Opportunistic Shortest Path Forwarding in Delay Tolerant Networks

Jaeseong Jeong
KAIST
Daejeon, KOREA
jsjung@netsys.kaist.ac.kr

Kyunghan Lee
KAIST
Daejeon, KOREA
khan@netsys.kaist.ac.kr

Yung Yi
KAIST
Daejeon, KOREA
yiyung@kaist.edu

Injong Rhee
NCSU
North Carolina, USA
rhee@ncsu.edu

Song Chong
KAIST
Daejeon, KOREA
songchong@kaist.edu

ABSTRACT

Delay Tolerant Networks (DTNs) are characterized by probabilistic links formed among mobile nodes indicating their probabilistic encounters. Prior work on DTN routing uses expected delays as a routing metric to decide the next hop relay node for packet delivery to the destination. However, they measure the expected delays by taking the minimum of the expected delays over all possible paths from a candidate relay. This metric, denoted by *MinEx*, does not account for the opportunity gain enabled by having multiple paths to the destination through encountering multiple future neighbors. Since DTN routing uses as the relay the first encountered node satisfying given routing criteria, the random delays to multiple relay nodes should be aggregated. Thus, the true expected delays can be measured by taking the expectation of the minimum delays, denoted as *ExMin*, over all possible probabilistic paths from the candidate.

Categories and Subject Descriptors

C.2.2 [**Network Protocols**]: Routing protocols

General Terms

Algorithm Measurement

Keywords

DTN, Delay Tolerant Network, Opportunistic, Forwarding

1. INTRODUCTION

DTNs have emerged as an attractive networking paradigm under environments where nodes are mobile so that transmission links among mobile nodes are dynamically established or torn down. Such environments are becoming increasingly prevalent due to the rapid growth of heterogeneous mobile devices and delay-insensitive applications. DTN is also known for its capacity preserving data delivery mechanism [8] in which data packets (also known as bundles [1]) are forwarded toward their destinations through multi-hop forwarding using mobile relay nodes.

A central problem in DTNs is the selection of relay nodes. The problem is unique from wired networks because relays are not necessarily determined before the transmission of packets by the source. This is due to the probabilistic nature of DTNs where it is unknown in advance whether a node will meet a particular node in the future and use that node as a relay. Since a relay is often determined at the time of meeting that node, DTN routing is called *opportunistic routing*. This opportunism is different from that used in wireless multi-hop networks (see [4,6,14,19]) which relies on the broadcast nature of wireless medium to choose the next hop forwarder: after broadcasting a packet, the next relay (or forwarder) is selected among the nodes who happen to receive the packets. In such networks, packet receptions are probabilistic while in DTNs, node encounters are probabilistic.

In DTNs, to choose a relay among its contemporarily established neighbors, each node measures a routing metric for each candidate, where the metric refers to the cost of delivery for its packet to the final destination if the packet is forwarded to that candidate. Lately there has been an extensive array of studies on DTN routing [3, 5, 9, 11, 15, 16], most of which propose a new protocol for choosing a relay. Typically, these protocols work as follows: they first compute the expected cost (based on the said metric) of multi-hop forwarding from each candidate node to the destination. For multi-hops, the cost is computed transitively (e.g., [16]) considering all the possibilities of routing paths starting from that candidate node. When a node finds a candidate whose cost is less than a certain threshold (often set to its current cost for delivery) and the minimum among its contemporary neighbors, the node forwards or replicates the packet to the candidate node. The metric is suitably chosen depending on the design objective, examples including delay [3], probability of meeting [11] and expected remaining time for meeting another relay or destination [16]. All of these metrics can be ultimately translated into the expected delays for the final delivery.

Practically all the existing DTN routing studies [3,11,15,16] using the metric of expected delay compute the expected delay from a node to the destination by taking the minimum of the expected delays over all possible paths to the destination from that node. We refer to such a metric as *MinEx*.

As an illustration, consider a DTN with four nodes `A`, `B`, `C` and `D` in Figure 1. Each link is *probabilistic* where its associated cost of

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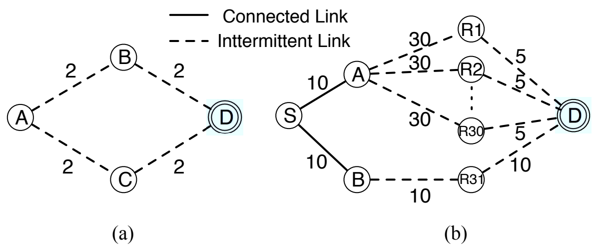

Figure 1: (a)An example to illustrate the difference between MinEX and ExMin: the MinEx of node A is 4 whereas ExMin is 3. (b) ExMin prefers the path through A over the path through B while MinEx does the opposite. The true expected delay of the two paths through A and B are 6 and 20 respectively.

2 is the expected delay for its two end nodes to meet in the future. Suppose that the probability distribution of the delays follows an exponential distribution with an intensity 1/2 (i.e., expected link delay is 2). MinEx from A to D yields the cost of 4, taking the minimum of the expected delays possible from A which has two choices of forwarding through either B or C.

However, MinEx ignores an important aspect of "opportunism" enabled by the two choices of probabilistic paths. Since A forwards a packet to whichever node it meets first as both nodes B and C have the equal cost, the one-hop cost from A to either B or C should be the minimum of two random delays[1] which is 1, the second hop cost is 2, and thus the total cost is 3. Therefore, the true expected delay from A is the expectation of the minimum random delays that B and C has for meeting A. We call such a metric *ExMin*. Intuitively, the expectation of the minimum can be viewed as taking the aggregation of the arrivals of the two possible choices since A chooses as a relay whichever node it meets first out of B and C. We elaborate on this more formally in Section 4.

Incorrect accounting of the opportunity gain has a significant impact on the end result leading to grossly different, yet much less optimal paths. Consider a DTN in Figure 1 (b) where packets are routed from S and D. Suppose that the currently established neighbors to S are A and B. The other links are probabilistic with costs representing the expected inter-meeting times between the two end nodes of the links. As S chooses the relay between A and B, it measures the expected delays from them. The expected delay through A has 6 ($= 30(1/30) + 5$) while that through B has 20. However, MinEx yields 35 and 20 as the expected delays through A and B, respectively. Thus, the conventional technique favors B over A as the relay. But in reality, A is a much better choice since its true expected delay is 6 instead of 35.

ExMin estimates more accurately the actual routing delays over probabilistic links since it accounts for the aggregation of the random arrivals of multiple future neighbors. We denote the ExMin value of a node R considering only the paths of k hops or less from R to the destination, by *ExMin(*R*)-k*. For example, in Figure 1(b), S uses ExMin(A)-2 and ExMin(B)-2. Intuitively, ExMin-2 tends to favor relays with many potential neighbors that have the destination as its potential neighbor because it takes the minimum of random delays. For instance, in Figure 1(b), it favors A over B. ExMin-k applies this intuition over multi-hop paths transitively.

2. RELATED WORK

A number of DTN routing studies are based on epidemic routing [18] which floods packets to every connected node. While it guarantees optimal forwarding under no channel contention, flooding incurs huge overhead in terms of channel resource, storage and power consumption in the network. Epidemic routing does not achieve the optimal performance when channel contention is considered. In order to find a DTN routing path without flooding, many popular DTN routing methods [10, 12] are heuristically developed. There are several theoretical studies [2, 3, 11, 13] trying to find the optimal DTN routing strategy. [3] proposes a technique to reorder packets in the transmission queue in order to maximize a given network utility. [2, 13] uses dynamic programming using backward induction and presents threshold schemes as a forwarding decision method. However, the backward induction works only when there are no transmission contention in the networks. Thus, it is applicable only to the networks with extremely low node density. [11] introduces snapshot optimality which approximates the optimal link and copy scheduling in DTNs. Unfortunately, none of the prior work propose a routing metric accounting for the opportunity gain, as ExMin does, enabled by the probabilistic nature of inter-contact times among nodes.

3. ASSUMPTIONS

We assume that each DTN node is equipped with a wireless radio and a computing device with some amount of storage. Packets are the basic means of communication and is typically large enough to carry one self-contained message with proper address information about its source and destination. Each node is identified by a unique ID. There are n nodes in the system and all nodes always move within a predefined area. We say that when two nodes are in the radio range of each other, they *meet* each other, or they are *connected*. Because of mobility, the neighbors of each node change over time. We assume that when two nodes are connected, there are connected sufficiently long enough to exchange all the packets of one node to another and there is no loss of packets. The transmission delays of packets once two nodes are connected are relatively very small compared to the time it waits to meet each other. So we assume that the transmission delays are negligible. The *inter-contact time* (ICT) of two nodes are the time taken for the two nodes to meet again after meeting the last time. We assume that each node i is aware of its own mobility patterns such as who it "regularly" meets and the distribution of inter-contact times (ICTs) with those nodes j. We mean by "regularly" that their meeting frequencies are statistically significant often to compute the ICT distribution. For any two nodes that meet regularly v and w, we can define a random variable $I_{v,w}$ representing the inter-contact time. If two nodes have history of regular meetings and they are aware of their ICT distribution, we say they are the *neighbors* of each other. When we represent a *link cost* between two nodes that are not currently connected, we use the mean inter-contact time (ICT), or simply *expected delay* and its distribution. Such links are probabilistic links.

Throughout this paper, we will refer to a canonical form of opportunistic routing commonly used in DTNs. It works as follows. A source node S has a packet to deliver to a destination node D. When S meets a set of nodes $\mathcal{N}$ while holding the packet, then it evaluates the following *forwarding conditions*. For each node v in $\mathcal{N}$, it computes a metric $\mathcal{M}(v)$, which is essentially the cost of delivering the packet to D through v. If (1) $\mathcal{M}(v)$ is less than $\mathcal{M}(\texttt{S})$ and (2) $\mathcal{M}(v)$ is the minimum among all $\mathcal{M}(l)$, $l \in \mathcal{N}$, then v is chosen as a *relay node* and S forwards the packet to v. After the forwarding, it deletes the packet from its storage. Any relay node holding the packet performs the same operation as S until the packet is delivered to D. In some cases, condition 1 is checked with

[1]For two exponential random variables $X_i \sim \exp(\lambda_i)$, $i = 1, 2$, $Y = \min(X_1, X_2) \sim \exp(\lambda_1 + \lambda_2)$.

a fixed threshold (see [2, 13]). If multiple copies of the packet are allowed, the packet is not deleted after the forwarding.

4. EXPECTATION OF MINIMUM (ExMin)

4.1 Definitions

Every prior work we know of that uses expected delays for routing metric uses the minimum of the expected delays. Formally, the minimum of the expected delays from v to the destination is computed as follows. For each node w in the neighbor set of v, we can define the minimum of the expected delays recursively as follows.

$$\text{MinEx}(v) = \min_{w \in v\text{'s neighbors}} \mathbb{E}\Big[I_{v,w} + \text{MinEx}(w)\Big],$$

MinEx(D) for destination node D is zero. We can limit the computation of MinEx only over the paths of k hops or less to the destination. Any paths not reachable to the destination within k hops have infinite cost. We denote such a metric by MinEx-k. MinEx-n considers all possible simple paths without any cycles.

A DTN routing is highly opportunistic as a source (or relay node) forwards its packets to the first node that it meets and satisfies the forwarding condition. Therefore, the expected delay must be computed using the expectation of the minimum expected delays possible through any neighbors of a candidate node. ExMin accounts for the increased probability of meetings when a node has many neighbors. Formally, for each node w in the neighbor set of v, we can define ExMin (v) as follows.

$$\text{ExMin}(v) = \mathbb{E}\Big[\min_{w \in v\text{'s neighbors}} (I_{v,w} + \text{ExMin}(w))\Big]. \quad (1)$$

ExMin(D) is zero.

In the same way as we define MinEx-k, we can define ExMin-k to limit the computation of ExMin to the paths of k hops or less.

4.2 Metric Computation

In the computation of the routing metric in Equation (1), we essentially compute the expectation of X, where

$$X = \min_{j \in \mathcal{N}} \{I_j + m_j\},$$

for a positive integer j and a finite index set $\mathcal{N}$. Note that I_j and m_j denote a random variable representing inter-contact time and a constant representing a neighbor's ExMin metric respectively. Recent studies reveal that the human-carried devices show a truncated power-law distribution [7] , whereas taxies in a city produce an exponential distribution [11]. It is reasonable to assume that the inter-contact time distribution between nodes v, w are given, because it can be collected from private contact histories and is known to v and w.

Assuming that I_js' are independent (i.e., the inter-contact times are independent for two different neighbors), it is convenient to first compute the CCDF of $\mathbb{P}[X > x]$, and then obtain the PDF of $\mathbb{P}[X = x]$ by differentiating the CCDF. When the distribution of the inter-contact time I_j is known, using the following:

$$\begin{aligned} \mathbb{P}[X > x] &= \mathbb{P}[I_j + m_j > x,\ j \in \mathcal{N}] \\ &= \prod_{j \in \mathcal{N}} \mathbb{P}[I_j + m_j > x]. \end{aligned} \quad (2)$$

Thus, we can get $\mathbb{P}[X > x]$ by computing $\mathbb{P}[I_j + m_j > x]$. Then, by definition of expectation, it is easy to compute $\mathbb{E}[X]$ either in the closed-form or numerically.

5. PERFORMANCE EVALUATION

5.1 Dataset

We use the Shanghai taxi traces [17] to create the network test scenarios to evaluate our proposed routing metrics.

In the traces, the location information of about 4000 taxies is recorded at every 40 seconds within an area of 102 km^2 for 28 days (4 weeks). In order to present more reliable results, we selected 1486 taxies (out of all 4000 taxies) which recorded more than 70 % of GPS readings with high accuracy.

Table 1: Tested Algorithms ('Opp.': 'Opportunism')

Algorithm	Info. required	Meeting Opp.
MinEx-2	local	×
MinEx-n	global	×
ExMin-2	local	○
ExMin-n	global	○

Table 1 lists all the routing metrics that we tested and shows their properties.

5.2 Simulation Results

We randomly selected 1000 S-D pairs which have their own sessions from sources vehicle to destination vehicles. We assume the application scenario of transmitting DVR video files or advertisement video files to the node wherever it is. We also vary the number of packets to see the performance for different traffic load(i.e., the number of injected packets to each S-D session). Note that all the injected packets are given to the source vehicles when the session starts. communication range of each taxi to be 300 meter, a typical range of WiFi. We make the routing control decisions at every 30 seconds. We repeated ten simulations by different S-D pairs which are randomly chosen with different seeds in each time. The 95% confidence interval of each simulation is also computed. Figure 2 shows the delays and delivery ratios of tested algorithms in the single-copy mode for various offered loads. We observe that ExMin-n outperforms MinEx-n by 8∼10% in delays. Since the metrics of MinEx-2 and ExMin-2 which use local information estimate only two hop paths, we observe that their delay performance is 8∼14% worse than MinEx-n and ExMin-n when the offered load is 50.

6. CONCLUSIONS

Probabilistic links formed among mobile encounters in DTN leads challenging routing problems. So far, a popular approach is to use expected delays as a routing metric to decide the next hop relay node for packet delivery to the destination, based on the minimum of the expected delays over the possible paths. This *MinEx* metric ignores the opportunity gain induced by probabilistic link delays in spite of opportunistic forwarding of selecting the relay that is first encountered. To exploit such an opportunism in the routing metric computation, we propose a new metric *ExMin-k* that takes the expectation of the minimum delays over k hops. Our simulation result shows that ExMin ourperforms MinEx in delay.

7. ACKNOWLEDGMENTS

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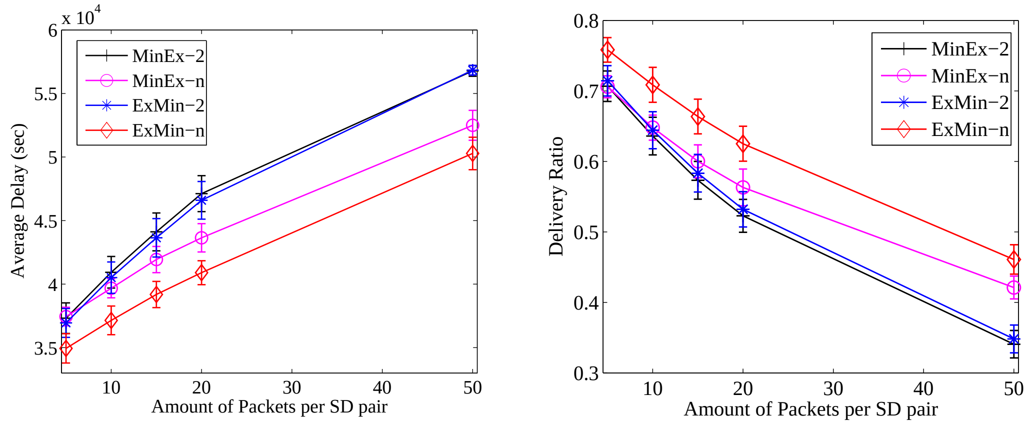

(a) Delay (b) Delivery Ratio

Figure 2: the Delay and Delivery Ratio of algorithms versus the offered load of 1000 S-D pairs. Each value shows 95% confidence interval.

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