packet, keeping the number of copies made for a packet limited.

6.5.3. Comparison of Different Routing Schemes

In this section, we compare the average packet delivery delay achieved by the different routing schemes considered in this paper, i.e., the 2-hop single-copy scheme with different bandwidth allocation (proportional allocation and priority scheduling), and the 2-hop K-copy scheme.

Fig 10(a) and (b) plots the average packet delivery delay achieved by these different schemes for the lightly loaded case ($\lambda = 0.02$) and heavily loaded case ($\lambda = 0.1$) under varying P_{SR}. For the 2-hop single-copy scheme with priority scheduling, which does not involve P_{SR}, horizontal lines are plotted. Furthermore, as the difference between modeling prediction and simulation result for this scheme as seen in Fig 5 is indiscernible in this smaller scale plot, a single line is plotted for simulation and modeling results. We observe that as expected, when the network is lightly loaded, the optimal source counter value K is larger than that of the heavily loaded case, more specifically, if $\lambda = 0.02$, $K^* = 20$; if $\lambda = 0.1$, $K^* = 2$.

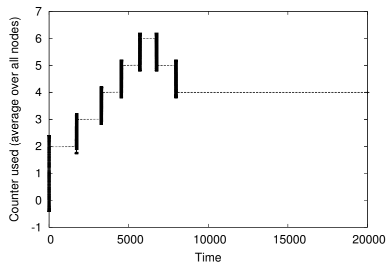
We observe that for the single-copy schemes, the priority scheduling outperforms the proportional allocation scheme. For the proportional allocation scheme, the parameter P_{SR} needs to be carefully selected to achieve performance comparable to the priority scheduling scheme.

Note that the relative ranking of different routing schemes, and the optimal values for the parameter settings, depend on the specific network setting. For example, when the network is lightly loaded, the two-hop K-copy scheme outperform the single-copy scheme, by utilizing the spare network bandwidth; whereas the single-copy scheme (with priority scheduling) performs best under a heavy load.

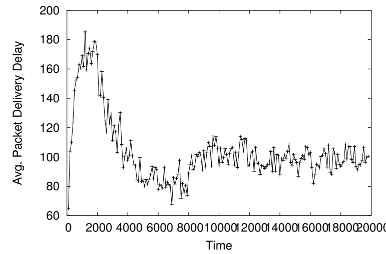
Overall, the models provide more accurate predictions when the network is lightly loaded.

7. Adaptive Source Control Scheme

Our modeling and simulation result suggests that routing control via source nodes' adjusting of counter values can be used to improve routing performance. To illus-



(a) Counter used by nodes over time



(b) Average delivery delay (averaged over 100s) over time

Figure 11: Dynamically adjusting K for two-hop K-copy scheme under $N = 101, \lambda = 0.05, \beta = 0.0049, P_{RD} = 0.5$ case

trate this potential benefit, we now propose a heuristic scheme where network nodes collaboratively search for the optimal counter value in an adaptive, distributed, and asynchronous fashion.

Each node runs in a sequence of *rounds*. When a node adjusts its counter (spray-and-wait counter or K in two-hop K-copy scheme), it enters a new round. For the initial two rounds, nodes use c_{min} and $c_{min} + c_{inc}$ counter values, where c_{min} is a preset minimum counter value and c_{inc} is the increment step. During each round, a node collects information about the delivery delay of packets transmitted using the current counter value[7]. After enough information has been collected, a node adjusts its counter and enters the next round. Each node stores history information about counter values that have been tried before as a vector of tuples (c, T_d^c, V_d^c), i.e., the counter value c, the corresponding average delivery delay T_d^c, and delay variance V_d^c.

Nodes collaborate in their search for the optimal counter value by exchanging control information when they encounter each other. If the two nodes are in the same round, they average their counter values. Otherwise, the node with smaller round number copy the other node's round number and counter value. The history information are also exchanged and updated, with newer information overrides older one.

During each round, a node monitors the average and *coefficient of variance* of delivery delay for all packets delivered using the current counter value, and checks if the criteria for starting a new round of counter adjustment are satisfied. Possible criteria include threshold values for the number of delivery delay samples, the coefficient of variance of delivery delay, and the number of source queue length (N_{SD}) observations.

Suppose that node i has observed that the average delay for packets using counter c_k to be d_k. Let c^* be the counter value that achieves the smallest average delivery delay in history, and d^* be the smallest delay. Node i follows the following rules to choose the new counter value.

1. If $c_k > c^*$ and $d_k > d^*$, then $c_{k+1} := (c^* + c_k)/2$.
2. If $c_k > c^*$ and $d_k < d^*$, then $c_{k+1} := c_k + c_{inc}$.

[7]The anti-packets are extended to include packet delivery delay.

3. if $c_k < c^*$ and $d_k > d^*$, then $c_{k+1} := (c^* + c_k)/2$.
4. if $c_k < c^*$ and $d_k < d^*$, then $c_{k+1} := c_k - c_{dec}$.

The c_{dec} is the decrement step. The rationale behind these rules is to let a node search for the minimum point in the U-shape curve of the delivery delay as a function of the counter value (e.g., Fig 2).

We conduct simulations to evaluate this simple heuristic scheme, using a threshold value of 200 for the number of delivery delay samples as the criterion for adjusting counter value. Fig 11.(a) plots the average counter used averaged over all nodes under the given simulation setting, and Fig 11.(b) plots the average packet delay's change over time. We can see that source nodes can quickly learn the optimal counter value.

These initial results illustrate the benefits of routing control via source nodes choosing optimal counters. To design an effective adaptive algorithm with guaranteed convergence, there are many issues to be addressed, for example, how to choose adjusting criteria and adjusting steps (c_{inc} and c_{dec}) to achieve fast and stable convergence behavior. We leave this as our future work.

8. Summary and Future Work

In this work, we investigated source routing control as an alternative approach to improve DTN routing performance. We first showed that for the spray-and-wait scheme, there exists an optimal counter value with which the minimum network-wide average packet delivery delay is achieved. Then in order to understand multi-hop multi-copy DTN routing schemes, we modeled the two-hop K-copy scheme 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 optimal counter value. In this process, we also discussed the capacity region of DTNs and provided an accurate analysis of the average packet delivery delay of the two-hop single-copy schemes. Relying on the insights gained from the modeling and simulation studies, we proposed an adaptive scheme that allow nodes to adjust their counter values (in search for an optimal counter value that minimize packet delivery delay). Our initial evaluation of this scheme demonstrated its effectiveness and suggested the potential of this approach for improving DTN routing performance.

The main limitation of this work lies in the fact that we have assumed a homogeneous exponential inter-meeting time mobility model and a homogeneous traffic model in our modeling studies. These assumptions justify our consideration of the homogeneous routing schemes, where all sources adopt the same source counter and all relay nodes employ the same transmission scheduling schemes. Although exponential inter-meeting time has been shown to be a good approximation for certain mobility model, recent works have shown that for a large class of mobility models, the inter-meeting time actually has a power law head and an exponential tail. How our results can be applied to such inter-meeting time distribution, and real mobility scenarios (especially those with heterogeneous meeting behavior) remains an open question that we will address in our future work. Throughout the paper, we have assumed a homogeneous traffic model where each node in the network is the source of one flow, and destination of another flow, and all flows have the same packet arrival rate. If the traffic model or the mobility model is no more homogeneous, the optimal routing scheme will not be a homogeneous scheme. For a simple example, a lightly loaded source node should use a larger source counter, and allocate more bandwidth for relay-to-destination traffic.

We also plan to investigate the more general case of multi-copy multi-hop DTN routing schemes. The model for the two-hop K-copy scheme with proportional allocation scheme (Section 6) is already very complex, the modeling of priority scheduling or other complicated scheduling scheme remains a big challenge.

Despite these limitations and open questions, our formal analysis for the two-hop routing schemes has provided some valuable insights to understanding more complicated schemes, and therefore is an important first step towards fully understanding the impact of source counter on the performance of DTN routing.

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