Exploiting Small World Properties for Message Forwarding in Delay Tolerant Networks

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Abstract—In Delay Tolerant Networks (DTNs), the connections between mobile nodes are always disrupted and constant end-to-end paths rarely exist. In order to cope with these communication challenges, most existing DTN routing algorithms favour the “multi-hop forwarding” fashion where a message can be forwarded by multiple relay nodes in the hope that one of the employed relay nodes can deliver the message to the destination node. Since aggressively employing relay nodes may incur the intolerable delivery cost in DTNs, it is meaningful to design a cost-efficient routing algorithm that can achieve a high delivery performance. In this paper, we first design a novel delivery metric to measure the forwarding capability of nodes. Then, we utilize small-world properties to design the principles of relay node selection, e.g., limiting the number of relays and finding the appropriate relay nodes, and further develop a cost-efficient social-aware forwarding algorithm called TBSF. Extensive simulations on real mobility traces are conducted to evaluate the performance of TBSF, and the results demonstrate its efficiency and usefulness.

Index Terms—delay tolerant networks; small-world phenomenon; relay node; social-aware routing

1 INTRODUCTION

With the recent popularization of mobile devices such as smart phone, a novel wireless communication paradigm known as Delay Tolerant Networks (DTNs) [1] emerges as complementary to existing ones. In DTNs, mobile nodes are connected intermittently, and constant end-to-end paths are rarely available. These properties make routing in DTNs to become a challenging problem. To cope with it, most existing DTN routing algorithms favour the “multi-hop forwarding” fashion where messages rely on relay nodes to carry and deliver them to destinations. In this way, several relay nodes are employed to provide more, and even better, opportunities to deliver messages to their intended destination node. For example, Epidemic routing [2], a naive multi-hop forwarding approach, excels in the delivery ratio by employing every possible encountered nodes as relay to deliver messages. However, it also incurs an intolerable delivery cost. Therefore, it is of great significance to cope with the problem of relay node selection.

Considerable effort has recently been devoted to the issue of relay node selection. Cao et al. [3] utilize the geographic information to guide the selection of relay nodes. They are generally applied to the cases where mobile model is known in prior. However, it is difficult to obtain these knowledge in DTNs. Some other forwarding algorithms, e.g., social-based ones [5]–[8], have shown their superiority in addressing the problem of relay node selection. They always select those nodes who are socially connected with destinations as relay. To find such nodes, they require frequent exchanging of a large amount of information to uncover social ties (e.g., node centrality and community structure) between nodes. However, exchanging and storing such information often incur large extra overhead to resource-constrained mobile nodes in DTNs. Hence a cost-efficient light-weight social-aware routing algorithm is desired.

In this paper, we develop a social-aware forwarding algorithm called TBSF (the-best-so-far), with the goal of solving the problem of relay node selection in an efficient way. The basic idea of TBSF is to utilize the small world properties to limit the maximum number of relay nodes for each message and to carefully choose the appropriate nodes as relay in each forwarding hop. The main contributions and originalities of our work are summarized as follows:

• We apply the “short average path length” feature [9] observed in the small-world phenomenon to determine the maximum number of relay nodes for each message.

• We investigate different connection situations and then present a novel delivery metric to measure the forwarding capability of nodes and discuss it. Based on this metric, we exploit the “high cluster coefficient” feature [10] observed in the small-world phenomenon to find good relay nodes by a
destination-dependent way, and further develop a social-aware forwarding algorithm called TBSF.

- We measure the performance of TBSF by comparing against some representative routing protocols using real-trace driven simulations, and the results prove the efficiency of TBSF.

The rest of this paper is organized as follows. Section 2 provides a brief overview of related work on message forwarding protocols and small world based algorithms in the human mobility network. Section 3 presents the network model and the problem statement. Section 4 details the design of TBSF protocol. Section 5 evaluates the performance of TBSF by comparing with existing famous DTN routing protocols. Finally, Section 6 concludes our work and discusses the future direction.

## 2 RELATED WORK

In DTNs, the “multi-hop forwarding” scheme has been extensively used in most routing protocols. The most famous example is Epidemic routing [2], in which each message is aggressively forwarded upon any transmission opportunity. Although it can achieve a high delivery ratio, it suffers an intolerable delivery cost due to its flooding nature. Consequently, considerable effort has been devoted to the problem of relay node selection. They often adopt some available network knowledge or technique, e.g., location information [3], node trajectory [4], network coding [11], and social ties [6], to address such problem. Compared with others, social-aware routing protocols have shown their superiority in guiding relay node selection. They often make use of social network analysis to identify the topology structure of a network, and then select those nodes who lie in the key location as the appropriate relay. Hui et al. [6] adopt community structure and betweenness centrality to uncover node location information, and then choose those nodes who are more closer to destinations as the next hop. Later, Mtibaa et al. [12] use the concept similar to PageRank to rank nodes and deliver messages to the nodes with a higher utility value. Wu et al. [13] utilize the community structure to identify the suitable relay nodes. All these approaches require exchanging a large amount of information to measure node centrality or to detect community structures, incurring the extra delivery cost to mobile nodes in DTNs. Moreover, some of them like BubbleRap [6] and PeopleRank [12] choose relay nodes in a destination-independent manner. This makes most messages flow to the high centrality nodes, resulting in these nodes’ storage space and energy are likely to be depleted quickly [14]. Thus, it is important to design a cost-efficient routing algorithm which could find the appropriate relay nodes in a low-cost way.

The “small-world” phenomenon, the principle that people are all linked by short chains of acquaintances, was first introduced by the pioneering work of Stanley Milgram in the 1960’s [9]. This phenomenon reveals two fundamental features of social network: “short average path length” and “high cluster coefficient”, and has been observed and studied in human mobility based wireless network, e.g., Ad-hoc network [15]–[17]. Cacciapuoti et al. [15] demonstrate the small world phenomenon exists in wide-scale mobile ad-hoc wireless networks. Later, Banerjee et al. [16] explore the use of directional beamforming for a wireless Ad-hoc network as a small world, and then propose a distributed algorithm for small-world creation that achieves path length reduction while maintaining connectivity.

Some other work [18]–[21] focuses on the small-world phenomenon in DTNs. Chaintreau et al. [18] report that the distribution of inter-contact time between human-carried mobile devices follows a power law distribution. Karagiannis et al. [19] introduce the dichotomy hypothesis, i.e., power law decay of inter-contact time distribution up to a point and exponential decay beyond, which can be observed in diverse mobility traces. Wei et al. [20] investigate the distribution of inter-contact time from the perspective of social relationships in DTNs. Eguyen et al. [21] uncover the existence of the small-world phenomenon in DTNs.

Recently, we exploit the small world properties to guide the design of relay node selection in DTNs [22]. However, we consider a simple delivery metric to measure the forwarding capability of nodes, limiting the benefits of the small-world-based routing protocol greatly. In this paper, we investigate different connection situations, and then present a novel delivery metric and incorporate it into [22] to further improve routing performance. Meanwhile, we also discuss the rationality of our proposed and evaluate its effectiveness.

## 3 NETWORK MODEL AND PROBLEM STATEMENT

### 3.1 Network Model

We consider a category of DTNs exhibiting certain social features like socially DTNs or mobile social network [23], in which communication devices are attached and moved with human beings and the transmission between any two mobile nodes happens only when they move into the reciprocal radio range of each other. Node mobility in MSN is of long-term regularities. For example, some pairs of nodes, e.g., acquaintances, consistently meet more frequently than other pairs, e.g., strangers, over time. Hence the historical contact information between nodes indicates their future encounter opportunities. In the past, a number of delivery metrics, e.g., contact frequency, last contact time, and contact duration, have been proposed to measure the forwarding capability of nodes.

We assume that all nodes are resource constrained, e.g., with limited storage space. All nodes are willing to forward messages for others. In other words, any node in a network can be regarded as a reliable

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1. here a mobile node refers to a mobile device
candidate relay node. Although messages in DTNs are delay tolerable, they are usually with a certain lifetime, which is often evaluated as time-to-live (TTL) since its generation. Within a message’s lifetime, multiple copies may be generated in the hope that at least one of them can be successfully delivered to the destination node. A message will be discarded until its TTL expires. In addition, unicast where each message has a single source-destination pair is considered. Note that we allow multiple unicast sessions coexisting in a network.

3.2 Problem Statement

In DTN, most routing protocols adopt the “multi-hop forwarding” strategy to transmit messages. The large number of relay nodes hops indicates the higher delivery ratio, but it also incurs the higher delivery cost (e.g., the number of relay nodes employed, the total consumption of energy and storage space, etc.). On the contrary, aggressively reducing the number of forwarding hops may degrade the delivery ratio. Therefore, it is important to employ a certain number of relay nodes for each message to reduce the delivery cost while preserving certain delivery performance, e.g., the successful delivery ratio.

Problem 1. How to determine the maximum number of relay nodes for each message to improve the delivery efficiency?

Delivery efficiency does not solely rely on the number of relay nodes employed by each message. When the number of relay nodes is limited, only few intermediate nodes are utilized to transmit messages. Hence the quality of relay nodes employed becomes critical to the delivery ratio and further affects the delivery efficiency. During the routing process, the message carrier must carefully decide whether the messages in the local buffer shall be forwarded to an encountered intermediate node or not. More specifically, the relay node selection problem involves two problems.

Problem 2. How to efficiently evaluate the forwarding capability of nodes in an effective way?

Problem 3. How to design an efficient strategy to find the high-quality relay nodes?

However, due to the uncertainty of future connections and lack of the entire network information, it is challenging to cope with these problems.

4 THE DETAILED DESIGN OF TBSF

In this section, we first give our motivation, and then present a novel delivery metric to quantify the forwarding capability of nodes by considering time-varying contact information. After that, we introduce our design principles on how to choose relay nodes, based on the small world properties. We further propose a social-aware routing protocol, called TBSF, to evaluate the effectiveness of our relay node selection scheme.

4.1 Motivation

Numerous previous work has proven that both complex network and social network expose the small world phenomenon [15], [21], [24], which has two key features: “short average path length” and “high cluster coefficient”. “Short average path length” means two people are connected by a short chain of acquaintances, while “high cluster coefficient” denotes people are likely to make friends with your friends’ friends. On the other hand, the benefits of the small world properties to improve the efficiency of Ad-hoc network have widely been proven in previous work [15]. Inspired by these, we exploit the small world properties for relay node selection in socially DTNs, in which the small world phenomenon has also been observed [21].

4.2 Delivery Metric

Since the future encounter opportunities are closely linked to past contacts in socially DTNs, historical contact information has been associated with a delivery metric to measure the strength of connections and to further quantify the forwarding capability of nodes. The encounter information based delivery metrics include last contact time, contact frequency, average duration, average inter-contact time, etc. The most commonly used metric is the average duration [25] because it indicates how many messages can be delivered in a contact. However, the traditional average duration only reflects the mean duration of each encounter, but fails to quantify contact frequency in a period of time. Moreover, this delivery metric does not consider the differences between recent contacts and older ones, which greatly weaken its prediction power. To end this, we propose a novel delivery metric to effectively evaluate the strength of connections so as to accurately quantify the forwarding capability of nodes.

![Fig. 1. An example of different connections between nodes i and j in time interval [0, T]. The width of shaded box represents a contact time, and the width between two shaded boxes denotes a separation period](image)

(a) case I

(b) case II

(c) case III
4.2.1 New Average Duration

We take the contacts happened between nodes \( i \) and \( j \) for example, as shown in Fig. 1. Suppose that each message has the same size, and at least a message needs to be forwarded in every contact. In addition, each contact is long enough to transmit at least a message.

We can see from Fig. 1 that both case (I) and (II) have the same average duration per each contact, proposed in [25]. While they have different contact frequency and total contact time. A longer total contact time means that nodes can exchange more messages in an encounter, and a high encounter frequency can enable nodes to transmit messages more frequently. Therefore, case (I) offers a better communication opportunity than (II) thanks to its messages more frequently. Therefore, case (I) offers a high encounter frequency can enable nodes to transmit the same average duration per each contact long enough to transmit at least a message. While they have different contact frequency and average duration per each contact, proposed in [25]. We can observe that a node frequently meets some nodes in a period and the encounter duration remains unchanged. Between two specific periods, nodes rarely encounter other nodes. Therefore, we argue that there is some association between the size of the time window and the length of the specific period, which has been further proved in Section 5.2. In this paper, we regard the average length of the specific period as the optimal size of the time window. In addition, different mobility traces have different the desirable size of the time window.

4.2.2 Time-varying Average Duration

When comparing case (I) and case (III), metric \( D \) fails to measure because they have the same average duration. However, they have different last contact time. Since the old contacts do not have the same predictive power as more recent ones [26], case (III) has a better communication opportunity. Therefore, it is reasonable to give recent contacts a greater weight when evaluating the strength of connections. Here we introduce a time-varying average duration, denoted as \( TD \), which comply with the conclusions in all cases in Fig. 1. This metric \( TD \) is defined as follows.

\[
TD_{i,j} = (1 - \beta) \times D_{i,j}(\text{old}) + \beta \times D_{i,j}(\text{recent}) \tag{2}
\]

where \( D_{i,j}(\text{old}) \) and \( D_{i,j}(\text{recent}) \) represent the \( D \) value of old and recent contacts respectively, the time factor \( \beta \) is used to regulate the importance of recent contacts and belongs to \([0,1]\). Compared with the previous delivery metrics, \( TD \) is more comprehensive, as it not only considers both total duration and contact frequency, but also takes time-varying contact information into account.

In order to distinguish between recent contacts and old ones, we employ a sliding time window to divide historical contacts into two parts. Only those contacts that happen in the current time window are considered to be recent contacts; otherwise, they are old ones. Besides, if a contact’s start time occurs outside of the current time window and its end time appears in a time window, this contact is considered to be a recent one. To the best of our knowledge, \( TD \) is the first delivery metric which considers the difference between old contacts and recent ones.

4.2.3 Time Window Size Discussion

In Eq. (2) a sliding time window is adopted to differentiate recent contacts and old ones. If the size of the time window is too large, lots of older contacts may be included into the current time window, which does harm to measure the strength of contacts. When the size of the time window is too small, only limited recent contacts who occur in the current window which also hinders to evaluate the strength of connections. Thus, it is necessary and crucial to set the optimal time window size. How to determine the optimal size of the time window?

We analyze a variety of real mobility traces introduced in Section 5.1 and notice an interesting phenomenon that the distribution of contacts is extremely regular. Fig. 2 shows the contact distribution of a node with other nodes on different mobility traces. From this graph, we can observe that a node frequently meets some nodes in a period and the encounter duration remains unchanged. Between two specific periods, nodes rarely encounter other nodes. Therefore, we argue that there is some association between the size of the time window and the length of the specific period, which has been further proved in Section 5.2. In this paper, we regard the average length of the specific period as the optimal size of the time window. In addition, different mobility traces have different the desirable size of the time window.

4.3 Design Principles

4.3.1 “short average path length”

One basic requirement to relay node selection is to limit the number of relay nodes for each message in an effective way. One well-known property of the small-world theory is “short average path length” [10], which describes the phenomenon that two people are connected by only a few people. For example, the “six degrees of separation” theory proves that every two people are six steps away in average. Since then, much effort has been contributed to analyze and prove the existence of this feature. Recent study [21] shows that the small world phenomenon is also pervasive in socially DTNs and indicates that a routing path for a successful message delivery consists of limited intermediate nodes. This motivates us to apply the “short average path length” feature to control the number of relay nodes for each message such that a routing protocol could reduce the delivery cost while maintain a certain delivery ratio.

4.3.2 destination-dependent relay node selection

The other basic requirement to relay node selection is to find the high-quality relay to deliver messages. Various metrics on the quantification of a node’s forwarding capability have been proposed in the literature. To find the appropriate relay nodes, we analyze and discuss the characteristics of different metrics. Some are destination-independent, such as betweenness centrality [6]. As we have known, destination-independent metric may make numerous messages flowing to few central nodes,
causing the energy and storage space of these nodes is easy to be depleted \cite{14}. To avoid this problem and enable destination-dependent relay node selection, we adopt the delivery metric $TD$, presented in Section 4.2, to measure the forwarding capability of a node to a specific destination. $TD$ not only considers both total duration and contact frequency, but also takes time-varying contact information into account. In addition, $TD$ requires much less information, only encountered nodes other than the entire network. All these characteristics make Eq. (2) as a suitable delivery metric to choose destination-dependent relay node selection in DTNs.

Besides the destination-dependent delivery metric, we also consider how to select good relay nodes from all encountered nodes. Due to the lack of future contacts, it is hard to determine whether an encountered node shall be selected as one of the relay nodes. Fortunately, we can know whether an encountered node is a relatively best one by comparing its forwarding capability with all that have been encountered before. This motivates us to design a destination-dependent relay node selection strategy so far by choosing the node with the highest forwarding capability among all encountered so far, until forwarding hops are used up or the message expires.

4.3.3 “high cluster coefficient”

In the larger-scale network where the source node may be far away from the destination, a message custody may not be able to encounter enough suitable relay nodes within its lifetime, causing it will lose some transmission opportunities. Besides the “short average path length”, another small-world feature is known as the “high cluster coefficient” \cite{10}, describing the phenomenon that people are likely to make friends with his/her friends’ friends. Inspired by this, we choose those nodes, having a relatively low forwarding capability but having a friend who possess a larger one, as the next hop to find more potentially high-quality relay nodes in the limited time. For example, when a node, say $i$, holding a message $m$ encounters node $j$ whose forwarding capability for $m$ is not the highest observed so far, but one of $j$’s neighbors, e.g., node $k$, has a larger forwarding capability, $i$ may also forward $m$ to $j$ in the hope that the message can be finally delivered by $k$. By this means, more potentially useful relay nodes can be selected out in a limited time and the delivery ratio could be potentially promoted.

4.4 TBSF Forwarding Algorithm

Based on the above design principles, we develop a light-weight social-aware routing algorithm called TBSF (the-best-so-far). The message forwarding procedures of TBSF when nodes $i$ and $j$ meet are summarized in Algorithm 1.

In TBSF, whenever a new message (e.g., $m$) is generated at a source node, it is set with an initial hop-to-forward (HoF) value $H_m$, denoting the maximum number of remaining relay nodes chosen for message $m$ and being decreased by one after each forwarding. The forwarding of $m$ stops when $H_m$ becomes 0. The initial value of $H_m$ is determined by the average path length of the target network. According to the small world theory, the initial value of $H_m$ is usually set at 5 or 6. Besides HoF, each message also maintains a delivery threshold (e.g., $\tau_m$), which will be used to judge whether an encountered node is the best relay node so far or not. The value of $\tau_m$ is initially set as the forwarding capability of the source node to $m$’s intended destination $d$, i.e.,

$$\tau_m = TD_{i,d}$$

and $\tau_m$ will be updated after each forwarding during the routing process. In addition, each node maintains its forwarding capability to others. The forwarding capability of node $i$ to $m$’s intended destination $d$, $P_{i,d}$, is defined as follows.

$$P_{i,d} = TD_{i,d}$$

Once $i$ and $j$ meet, as shown in line 1 in Algorithm 1, they first exchange the information about their own and

2. The best relay node so far denotes the one that has the biggest forwarding capability among all nodes observed by the peer node in the past.
their neighbors’ connection strength as evaluated in Eq. (2). Then, \( i \) tries its best to forward as many messages as possible to \( j \) until they move out of the reciprocal communication range of each other. Message \( m \) will be forwarded to \( j \) if \( j \) satisfies any of the following three conditions:

1) Node \( j \) is the destination node of message \( m \) (line 3). Certainly \( m \) shall be forwarded to \( j \) since this completes the delivery of message \( m \), which shall be removed from \( i \)'s buffer after forwarding.

2) The value of HoF (\( H_m \)) is larger than 1 and \( j \) has the largest forwarding capability to \( d \) among all the nodes observed by \( i \) so far, i.e., \( TD_{j,d} > \tau_m \) (line 6).

3) The value of HoF (\( H_m \)) is larger than 2 and there exists one of \( j \)'s neighbors (\( \mathbb{N}_j \)) with the largest forwarding capability to \( d \) among all the nodes observed by \( i \) so far (line 10). The condition \( H_m > 2 \) is to ensure that there will still be enough remaining forwarding hops for \( j \)'s neighbor (e.g., \( k \)) to forward the message after \( k \) receives \( m \) from \( j \).

Before actual forwarding, the values of \( \tau_m \) and \( H_m \) to be included in the message shall be updated first. The value of \( \tau_m \) will be updated to the forwarding capability of either node \( j \) (line 7) or its neighbor \( k \) (line 11), and \( H_m \) is decreased by 1 (lines 8 and 12).

Finally, at the end of the contact, the connection metric between nodes \( i \) and \( j \) shall be updated according to Eq. (2), as in line 16. This information will be further utilized in the future.

**Algorithm 1 TBSF** (procedures on \( i \) when it meets \( j \))

1: exchange connection strength information with \( j \)
2: for message \( m \) carried by \( i \) do
3: \( \text{if } d == j \text{ then} \)
4: \( \quad \text{forward } m \text{ to } j \)
5: \( \quad \text{remove message } m \text{ from } i \)'s local buffer
6: \( \text{else if } P_{j,d} > \tau_m \text{ and } H_m > 1 \text{ then} \)
7: \( \quad \tau_m \leftarrow TD_{j,d} \)
8: \( \quad H_m \leftarrow H_m - 1 \)
9: \( \quad \text{forward } m \text{ to } j \)
10: \( \text{else if } \exists k \in \mathbb{N}_j, P_{k,d} > \tau_m \text{ and } H_m > 2 \text{ then} \)
11: \( \quad \tau_m \leftarrow TD_{k,d} \)
12: \( \quad H_m \leftarrow H_m - 1 \)
13: \( \quad \text{forward } m \text{ to } j \)
14: \( \text{end if} \)
15: \( \text{end for} \)
16: \( \text{update the value of } TD_{i,j} \text{ according to Eq. (2)} \)

## 5 PERFORMANCE EVALUATION

### 5.1 Simulation Setup

To evaluate the performance of TBSF, we implement it in a widely-adopted DTN simulator ONE (opportunistic network environment simulator). In addition, two representative DTN routing protocols, BubbleRap and PeopleRank, are considered, and three practical mobility datasets, e.g., Infocom2006 [27], Reality [28] and Pmtr [29], are incorporated into the simulator. Some key characteristics of these mobility datasets are described in Table 1. We believe that these datasets cover a rich diversity of social environments, from small conference (Infcom2006) to spacious campus (Reality, Pmtr), with a duration from several days (Infcom2006) to almost one year (Reality). In our simulations, a new message is created every 30 to 40 seconds, and the source or destination nodes are randomly selected from the network.

We extensively evaluate and compare routing protocols based on the following performance metrics.

- **Delivery Ratio**: the ratio between the number of messages that are successfully delivered to their destination nodes within their lifetime to the total number of messages generated.
- **Delivery Cost**: the average number of forwarding used for the successfully delivered messages.
- **Delivery Delay**: the average time required to deliver a message to its destination node since its generation time.

### 5.2 Time Window Size Evaluation

In order to examine the effect of different time window sizes, we execute a forwarding algorithm who employs \( TD \) to measure the forwarding capability of nodes and then makes forwarding decisions on several mobility datasets. Fig. 3 reveals the delivery ratios under different time window sizes in datasets Infocom2006. From the
The delivery efficiency is quantified as the ratio between the time window size from 150 to 250 for Infocom2006 specific datasets. In the following simulations, we adopt the optimal window sizes depended on mobility traces. We do not present these simulation results for saving space. These simulation results are consisted with, or even validate, our previous discussion in Section 4.2.3; the optimal window size depends on specific datasets. In the following simulations, we adopt the time window size from 150 to 250 for Infocom2006 when quantifying the forwarding capability of nodes.

5.3 Maximum Forwarding Hops Evaluation

The delivery efficiency is quantified as the ratio between the delivery ratio and the delivery cost. We examine the effect of the maximum number of relay nodes and show the results in Fig. 4.

We first notice that the delivery efficiency peak occurs when the maximum number of relay nodes is 5 or 6. This is consistent with, or further validates, the result indicated by the small world theory that people are all connected by a short chain of acquaintances. Before reaching the highest value, the delivery efficiency shows as an increasing function of the number of relay nodes. This is because only few messages are successfully delivered under the slight maximum number of relay nodes, which even implies a low delivery cost. With the increasing of relay nodes, the delivery ratio increases faster than the cost, and thus the delivery efficiency is improved. However, after the peak value, increasing the number of relay nodes contrarily degrades the delivery efficiency. This is because that, in such situation, the delivery cost increases faster than the delivery ratio.

We are going to detail the performance of TBSF from the perspective of message TTL and relay buffer size, respectively. In the following simulations, the maximum number of relay nodes in TBSF is set as the value with the best delivery efficiency, e.g., 5 for Infocom2006, 6 for both Reality and Pmtr, as shown in Fig. 4.

5.4 On the Effect of Message TTL

5.4.1 Delivery Ratio Comparison

Fig. 5 shows the delivery ratio of BubbleRap [6], PeopleRank [12], TBSF-basic [22] and TBSF on various mobility traces, as a function of TTL. From this graph, we notice that TBSF outperforms both BubbleRap and PeopleRank. For example, as shown in Fig. 5(b), TBSF outperforms BubbleRap and PeopleRank by 26% and 53%, respectively, on mobility traces Reality when TTL is 3h. We attribute the advantage of TBSF over BubbleRap and PeopleRank to two factors. Firstly, TBSF selects relay nodes in a destination-dependent way. It could avoid the problem experienced by BubbleRap and PeopleRank that many messages may be forwarded to few central nodes, in which some messages may be discarded when the relay buffer overflows. Secondly, TBSF always employs the relay node with an improved forwarding capability for each message. The high-quality of the selected relay nodes ensures the superior delivery ratio. In addition, TBSF also outperforms TBSF-basic by 10% on mobility traces Reality when TTL is 3h. This is caused by TBSF employs the time-varying delivery metric $TD$, considering the difference between old contacts and recent ones and gives them different weights, to better quantify the forwarding capability of nodes.

Another interesting phenomenon noticed from Fig. 5 is that the delivery ratio shows as an increasing function of TTL. This is because a larger TTL provides a message to have more forwarding opportunities to be delivered to its destination. However, the increase of delivery ratios becomes marginal after the TTL reaches some value, e.g., 3d and 6h in Reality and Infocom2006, respectively. This is because the forwarding capability (e.g., the available reliable relays) in the network becomes the performance bottleneck when TTL is big enough.

5.4.2 Delivery Cost Comparison

Fig. 6 gives the evaluation results on the delivery cost of all the routing protocols on different mobility traces. The delivery cost is measured as the average number of forwarding used for all successfully delivered messages. We first see that TBSF has the lowest delivery cost among all the four protocols on all datasets.

Compared with BubbleRap and PeopleRank, TBSF has a lower delivery cost, e.g., 48% of BubbleRap and 42% of PeopleRank in Infocom2006 when TTL is 12h, as shown in Fig. 6(c). We attribute its strength to the following two reasons. Firstly, the maximum number of relay nodes is limited to a small but reasonable value in TBSF, while both BubbleRap and PeopleRank do not control such number. Secondly, both BubbleRap and PeopleRank select relay nodes in a destination-independent manner. Many messages flow to central
nodes and would be discarded when the relay buffer overflows. These discarded messages are wasted and thus increase the average forwarding cost of successfully delivered messages. However, TBSF works in a destination-dependent manner, which can avoid this phenomenon. Furthermore, we also see that the delivery cost of TBSF is always lower than TBSF-basic, e.g., 78% of TBSF on Infocom2006 when TTL is 30m. The behind reason is the delivery metric presented in TBSF has a larger power for node’s forwarding capability prediction than that in TBSF-basic, resulting in the relay nodes selected have a larger forwarding capability.

5.4.3 Delivery Delay Comparison

Fig. 7 shows the evaluation results on the normalized average delivery delay on different values of TTL. Due to the large span of the delivery delay, it is difficult to clearly show their absolute values on one figure. Instead, we normalize the delivery delay of all comparison routing protocols to that of Epidemic, which shall have the lowest delivery delay because of its flooding nature.

As shown in Fig. 7, it is obvious that TBSF performs better than both BubbleRap and PeopleRank. Taking Reality as an example, we observe that the delivery delay of TBSF is 9% and 15% lower than BubbleRap and PeopleRank, respectively. Recall that BubbleRap and PeopleRank choose relay nodes in a destination-independent manner. It is likely that many messages are flowed to few relay nodes. This problem is avoided thanks to the destination-dependent relay selection in TBSF. In addition, TBSF also forwards messages to the node with a relatively low forwarding capability but its neighbor has a higher forwarding capability. This can provide more opportunities for messages to reach their destination nodes early. Hence, the low delivery delay is achieved. Fig. 7 also reveals that, compared with TBSF-basic, TBSF always has a relative delivery delay on all mobility traces. This is due to TBSF forwards messages to the nodes who are much closer to the message’s destination by using a delivery metric $TD$, taking the time-varying contact information into account.

In addition, we can also see from Fig. 7 that the delay gap between TBSF and others, e.g., BubbleRap and PeopleRank, becomes larger with the increasing of TTL. A small TTL denotes messages have a short time to be transmitted, resulting in only messages whose destinations are around their sources can be delivered successfully before they expire. Thus, all these protocols have low delivery delay and the delay gap is correspondingly small. As TTL increases, it will provide more time for routing strategy to find relay nodes and to transmit messages to destination. Thus, the performance difference of various routing strategies is exposed, and the gap between them also becomes obviously. After TTL reaches a certain value, the average delay converges because it is determined by the network connectivity,
other than life time. Nevertheless, we can observe the substantial benefit of TBSF under any values of TTL.

5.5 On the Effect of Relay Buffer Size

We also evaluate the effect of relay buffer size to evaluate the performance of TBSF in terms of delivery ratio, delivery cost and delivery delay. The results obtained from mobility traces Reality are shown in Fig. 8. We first notice that TBSF is more insusceptible to the effect of relay buffer size, compared with other routing protocols. BubbleRap and PeopleRank are quite affected owing to their destination-independent relay selection manner, which depends on few nodes to transmit messages. Thus, the relay buffer size of central nodes becomes the bottleneck of the overall delivery performance. In TBSF and TBSF-basic, the burden on the relay buffer size is distributed to more relay nodes, and thus they are not much affected by the relay buffer size. Moreover, we also observe that TBSF is more robustness to relay’s buffer size than TBSF-basic under all performance metrics thanks to the superiority of delivery metric $TD$ presented in TBSF. On the other hand, we can always see that the delivery ratio shows as an increasing function of the relay buffer size while both the delivery cost and the delivery delay are decreasing functions of the relay buffer size.

6 CONCLUSIONS AND FUTURE WORK

In this paper, we investigate the small world phenomenon in DTNs and exploit it to design a cost-efficient message forwarding algorithm. To this purpose, we present a novel delivery metric to measure the forwarding capability of a node to a specific node. Based on this metric, we make use of the small world properties to guide the design of TBSF. The “short average path length” feature is used to limit the maximum number of relay nodes selected, and the “high cluster coefficient” feature is employed to find the high-qualify relay nodes within the lifetime of messages. We develop a social-aware forwarding algorithm called TBSF, in which message carriers always forward messages to the node with an increased forwarding capability before the maximum number of relay nodes is reached. Real-trace driven simulation results validate the superior efficiency of TBSF. In the future, we will take other connection factors, e.g., contact frequency and its fluctuation, into account to design an efficient delivery metric in order to better measure the forwarding capability of nodes.

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