An Efficient Prediction-based Routing Protocol in Delay Tolerant Networks

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***Abstract*—Delay Tolerant Networks (DTNs) are characterized by sparse node density, uncertain node mobility and lack of global information, which make routing one of the most challenging problems. In this paper, we propose a new routing protocol for DTNs. We observe that the forwarding performance of a node is not only determined by its contact schedules with the destination but also affected by its contacts with the neighbor where the packet is received from, which has not been considered in most of existing routing schemes in DTNs. Based on this observation, we design a novel routing metric, called Instant Delivery Probability (IDP), which provides an accurate estimation on node forwarding performance in terms of packet delivery ratio and can be efficiently calculated with local information. The single-copy and multi-copy forwarding algorithms are also presented, where each message is opportunistically forwarded to the nodes with largest IDP to maximize the delivery probability. Extensive trace-driven simulations show that our routing protocol with IDP significantly improves the routing performance compared to the state-of-the-art forwarding strategies.**

I. Introduction

A Delay Tolerant Network (DTN) is a mobile wireless network where nodes are intermittently connected due to the sparsity of node density and the uncertainty in node mobility. Since a contemporary path between the source and destination nodes rarely exists, data dissemination in DTNs follows a store-carry-forward paradigm: each node stores and carries the received packets and opportunistically forwards them upon contacts with other nodes. In practice, DTNs have a variety of applications, which include pocket switched networks [1], vehicular ad hoc networks [2], large-scale disaster recovery networks [3] and so on.

The inherent uncertainty about network connectivity makes routing one of the most challenging problems in DTNs. Existing solutions can be placed on a spectrum from blind forwarding [4], [5] in which packets are routed without any knowledge about the network to the oracle-based algorithms [6] which assume even future contact schedules are available for nodes to make routing decisions. Between these two extremes are the schemes where node mobility behavior is predicted based on the historical contacts [7]–[11]. Packets are transmitted to the nodes with higher forwarding capability estimated by a certain metric until they reach the destination. Therefore, such schemes are also called prediction-based routing protocols. Generally, prediction-based routing protocols could achieve higher delivery efficiency than blind forwarding strategies and are much more practical when compared to the oracle-based algorithms.

Packet delivery ratio is one of the most important metrics for evaluating the performance of forwarding strategies in DTNs [6], [12]. Most of existing prediction-based routing protocols take some heuristic characteristics of node contacts, such as the contact frequency [7], the time elapsed since the last encounter [8], [13] and the inter-contact time with the destination [14], as routing metrics to estimate node forwarding performance and select the intermediate nodes. For example, a node transmits a packet to its neighbor which has the highest contact frequency with the destination under the intuition that the more frequently two nodes encounter with each other, the shorter the inter-contact times as well as the packet transmission delay are, and thus the higher the packet delivery ratio is expected to be. However, these metrics do not make effective use of the information contained in node contact history and cannot accurately evaluate node forwarding capability, which makes traditional prediction-based routing protocols always suffer from severe performance degradation (See Section II-B for more details).

In this paper, we propose a new prediction-based routing protocol for DTNs. We observe that the performance for a node to relay a packet to the destination depends on not only the contact schedules between them but also its contacts with the predecessor where the packet is received from. Inspired by this observation, we design a novel routing metric, called Instant Delivery Probability (IDP), which calculates the probability of a node to successfully deliver a certain packet to the destination before it expires. A single-copy routing algorithm is developed, which opportunistically forwards a packet to the nodes with maximum IDP to increase the delivery ratio. The extension for the multi-copy forwarding scenario is also discussed. Through extensive trace-driven simulations, we demonstrate that our routing protocol significantly improves the packet delivery ratio with low transmission cost.

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II. PRELIMINARIES

A. System Model

Consider a DTN with a collection of mobile nodes. Data can be transmitted between two nodes only when they are within the communication range of each other, which is referred to as a contact between them. Contact duration is the time interval over which two nodes are continuously in contact, and the inter-contact time is defined as the time interval between two successive contacts associated with them. According to the observations on node mobility in [10], [15], we assume that the inter-contact times between a pair of nodes are independent and identically distributed (i.i.d.). The distribution of inter-contact times between different nodes are not necessary to be identical, but they are independent of each other. In addition, since contact duration is observed to be much smaller than inter-contact time in a number of real mobility traces [16], [17] [1], we will only consider the delivery latency caused by intermittent node connection and ignore the transmission delay induced by contact durations.

Each message is associated with a time-to-live when it is generated at the source node. Expired copies of messages will be deleted immediately. In this paper, we concentrate on the gradient routing in DTNs [18], where routing decisions are made based on local information to avoid the significant overhead incurred by the dissemination of the link state information throughout the network.

B. Motivation

In the literature, the time elapsed since the last encounter, the contact frequency and the inter-contact time with the destination are three most commonly used routing metrics. In this subsection, we use a simple example to illustrate the inefficiency and inaccuracy of these metrics in evaluating node forwarding capability. The analysis also provides some insights into the design of the routing metrics for DTNs, which motivates the novel routing metric and forwarding strategies we propose in the next section.

Consider a toy DTN with 4 mobile nodes. The source node S has a packet destined to node D. Assume that S and D never have a contact with each other, and there are two candidates, nodes A and B, which can act as the relay to forward the packet to the destination D for S. Fig. 1 shows the contact schedules between each pair of nodes. Here, in order to simplify our analysis, we assume that the inter-contact times of all the node pairs are constant and the inter-contact times between nodes A and D are the same with those between nodes B and D, but the contacts happen at different times. We also assume that the source node S encounters both A and B simultaneously at time t and will choose one of them to deliver the packet to the destination D. Since nodes A and B have the same contact frequency and inter-contact times with node D, if the routing metrics are designed based on them, the forwarding capability of the two nodes are expected

[1]For example, the mean inter-contact time is 387.1 hours and the mean contact duration is only 0.3 hours for Dartmouth, 280.6 hours and 0.8 hours for MIT, 4.9 hours and 0.03 hours for Infocom2005, respectively [16].

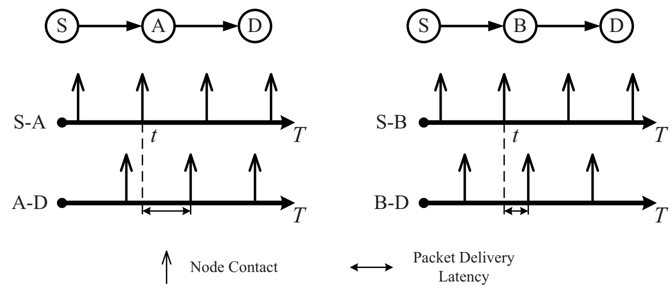


Fig. 1: A simple example to illustrate the inefficiency of existing routing metrics.

be identical and either one of them can be selected as the intermediate node. If the routing decision is made according to the time elapsed since the last encounter with the destination, node A will be preferred since it meets node D more recently than B. However, we observe that the time for A or B to deliver the packet to the destination D is not only determined by its contact schedules with D but also the contact time with S, and here node B has much smaller delivery delay than that of node A. Thus, node B should be selected as the forwarder.

From the above example, we can observe that the forwarding performance of a node to the destination in DTNs is not only determined by the contact schedules between them but also affected by its contacts with the predecessor where the packet is received from. Since the contact frequency, the time elapsed since the last encounter and the inter-contact time with the destination fail to consider this characteristic, all the routing metrics designed based on them cannot accurately evaluate the node forwarding capability.

III. ROUTING BASED ON INSTANT DELIVERY PROBABILITY

A. Instant Delivery Probability

Inspired by the observation we made in Section II-B, in this subsection, we introduce a new routing metric for DTNs, which is called Instant Delivery Probability (IDP). IDP is defined as the probability for a node to successfully transmit a certain packet to the destination before it expires. We first consider the case of single-copy forwarding. Assume node i carries a packet $\pi = (s, d, t_\pi)$ to be delivered to node d. Here, s is the source node, d is the destination node and t_π is the expiration time of the packet, respectively.

If node i decides to directly forward the packet π to the destination d, node d can successfully receive it before t_π only when node i encounters the destination d within the residual time-to-live of the packet. Let I_{id} denote the inter-contact times between nodes i and d, which is a random variable with a certain distribution. Then, at time t, the probability $P(i, i, \pi, t)$ that node i is able to transmit the packet π to node d can be

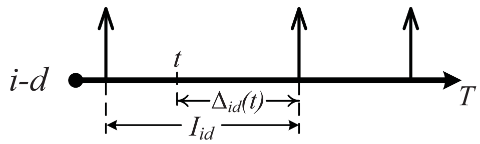


Fig. 2: The timetable for node i to directly deliver packet π to the destination d.

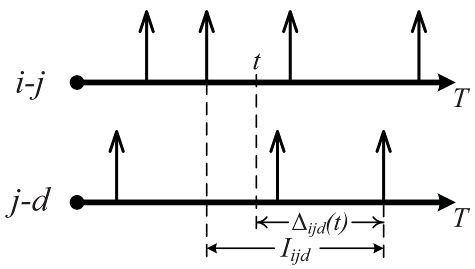


Fig. 3: The timetable for node i to deliver packet π to the destination d via node j.

calculated as follow:

$$\begin{aligned} P(i,i,\pi,t) &= \Pr[\Delta_{id}(t) \leq t_\pi - t] \\ &= \Pr[I_{id} \leq t_\pi - T_{id}(t) | I_{id} \geq t - T_{id}(t)] \\ &= \frac{\Pr[t - T_{id}(t) \leq I_{id} \leq t_\pi - T_{id}(t)]}{\Pr[I_{id} \geq t - T_{id}(t)]}, \end{aligned} \quad (1)$$

where $\Delta_{id}(t)$ denotes the residual inter-contact time between nodes i and d at time t and $T_{id}(t)$ represents the most recent contact time of nodes i and d before time t. The timetable of the packet delivery in this scenario is shown in Fig. 2.

Alternatively, node i could relay the packet to the destination d via one of its neighbors, say node j. Fig. 3 shows the timetable. In order to calculate the delivery probability in this scenario, we define a new random variable, called two-hop inter-contact time. Given the neighboring node j, the two-hop inter-contact time between node i and the destination d via node j is the summation of the inter-contact time between nodes i and j and the residual inter-contact time between nodes j and d when nodes i and j encounter, which is denoted as I_{ijd}. Then, according to the timetable illustrated in Fig. 3, the probability for node i to deliver the packet π to the destination d via the intermediate node j before it expires can be derived as follows:

$$\begin{aligned} P(i,j,\pi,t) &= \Pr[\Delta_{ijd}(t) \leq t_\pi - t] \\ &= \Pr[I_{ijd} \leq t_\pi - T_{ij}(t) | I_{ijd} \geq t - T_{ij}(t)] \\ &= \frac{\Pr[t - T_{ij}(t) \leq I_{ijd} \leq t_\pi - T_{ij}(t)]}{\Pr[I_{ijd} \geq t - T_{ij}(t)]}, \end{aligned} \quad (2)$$

where $\Delta_{ijd}(t)$ and $T_{ij}(t)$ denote the residual two-hop inter-contact time between nodes i and d via node j at time t and the most recent contact time of nodes i and j before time t, respectively.

Let $\mathcal{N}_i$ denote the set of neighbors of node i. Then, the IDP of node i with respect to packet π at time t is equal to the maximum delivery probability node i could achieve to transmit packet π to the destination, i.e.,

$$\mathcal{IDP}(i,\pi,t) = \max_{j \in \mathcal{N}_i^+} P(i,j,\pi,t), \quad (3)$$

where $\mathcal{N}_i^+ = \mathcal{N}_i \cup \{i\}$.

In order to calculate $\mathcal{IDP}(i,\pi,t)$, node i has to know the distributions of $\mathcal{I}_{id}$ and $\mathcal{I}_{ijd}$ for each neighboring node j according to Eqn. (1) and Eqn. (2). Therefore, when two nodes encounter with each other, they will records the information of this contact to update the distribution of their inter-contact times and also exchange their contact history with other neighbors to update the two-hop inter-contact times. Compared to the cost for the dissemination of link-state information throughout the network, the communication overhead incurred by IDP is very low.

B. Opportunistic Forwarding Algorithm

Since the value of IDP for each node is time-variant as shown in Eqn. (3), the optimal forwarder selected based on IDP will also change over time. Therefore, a node has to make the routing decision for a packet each time it encounters with other nodes. Assume node i carries a packet π that is destined to node d and it meets node j at time t. To maximize the packet delivery probability and thus the delivery ratio, node i will forward packet π to node j only if

$$\mathcal{IDP}(i,\pi,t) > \mathcal{IDP}(j,\pi,t). \quad (4)$$

In practice, node i may meet several nodes at the same time. In that case, packet π will be transmitted to the node with the largest value of IDP. Let $\mathcal{E}_i(t)$ denote the set of nodes that node i encounters at time t. Then, the relay node $r(\pi,t)$ for packet π at time t can be determined as follows:

$$r(\pi,t) = \arg\max_{j \in \mathcal{E}_i^+(t)} \mathcal{IDP}(j,\pi,t), \quad (5)$$

where $\mathcal{E}_i^+(t) = \mathcal{E}_i(t) \cup \{i\}$. If there are more than one node with the maximum IDP, node i just randomly selects one from them as $r(\pi,t)$. If $r(\pi,t) = i$, node i will continue to carry the packet until its next contact opportunity; otherwise, it will send π to node $r(\pi,t)$, which then becomes the new forwarder.

C. Extension

Due to the unavailability of global knowledge about the network state in DTNs, the performance that the single-copy routing protocols could achieve is usually far from optimal. A common method to further increase the delivery ratio and reduce the delivery latency is to disseminate multiple copies of the same message to different nodes in the network, which is called multi-copy forwarding. The message is successfully delivered if one of these nodes encounters the destination within its time-to-live.

We consider a generalized version of the Spray and Wait mechanism [19], [20] as the framework for packet replication. The mechanism works as follows: each message copy is associated with several logical tickets, which determines the maximum number of replicas that can be created from this copy. When two nodes encounter with each other, the tickets will be redistributed between them. The total number of tickets for a message is upper-bounded by a threshold.

In the case of multi-copy forwarding, the calculation of the delivery probability should take the number of tickets into consideration as well. Let $\mathcal{IDP}(i, \pi, m, t)$ denote the instant delivery probability of node i when it carries a copy of packet π with m tickets at time t. Assume that each copy of the same packet is forwarded independently without any knowledge of the status of the other copies. Since the inter-contact times associated with different node pairs are independent of each other, we have

$$\mathcal{IDP}(i, \pi, m, t) = \max_{\mathcal{N} \subseteq \mathcal{N}_i^+, |\mathcal{N}| \leq m} \Big[1 - \prod_{j \in \mathcal{N}} \big(1 - P(i, j, \pi, t)\big)\Big]. \tag{6}$$

Assume that node i encounters node j at time t and the total number of the tickets associated with packet π they carry is u. Let $\mathcal{S}_u$ be the set of all the possible distributions of the tickets between nodes i and j. For each distribution $s \in \mathcal{S}_u$, let s_i and s_j represent the number of tickets assigned to nodes i and j, respectively, where $s_i + s_j = u$. Then, the tickets associated with packet π will be redistributed between nodes i and j to maximize the packet delivery probability, i.e.,

$$s(\pi, u, t) = \arg\max_{s \in \mathcal{S}_u} \mathcal{IDP}(i, \pi, s_i, t) \cdot \mathcal{IDP}(j, \pi, s_j, t). \tag{7}$$

Similarly, when node i meets several nodes simultaneously, the optimal ticket redistribution of packet π among them at time t can be determined as follows:

$$s(\pi, u, t) = \arg\max_{s \in \mathcal{S}_u} \left(\prod_{j \in \mathcal{E}_i^+(t)} \mathcal{IDP}(j, \pi, s_j, t) \right). \tag{8}$$

Note that when $m = 1$ and $u = 1$, Eqn. (3) and (5) will reduce to Eqn. (6) and (7), respectively, which indicates that the single-copy routing protocol we designed above is a special case of the multi-copy routing protocol where the total number of tickets associated with packet π is equal to 1.

IV. Simulation

In this section, we evaluate the performance of our single-copy routing protocol with IDP and compare it to the existing forwarding strategies designed based on the heuristic metrics. Simulation results show that our protocol significantly improves the efficiency of packet forwarding in DTNs and outperforms all the other schemes in different scenarios. Due to the space limit, we leave the performance evaluation of our multi-copy routing protocol as the future work.

A. Data Sets

Our simulations are conducted based on two distinct empirical data sets: one is the mobility trace collected in Infocom 2006 conference(Infocom2006) [21], which records the contacts between short-range Bluetooth enabled devices (i.e., iMotes) carried by a group of attendees for 4 days. The other one is the contact trace collected from the University of California, San Diego (UCSD) [22], which contains client-based logs of WiFi access points (APs) during 3 months. In

TABLE I: The characteristics of the data sets

Trace	Infocom	UCSD
Year	2006	2002
Device	iMote	PDA
Technology	Bluetooth	WiFi
Number of Devices	98	275
Duration (Days)	4	77
Number of Contacts	$22,459$	$46,302$

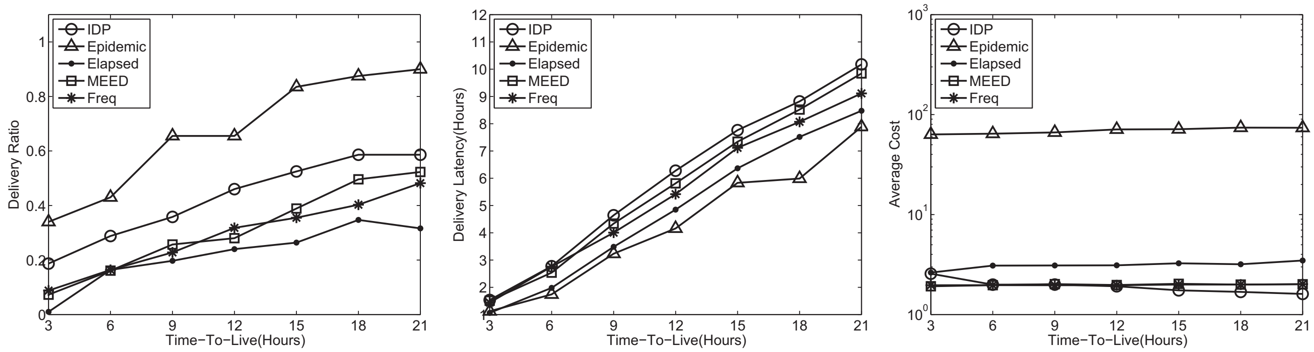
order to obtain the data about inter-device contacts in UCSD for our simulations, we assume that two mobile devices have a contact with each other when both of them are connected to the same AP. The main characteristics of these two data sets are summarized in Tab. I. Note that the average node degree in UCSD is much smaller than that in Infocom2006, which indicates that the DTN formed in UCSD is sparser than that in Infocom2006.

B. Simulation Setting

We implement the Epidemic routing protocol and a variety of single-copy routing protocols with the heuristic metrics. All of them are distributed algorithms and work with local information.

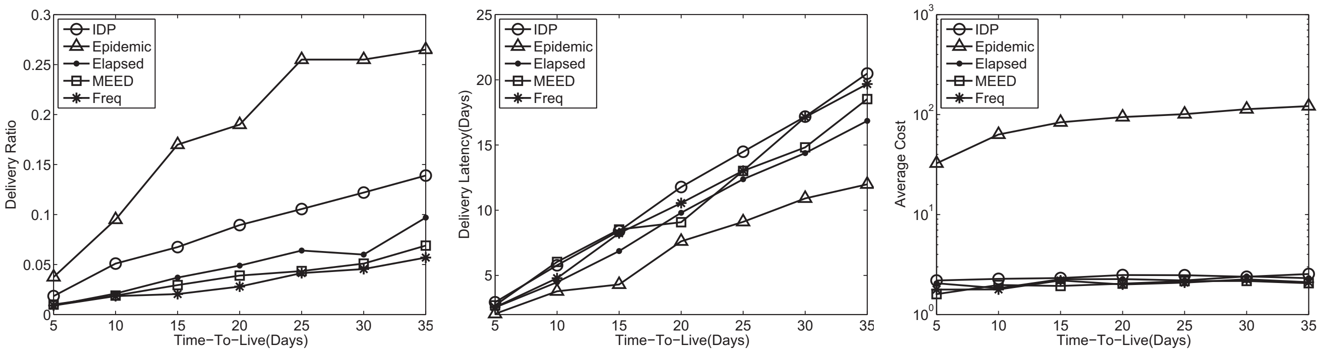
- **Epidemic Routing (Epidemic) [5]:** In Epidemic routing, a node replicates a packet to every encountered node that has not received it yet, until the packet times out. Therefore, Epidemic routing could achieve the minimum delivery latency, which yields an upper bound on the packet delivery ratio.
- **Contact Frequency (Freq) [7]:** Packets are transmitted from one node to its neighbor which has the highest contact frequency with the destination.
- **Elapsed Time (Elapsed) [8]:** Each node maintains a table which records the time elapsed since its most recent contact with every other node in the network. A node will forward the packet to the first encountered node that met the destination more recently than itself. This protocol is also known as FRESH [8].
- **Minimum Estimated Expected Delay (MEED) [14]:** MEED is designed based on inter-contact times, which estimates the expected delay for one node to deliver a packet to the destination under the assumption that packet arrive time is uniformly distributed. A node will relay a packet to the neighbor with the minimum value of MEED for the destination. In [14], MEED is computed with global information. To make fair comparison, it is calculated with local information during our simulations.

In our simulations, packet generation follows a Poisson process, where the average packet arrival rate is appropriately chosen according to the duration of each trace. The source and destination of each packet is randomly selected from all the nodes in the network. We use the following metrics to evaluate the performance of the routing protocols: delivery ratio, delivery latency and average cost. Delivery ratio is formally defined as the ratio of the number of successfully delivered packets to the number of all the packets transmitted



(a) Delivery Ratio. (b) Delivery Latency. (c) Average Cost.

Fig. 4: Performance comparison of different routing protocols in Infocom2006 trace.



(a) Delivery Ratio. (b) Delivery Latency. (c) Average Cost.

Fig. 5: Performance comparison of different routing protocols in UCSD trace.

in the network. Delivery latency is the average end-to-end delay experienced by each received packet. Average cost is defined as the average number of transmissions for each packet to be delivered to the destination. All the results are averaged over 10 simulation runs.

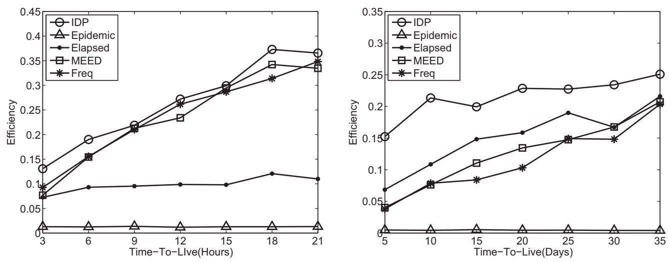
C. Results

We first evaluate the performance of our routing protocol based on the Infocom2006 trace. Fig. 4 (a) shows the comparison of packet delivery ratio under different values of time-to-live, which varies from 3 hours to 21 hours. It is illustrated that when the time-to-live is small (e.g., 3 hours), the delivery ratio of all the routing protocols is very low due to lack of forwarding opportunities. The delivery ratio increase as the time-to-live increases. Specifically, Elapsed has the smallest delivery ratio. The reason is that the design of Elapsed is based on the assumption that the duration of a time interval and the distance traveled within it is positively correlated [8], which is not true according the observations from real mobility traces. The delivery ratio achieved by MEED and Freq is roughly equal to each other. IDP performs better than Elapsed, MEED and Freq. Its delivery ratio is closed to that of Epidemic, especially when the time-to-live is short. For example, when the time-to-live is 6 hours, the delivery ratio of IDP is 1.8 times of that of Elapsed, MEED as well as Freq, and it is 67% of the delivery ratio of Epidemic.

The delivery latency of different forwarding strategies are compared in Fig. 4 (b). The results show that Epidemic has the shortest delivery latency among all the routing protocols. The delivery latency of IDP is approximately equal to that of MEED and Freq, and it is larger than that of Elapsed. Since IDP is designed to maximize the delivery ratio, a node with large transmission delay may also be selected as the forwarder as long as the delay is within the time-to-live and its delivery probability is high, which causes the additional delay. Note that the delivery latency of IDP is around 50% of the time-to-live in all the simulation scenarios. Therefore, it is acceptable for the applications where the delivery ratio is considered as the primary performance metric.

Fig. 4 (c) illustrates the average cost of the routing protocols with various time-to-live. It is observed that Epidemic suffers from significant overhead compared to other schemes. IDP always has the lowest transmission cost, which is only 3% of the cost incurred by Epidemic.

We also study the performance of Epidemic, Elapsed, MEED, Freq and IDP with the UCSD trace. As shown in Fig. 5, the results are similar to those obtained from Infocom2006 traces. Since the network of UCSD is much sparser than that formed in Infocom2006, the delivery ratio of all the strategies degrades severely and the delivery



(a) Infocom2006. (b) UCSD.

Fig. 6: Comparison of delivery efficiency in Infocom2006 and UCSD traces.

latency drastically increases. In addition, it is observed that the improvement in packet delivery ratio achieved by IDP is much more significant in the UCSD trace than that with Infocom2006 trace. For example, when the time-to-live is 10 days in Fig. 5 (a), the delivery ratio of IDP is 2.4 times of Elapsed, 2.7 times of MEED and 2.8 times of Freq, respectively. Moreover, we find that although the scale of the network in UCSD is much larger than that of Infocom2006, the average cost of all the single-copy routing protocols is almost the same in the two different scenarios, which is shown in Fig. 5 (c).

The delivery ratio, delivery latency and average cost are commonly used metrics to evaluate the routing performance in DTNs. But all of them cannot characterize the relation between the achievement of a routing protocol and its overall cost. Therefore, we also consider a new metric during our simulations, called delivery efficiency, which is defined as the ratio of the delivery ratio to the total number of transmissions for all the packets in the network. Fig. 6 compares the delivery efficiency of the routing schemes in Infocom2006 and UCSD traces, which shows that IDP achieves the optimal delivery efficiency compared to Epidemic, Elapsed, MEED and Freq. Moreover, the improvement is much more significant when the time-to-live is small and the network is sparser.

V. Conclusion

Routing is one of the most challenging problems in DTNs due to the uncertainty of network connectivity and lack of global information. In this paper, we propose a new routing protocol for DTNs. We design a novel routing metric, called Instant Delivery Probability (IDP), which provides an accurate estimation on the delivery ratio and can be calculated with local information. The single-copy and multi-copy routing algorithms are also developed, where the nodes with the largest value of IDP are selected as forwarders to maximize the packet delivery ratio. Extensive simulations show that the routing protocol with IDP significantly improves the routing performance compared to the state-of-the-art forwarding strategies with the heuristic metrics.

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