# A Multi-Copy Delegation Forwarding Based on Short-term and Long-term Speed in DTNs

En Wang*,†, Yongjian Yang*, Jie Wu† and Wenbin Liu‡

*Department of Computer Science and Technology, Jilin University, China
†Department of Computer and Information Sciences, Temple University, USA
‡Department of Software, Jilin University, China
Email: wangen0310@126.com, yyj@jlu.edu.cn, jiewu@temple.edu, nike_lwb@126.com

*Abstract*—Delay Tolerant Networks (DTNs) are featured by unpredictable mobility patterns and easily-interrupted connections. Forwarding strategy has always been the research focus, in order to improve the delivery ratio. An enormous amount of researches pay attention to solving the following two problems: whether to forward, and how to forward. Therefore, forwarding metrics and forwarding strategies both play important roles in DTNs. In this paper, we consider a generalized random-waypoint model with heterogeneous nodes, the node's speed is regarded as the forwarding metric, which includes the short-term and long-term speed. Subsequently, we propose a multi-copy Delegation Forwarding based on Short-term and Long-term speed in DTNs (DFSL), which first determines a comprehensive mapping from short-term speed and long-term speed to the actual forwarding metric. Then, according to the forwarding metric and delegation forwarding strategy, DFSL utilizes some efficient nodes with higher forwarding metrics to assist in delivering messages, in order to improve the delivery ratio, while reducing the forwarding cost. Finally, we conduct simulations based on the synthetic mobility pattern and real trace. The results show that, compared with other multi-copy forwarding strategies, DFSL achieves the highest forwarding efficiency, which is defined as the result of delivery ratio divided by forwarding cost.

*Index Terms*—DTNs, Multi-copy, Forwarding metric, Delegation forwarding, Short-term speed, Long-term speed.

## I. INTRODUCTION

Delay tolerant networks (DTNs) [1] are sparse mobile networks in which the contemporarily connected path from source to destination may not exist at any time due to a lack of stable connections. As a result, DTNs have been proposed to be used in pocket-switched networks [2], deep space satellite networks [3], vehicle and pedestrian networks [4], wildlife tracking [5], and disaster response networks [6]. In DTNs, routing protocols are usually realized in the store-carry-and-forward paradigm. Nodes prefer maintaining and forwarding messages to some relays with higher forwarding ability. However, how to judge the node's forwarding ability, and how to decide on the forwarding strategy are still the problems to be addressed. Therefore, forwarding metric [7] and forwarding strategy [8] are both important for achieving better delivery performance.

To solve the first problem, how to judge the node's forwarding ability, we attempt to determine whether an encounter is better than the message holder according to a utility function, which is referred to as *forwarding metric*. In view of the state-of-the-art researches, a variety of forwarding metrics including contact frequency [9], last contact time [10], contact duration
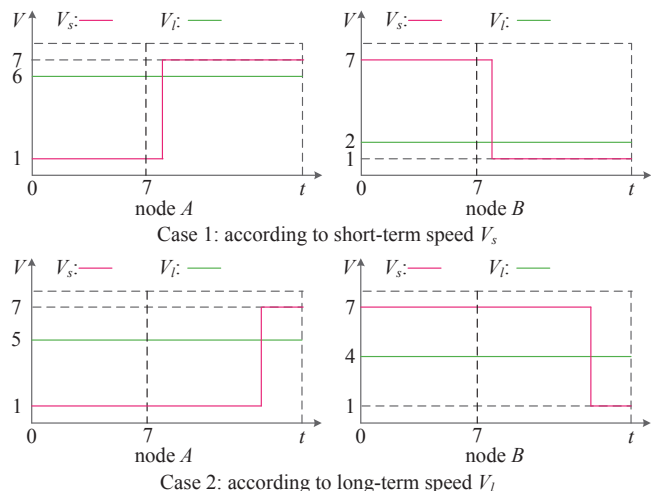


Fig. 1. The descriptions of two cases that the forwarding decisions are made according to short-term and long-term speed, respectively ($V_s$: short-term speed, $V_l$: long-term speed, node $A$ encounters node $B$ at the 7th second). In case 1, according to the short-term speed, node $A$ with the short-term speed of $1m/s$ makes the decision to forward the message to node $B$ with the short-term speed of $7m/s$. In case 2, according to the long-term speed, node $A$ with the long-term speed of $5m/s$ makes the decision to keep the message from sending to node $B$ with the long-term speed of $4m/s$. However, the above decisions are both incorrect.

[11], and total contact rate [12], *etc.* have been proposed to measure the nodes' forwarding abilities. It is not difficult to find that the aforementioned forwarding metrics quantify either the short-term (e.g., last contact time) or the long-term forwarding ability (e.g., total contact rate).

In this paper, we believe that the node's speed at different time plays an important role in forwarding ability in DTNs. Moreover, the short-term and long-term speed could be used to reflect the transient and longstanding forwarding abilities, respectively. It is not difficult to find that the short-term speed is time-varying, while the long-term speed is time-constant. We argue that only using the short-term or long-term speed as the forwarding metric could not achieve the optimal delivery performance. It is mainly because making the forwarding decision only on the basis of short-term speed could not guarantee the subsequent forwarding performance; the node with high short-term speed is likely to slow down in subsequent time. On the other hand, making the forwarding decision just according to the long-term speed may result in missing the opportunities for forwarding the message to some

efficient nodes with high short-term speed.

Fig. 1 shows the comparison between the two cases in which node $A$ encounters node $B$ at the 7th second. In case 1, when they encounter each other, the short-term speed ($1m/s$) of node $A$ is lower than that ($7m/s$) of node $B$, while the long-term speed ($6m/s$) of node $A$ is higher than that ($2m/s$) of node $B$. If we make the decision only according to the short-term speed, node $A$ should send the message to node $B$ at the meeting time. However, as can be seen in case 1, after a short while, the short-term speed of node $A$ reaches high level ($7m/s$), while that of node $B$ reaches low level ($1m/s$), which indicates that we have made a wrong forwarding decision. Similarly, in case 2, the long-term speed ($5m/s$) of node $A$ is higher than that ($4m/s$) of node $B$, while the short-term speed ($1m/s$) of node $A$ is lower than that ($7m/s$) of node $B$. If we make the decision only according to the long-term speed, node $A$ should keep the message from sending to node $B$. However, in the subsequent time, the speed of node $B$ is significantly higher than that of node $A$, which means that the forwarding decision in case 2 is also incorrect. In conclusion, simply using neither the short-term speed nor the long-term speed as the forwarding metric could achieve a comprehensive and satisfying forwarding decision. Therefore, it is necessary to determine a mapping function from the short-term and long-term speed to a quantified forwarding metric, which reflects the actual forwarding ability. To this end, we also design an efficient but low cost estimation of both short-term and long-term speed.

To solve the second problem of how to decide the forwarding strategy, we use Delegation Forwarding [13] for reference and propose a multi-copy forwarding strategy according to the forwarding metric, in order to improve the delivery ratio, while reducing the forwarding cost. There has always been a trade off between delivery ratio and forwarding cost. In other words, if we control the number of message copies (e.g., Single-copy routing), we could not achieve a satisfactory delivery ratio. Similarly, if we do not control the number of message copies (e.g., Epidemic routing [14]), the forwarding cost becomes unacceptable. Delegation forwarding is proposed to balance the trade off: it selects some efficient relays to assist in delivering messages. In the combination of the proposed forwarding metric and delegation forwarding, we achieve a multi-copy delegation forwarding based on short-term and long-term speed, which is referred to as DFSL. Simulation results show that DFSL not only improves the delivery ratio, but also reduces the forwarding cost.

The main contributions of this paper are briefly summarized as follows:

- We present a mapping function from the short-term and long-term speed to a quantified forwarding metric, which could be used to reflect the actual forwarding ability. We also design an efficient but low cost estimation of short-term and long-term speed.
- In the combination of the forwarding metric and Delegation Forwarding (DF) [13] strategy, a multi-copy delegation forwarding based on short-term and long-term speed

is proposed in DTNs.
- We conduct extensive simulations based on the synthetic mobility pattern and real trace. The results show that, compared with other multi-copy forwarding strategies, DFSL achieves the highest forwarding efficiency, which is defined as the result of delivery ratio divided by forwarding cost.

The remainder of the paper is organized as follows. We review the related work in Section II. The multi-copy delegation forwarding based on short-term and long-term speed is presented in Section III. In Section IV, we evaluate the performance of DFSL through extensive simulations. We conclude the paper in Section V.

## II. RELATED WORK

### A. Forwarding Metric

Forwarding metric is used to measure the strength of a connection, and further quantify the node's forwarding ability. The forwarding metric can be destination-specific or destination-independent [13]. A destination-specific forwarding metric varies depending on the destination of a message. For example, FRESH [15] uses the time elapsed since the last contact with the destination as a forwarding metric. However, some forwarding metrics such as the total contact rate of a node has no relationship with the different destinations, and hence, is regarded as destination-independent.

In this paper, the speed is regarded as the forwarding metric, which is destination-independent and time-varying. The short-term and long-term speeds are used to reflect the nodes' transient and longstanding forwarding abilities, respectively. We argue that simply using the short-term or long-term speed as the forwarding metric could not obtain the optimal delivery performance. A mapping function from the short-term and long-term speeds to a quantified forwarding metric is wanted.

### B. Forwarding Strategy

According to the difference regarding the maximum allowable number of message copies, the existing forwarding strategies in DTNs can be grouped into limited-copy and unlimited-copy strategies.

The limited-copy forwarding strategies could be divided into single-copy and multi-copy forwarding strategies. In the single-copy forwarding strategies, only one message copy is generated and forwarded to another node, which is better than the current message holder. Han [16] presents an optimal single-copy multi-path forwarding strategy for satisfying the delay requirement, while minimizing the forwarding cost. The intuition behind the multi-copy forwarding strategy is to choose fixed-number relays to assist in finishing the delivery. Spray and Wait [17] is proposed to limit the maximum number of message copies and adopt a binary splitting method to disseminate message copies into the network; the process then goes on until any message holder encounters the destination. Zheng and Wu [18] propose a multi-copy two-hop routing algorithm to minimize delivery delay in mobile social networks. A forwarding set is maintained based on the number

of remaining message copies, as well as the number of relays that have not received a message copy.

The unlimited-copy forwarding strategy mainly includes the flooding strategies and the conditional flooding strategies. The flooding strategy aims to improve the delivery ratio without considering the other constraint conditions. Therefore, the routing protocols in this category are usually purely theoretical. Epidemic [14] utilizes every contact opportunity to increase the probability for a message to reach the destination. It is obvious that Epidemic obtains the optimal delivery ratio when the network resources (buffer, energy, bandwidth, *etc*.) are sufficient. However, it is commonly unusable in a real network environment. Conditional flooding strategy does not restrain the total number of message copies. While it conditionally chooses the message to replicate. Therefore, it attempts to avoid the waste of network resources through employing some efficient nodes. In Delegation Forwarding [13], a node will forward a message only if it encounters another node whose forwarding metric is greater than any seen by the message so far. Through this way, it reduces the forwarding cost while achieving higher delivery performance.

## III. The Multi-Copy Delegation Forwarding Strategy

In order to build an accessible problem formulation and explain the artful strategy insights, we first introduce the mobility model, and problem description. Next, we determine a forwarding metric reflecting the node's actual forwarding ability. Finally, in the combination of forwarding metric and delegation forwarding strategy, a multi-copy delegation forwarding based on short-term and long-term speeds is proposed.

### A. Mobility Model

We hold the opinion that, the mobility model is significant in deciding the forwarding strategy. We also find that the random-waypoint mobility pattern is really useful in assisting the research in terms of the forwarding metric. We improve the random-waypoint mobility pattern as follows, with each node repeating its own behavior: selecting a destination arbitrarily, and walking along the shortest path with a fixed speed to reach the destination, and then staying for a while. However, different from the original random-waypoint mobility pattern, the fixed speed is chosen from a specific range. With this in mind, we can decompose the random-waypoint mobility process into three selecting operations and two phases. Two phases include the moving process to the destination, and the staying process at the destination. They are referred as the active phase and rest phase, respectively. At the beginning of the active phase, a node should do the following two selecting operations: select the location of the destination and select the moving speed. At the beginning of the rest phase, a node also needs to select a rest duration, which is related to the moving speed (i.e., the higher the moving speed is, the longer the duration the node rests for). The above mobility model matches that of our daily habit. We choose a walking speed to reach the destination, and then we stay there for having a

rest or addressing some issues. Maybe the faster we walk, the longer the amount of time we need to rest for.

### B. Problem Description

As was previously mentioned, there must be a measuring method to decide which node is better for forwarding the message. However, the short-term speed ($V_s$) and long-term speed ($V_l$) are both important in terms of measuring the node's forwarding ability. We should determine a reasonable forwarding metric. Moreover, even if the forwarding metric is achieved, how to disseminate the message copies is still a problem to be addressed. In order to maximize the delivery ratio, this paper primarily addresses the following two challenging problems. (1) The short-term speed reflects the transient forwarding ability, while the long-term speed indicates the permanent average forwarding activity; how to determine a comprehensive forwarding metric to quantify the actual forwarding ability. (2) Even if we obtain the node's actual forwarding ability, we also need to consider the forwarding strategy, in order to improve the delivery ratio, while reducing the forwarding cost.

To deal with the first problem, we attempt to use a forwarding metric to measure the forwarding ability, which should be related to both the short-term and long-term speeds. As was previously mentioned, if we make a forwarding decision only according to the short-term speed, the node with high short-term speed may well slow down in subsequent time. On the other hand, if we make a forwarding decision just according to the long-term speed, the opportunities for forwarding the message to some efficient nodes with high short-term speed are likely to be missed. Therefore, any of the above two decisions alone could not achieve the optimal delivery performance, there must be a mapping function from the $V_s$ and $V_l$ to a forwarding metric $F$, which could be used to reflect the actual forwarding ability (as shown in Eq. (1)).

$$F = f(V_s, V_l) \tag{1}$$

However, many mapping functions could be used to determine the forwarding metric. After analysis, the reason why both the short-term and long-term speeds cannot obtain the optimal result is that they use an incorrect time slice to calculate the average speed. Therefore, we try to find a suitable time slice to calculate the average speed, which is used to measure the forwarding ability. Fig. 2 is a detailed example of the forwarding metric utilizing both short-term and long-term speed. The situation is similar to that in Fig. 1. In case 1 of Fig. 1, the forwarding decision is made according to the short-term speed, and therefore, node $A$ will forward the message to node $B$ when they meet each other at the 7th second. Similarly, in case 2, node $A$ will not forward the message to node $B$, considering that the long-term speed of node $A$ is higher than that of node $B$. It is obvious that the decisions in the above two cases are incorrect. However, in Fig. 2, the forwarding decision is made according to the average speed of a specified time slice. For node $A$, the beginning of the time slice is the 7th second, and the end of the time slice is the 12th second
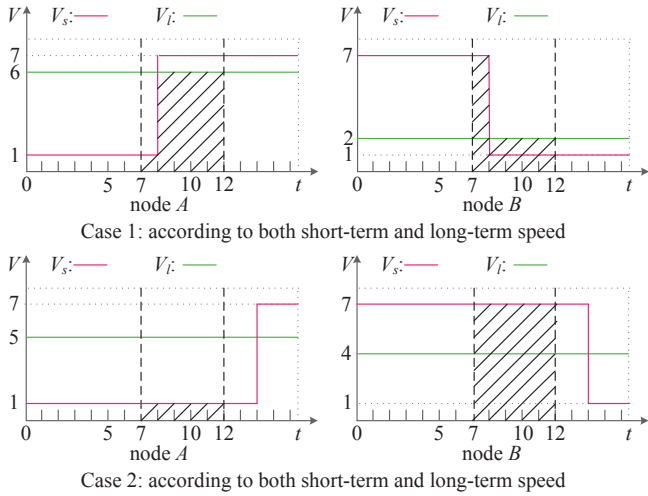
Fig. 2. A detailed example of the forwarding strategy utilizing both short-term and long-term speed in DTNs ($V_s$: short-term speed, $V_l$: long-term speed, node $A$ encounters node $B$ at the 7th second, and their expected time to encounter another node with a higher forwarding ability is the 12th second. The area of the shaded part represents the forwarding ability, which is referred to as forwarding metric).

TABLE I
MAIN NOTATIONS USED THROUGHOUT THE PAPER

| Notation | Meaning |
|---|---|
| $N$ | Total number of nodes in the network |
| $d$ | Communication radius |
| $L$ | Side length of the square network area |
| $\omega$ | A constant specific [19] to the random-waypoint model |
| $\varepsilon$ | The offset range for the uniform distribution of $V_s$ |
| $V_s$ | The short-term speed in uniform distribution $[V_e-\varepsilon, V_e+\varepsilon]$ |
| $V_e$ | The expectation of $V_s$, in a uniform distribution $[V_d, V_u]$ |
| $V_u$ | The upper bound of the uniform distribution of $V_e$ |
| $V_d$ | The lower bound of the uniform distribution of $V_e$ |
| $V_l$ | The long-term speed |
| $t_a$ | The duration time of the active phase |
| $T_a$ | The expectation of $t_a$, $T_a = E(t_a)$ |
| $t_r$ | The duration time of rest phase |
| $T_r$ | The expectation of $t_r$, $T_r = E(t_r)$ |
| $t_i$ | The interval time between the beginning of the current phase (active phase or rest phase) and the current time |
| $\alpha$ | The proportion between $V_e$ and $T_r$, $T_r = \alpha V_e$ |
| $F_a$ | The node's forwarding metric in the active phase |
| $F_r$ | The node's forwarding metric in the rest phase |

for meeting another node whose speed is higher than that of node $A$. It is not difficult to find that time slices could be different for the different nodes. For instance, in case 1 of Fig. 2, the node $A$'s average time slice speed is $5m/s$, and the node $B$'s average speed is $3m/s$, therefore, node $A$ makes a correct decision to keep the message from sending to node $B$. Similarly, in case 2, node $A$'s average speed is $1m/s$, and the average speed of node $B$ is $7m/s$; node $A$ also makes a correct decision to forward the message to node $B$.

The second problem is addressed according to the thought of delegation forwarding; we attempt to select some efficient nodes with the higher forwarding metric among all the ever-encountered nodes. To summarize, we present a multi-copy delegation forwarding based on short-term and long-term speed in DTNs. The simulation results show that, compared with other multi-copy forwarding strategies, DFSL achieves the highest forwarding efficiency. The main notations used in this paper are illustrated in Table I.

### C. Forwarding Metric

Each node has a time-varying short-term speed $V_s$, and a time-constant long-term speed $V_l$. The lifetime of a node could be divided into two categories: active phase $t_a$ and rest phase $t_r$. In the active phase, each node randomly selects its short-term speed $V_s$ from $[V_e-\varepsilon, V_e+\varepsilon]$, where $\varepsilon$ is a constant and $V_e$ is randomly selected from $[V_d, V_u]$. Therefore, the expectations of $V_s$ and $V_e$ are shown in Eq. (2) and Eq. (3), respectively.

$$E(V_s) = V_e \tag{2}$$

$$E(V_e) = \frac{V_u + V_d}{2} \tag{3}$$

As was previously mentioned, each node in DTN randomly chooses a $V_e$ from the range $[V_d, V_u]$ at the initial time, and

will not change $V_e$ during its whole lifetime. Therefore, different nodes may have different $V_e$. However, the expectation of $V_e$ is fixed as $\frac{V_u+V_d}{2}$. At the initial time of each active phase, each node selects its short-term speed from the range $[V_e - \varepsilon, V_e + \varepsilon]$; the short-term speed does not change until the end of this active phase. As shown in Fig. 3, $V_s$ may be different for each active phase, while $V_e$ will be static. It is worth noticing that, in the rest phase, $V_s = 0$.

Then, we take the long-term speed $V_l$ into consideration, which does not change during the whole lifetime, and could reflect the node's permanent activity level. As shown in Table I, the expected active duration $T_a = E(t_a)$, and the expected rest duration $T_r = \alpha V_e$ (the expected rest duration is in direct proportion to the expected short-term speed). So the expected $V_l$ is expressed as follows:

$$E(V_l) = \frac{E(t_a)E(V_s)}{E(t_a) + E(t_r)} = \frac{T_a V_e}{T_a + \alpha V_e}, \tag{4}$$

where the variation trend of $E(V_l)$ is the same as that of $V_e$. Therefore, the mobility model is in fact closer to that of the actual daily life. For each active phase, the short-term speed may be different. However, the long-term speed lies on the physical feature, which is normally constant. In order to determine the forwarding metric, we first define the intermeeting time, minimum intermeeting time and efficient intermeeting time, as follows:

*Definition 1:* Intermeeting time, which is the elapsed time from the end of the previous contact to the start of the next contact between nodes in a pair.

*Definition 2:* Minimum intermeeting time, which is the minimum elapsed time for a specific node from the end of the previous contact to reach and contact any other node.

*Definition 3:* Efficient intermeeting time, which is the minimum elapsed time for a specific node from the end of the previous contact to reach and contact another node with a higher forwarding ability.

According to the recent researches [19], the intermeeting times tail off exponentially in many popular mobility patterns.
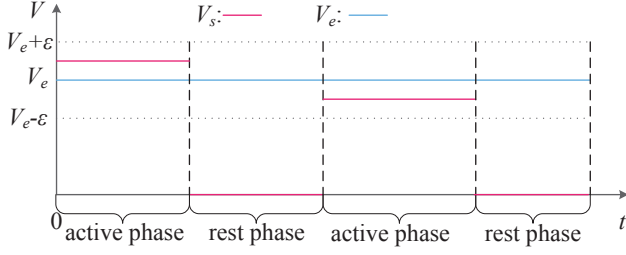
Fig. 3. An example to illustrate the changes of $V_s$ and $V_e$ during the active and rest phases



Fig. 4. The intermeeting time's distribution under the improved random-waypoint mobility pattern.

To further prove that the above conclusion remains valid in the improved mobility pattern, we first perform simulations on the intermeeting times to examine whether they can fit an exponential distribution. As can be seen in Fig. 4, the intermeeting times approximately follow an exponential distribution: $f(x) = \lambda e^{-\lambda x}$ $(x \geq 0)$, where $\lambda$ is the parameter for the exponential distribution of intermeeting times. We attempt to obtain the expectation of intermeeting times; with this in mind, the problem changes into calculating the parameter $\lambda$.

Next, we take the following situation into consideration, the average speed in the active phase of node $A$ and node $B$ are $V_a$ and $V_b$, respectively. We use the notation $V_r$ to express the relative speed between node $A$ and node $B$. According to the research results in [20], the expectation of relative speed can be calculated numerically through Eq. (5).

$$E(V_r) = \int_o^{2\pi} \frac{1}{2\pi} \sqrt{V_a^2 + V_b^2 - 2V_a V_b \cos\theta} \, d\theta \qquad (5)$$

Consider that $V_e$ represents the expectation of $V_s$. On the other hand, the variation trend of $E(V_l)$ is also the same with that of $V_e$. Therefore, $V_e$ can be used to reflect the expectation of the node's speed. When $V_a = V_b = V_e$, the following result can be derived from Eq. (5): $E(V_r) = \frac{4V_e}{\pi}$. On the basis of the research result in [20], the parameter in the exponential distribution of intermeeting times can be expressed as Eq. (6), where $\omega = 1.3683$ is a constant specific to the improved random-waypoint model, $d$ is the communication radius, and $L$ is the side length of the square network area.

$$\lambda = \frac{2\omega d E(V_r)}{L^2} = \frac{8\omega d V_e}{\pi L^2} \qquad (6)$$

Considering that there are $N$ nodes in the network, a specific node has a series of intermeeting times ($T_i$, $i \in \{1, 2, 3 \ldots, N-1\}$) with the other $N-1$ nodes; the intermeeting times follow an approximately exponential distribution with the parameter $\lambda$. Therefore, the minimum intermeeting time is defined as follows: $T_m = Min_{i\in\{1,2,3...,N-1\}} T_i$; it follows an approximate exponential distribution with the parameter $\lambda_m$, which is shown as Eq. (7). The mathematical expectation of the minimum intermeeting times is expressed as Eq. (8).

$$\lambda_m = N\lambda = \frac{8N\omega d V_e}{\pi L^2} \qquad (7)$$

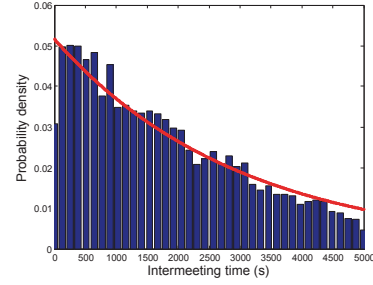$$T_m = \frac{1}{\lambda_m} = \frac{\pi L^2}{8N\omega d V_e} \qquad (8)$$

Our purpose is to find a reasonable time slice, which could be used to calculate the average speed. The average speed is further used as a forwarding metric to measure the actual forwarding ability. In this paper, we consider that the efficient intermeeting time which is defined by definition 3 should be the reasonable time slice for calculating forwarding metric. It is mainly due to the fact that the average speed of efficient intermeeting time (i.e., the minimum elapsed time for a specific node from the end of the previous contact to reach and contact another node of higher forwarding ability) could comprehensively reflect the node's efficient forwarding ability. In order to obtain the efficient intermeeting time, according to the fact that the message holder's expectation of $V_s$ is $V_e$, and the expectation of $V_s$ for any other node is randomly selected from $[V_d, V_u]$. Therefore, the parameter $\lambda_e$ in the exponential distribution of efficient intermeeting times can be expressed as Eq. (9). Furthermore, $T_e$ (i.e., the expectation of efficient intermeeting times) is achieved by Eq. (10).

$$\lambda_e = \frac{V_u - V_e}{V_u - V_d} \lambda_m = \frac{V_u - V_e}{V_u - V_d} \frac{8N\omega d V_e}{\pi L^2}, \qquad (9)$$

$$T_e = \frac{1}{\lambda_e} = \frac{V_u - V_d}{V_u - V_e} \frac{\pi L^2}{8N\omega d V_e}, \qquad (10)$$

where two functions of variable $V_e$ coexist: $\frac{V_u - V_d}{V_u - V_e}$ and $\frac{\pi L^2}{8N\omega d V_e}$. Along with the increase of $V_e$, $\frac{\pi L^2}{8N\omega d V_e}$ decreases, which indicates that a higher expectation of short-term speed results in a shorter intermeeting time. This is reasonable and natural. Then, we consider the function $\frac{V_u - V_d}{V_u - V_e}$. Along with the increase of $V_e$, $\frac{V_u - V_d}{V_u - V_e}$ increases. After analysis, a higher $V_e$ leads to the lower probability of seeing a node with a higher forwarding ability. Therefore, it will take a long time to see a node with a higher forwarding metric. In order to further prove that the function makes sense, we examine the following two special situations: (1) When $V_e$ is close to $V_d$, $T_e$ is approximately equal to $\frac{\pi L^2}{8N\omega d V_d}$, which indicates that whenever the message holder encounters a node, it will send the message to the encounter because the speed of the message holder is the lowest. (2) When $V_e$ approaches $V_u$, $T_e$ approximately equals $+\infty$, which means that whenever the message holder encounters a node, it will not send the message to the encounter, for the reason that the speed of the message holder is the highest. In conclusion, the method we used to calculate $T_e$ actually makes sense.

Finally, we attempt to achieve the average speed of the efficient intermeeting time. As illustrated in Table I, when the meeting time is in the active phase, $T_a$ represents the expectation of the current active phase's duration, and $t_i$ is the interval time between the beginning of the current active phase and the current time. When $T_a \leq t_i$, which indicates that the node should turn to the rest phase, we regard the long-term speed as the average speed of the following efficient intermeeting time. When $T_a > t_i$ and $T_e \leq T_a - t_i$, which means that the node will be in the active phase in the following efficient intermeeting time, we regard the short-term speed as the average speed. When $T_a > t_i$ and $T_e > T_a - t_i$, which indicates that the node will stay in the active phase for a while, and will then turn to the rest phase. In conclusion, when the meeting time is in the active phase, the forwarding metric $F_a$ is achieved as follows:

$$
F_a = \begin{cases} V_l & T_a \leq t_i \\ V_s & T_a > t_i, T_e \leq T_a - t_i \\ \frac{(T_a - t_i)V_s + (T_e - T_a + t_i)V_l}{T_e} & T_a > t_i, T_e > T_a - t_i \end{cases}
$$

We omit the detailed description for the situation in which the node's meeting time is in the rest phase, for the reason that it is similar to the previous situation. It is worth noticing that $V_s = 0$ in the rest phase. Therefore, the forwarding metric in the rest phase $F_r$ is shown as follows:

$$
F_r = \begin{cases} V_l & T_r \leq t_i \\ 0 & T_r > t_i, T_e \leq T_r - t_i \\ \frac{(T_e - T_r + t_i)V_l}{T_e} & T_r > t_i, T_e > T_r - t_i \end{cases}
$$

According to the above analyses, for each node, if the following parameters: $V_s$, $V_l$, $T_a$, $T_r$, $T_e$ and $t_i$ are achieved, it could calculate the forwarding metric, DFSL is further available. It is not difficult to find that, $V_s$ is easy to maintain for each node. Moreover, if $V_e$ could be achieved through a low cost estimation, $V_l$ and $T_e$ could be calculated through Eq. (4) and Eq. (10), respectively. We could achieve $V_e$, $T_a$ and $T_r$ through the historical statistics. Therefore, for each node, it just needs to record the interval time between the beginning of the current phase (active phase or rest phase) and the current time, which is defined as $t_i$. In conclusion, we design an efficient but low cost estimation of short-term speed, long-term speed and other necessary parameters.

### D. Multi-copy Delegation Forwarding

In Section III-C, we obtain the node's forwarding metric, which is calculated through $F_a$, when the meeting time is in the active phase. Meanwhile, when the meeting time is in the rest phase, the forwarding metric is achieved by $F_r$. Therefore, for each node, it has a forwarding metric, which represents its forwarding ability. So far, the first problem in Section I is solved; we could judge the node's forwarding ability and determine which node is better according to the forwarding metric. Next, we attempt to make the forwarding strategy, in order to decide how to disseminate the message copies.

Based on the forwarding metric, two simple forwarding strategies are naturally proposed. The first one is the Single-copy forwarding strategy, which only forwards the message to a node with a higher forwarding metric. The second one is Epidemic forwarding strategy, which replicates the message to every encounter. It is not difficult to find that the Single-copy forwarding strategy uses the least network resources, while its delivery ratio could not be guaranteed. However, the Epidemic forwarding strategy could achieve the highest delivery ratio when the network resource is enough, while it also spends the highest forwarding cost. Therefore, the above forwarding strategies could not achieve the satisfactory performance in terms of balancing delivery ratio and forwarding cost. Taking the delegation forwarding strategy into consideration, we attempt to select some of the most efficient nodes to deliver messages. In combination of the forwarding metric and delegation forwarding, we propose our multi-copy Delegation Forwarding based on Short-term and Long-term Speed (DFSL), whose pseudo-code is shown in Algorithm 1.

As shown in Algorithm 1, there are $N$ nodes, and $C$ kinds of different messages in DTN. For each node $i$, it has both a forwarding metric $F_i(t)$ at time $t$, which is time-varying, and a threshold $H_i$. To reduce forwarding cost with all the forces, we make the requirements for forwarding more stringent, compared with the normal strategy, which forwards the message to a better node. Our approach seeks to forward the message only to the nodes with the highest forwarding metric in the system. Conceptually, we would like to create a small number of message copies, and place them with the nodes which are the very best candidates with the highest delivery ability. Thus, the forwarding question in our approach becomes "is $N_j$ among the very highest quality nodes for message $m$". Therefore, in our strategy, a node will replicate a message copy only if it encounters another node whose forwarding metric is greater than any seen by the message so far. However, due to the fact that the forwarding metric in our strategy is time-varying, when node $i$ encounters node $j$, node $i$ will replicate a message copy to node $j$ if and only if node $j$'s forwarding metric is higher than both the node $i$'s current forwarding metric and the highest forwarding metric existing in the threshold $H_i$.

*Theorem 1: The forwarding cost of DFSL satisfies* $E[C_{DFSL}] \approx \frac{E[C_{delegation}]}{2} \lesssim \frac{5}{6}\sqrt{N}$.

*Proof*: It is well known that the upper bound of Delegation Forwarding' forwarding cost [13] is $C_{delegation}(g) \lesssim (1 + \sqrt{g})\sqrt{N}$, where $g$ is the gap between the initial threshold value and the highest threshold value, $N$ is the total number of nodes. Without loss of generality, we could map the forwarding metric into the scope of $[0, 1]$. Therefore, it is not difficult to find that the expectation of $g$ is $1/2$. Furthermore, the expectation of Delegation's forwarding cost is achieved as follows: $E[C_{delegation}] \lesssim \frac{5}{3}\sqrt{N}$. In contrast, the usual forwarding algorithm makes no threshold value. A message starting at a node with gap $g$ will eventually reach each of the nodes with higher quality, so that the expected cost is $E[C_{no-delegation}] \lesssim \frac{N}{2}$. Compared with the Delegation

**Algorithm 1** DFSL

**Input:**

   Nodes: $n_1, n_2, \cdots, n_N$
   Messages: $M_1, M_2, \cdots, M_C$
   Forwarding metrics: $F_1(t), F_2(t), \cdots, F_N(t)$

1: Node $n_i$ has forwarding metric $F_i(t)$ at time $t$ and threshold $H_i$
2: INITIALIZE $\forall i : H_i \leftarrow F_i(0)$
3: On contact between $n_i$ and $n_j$ (contact time: $t_c$)
4: **for** $k = 1$ to $C$ **do**
5:    **if** $M_k$ is currently held by $n_i$ **then**
6:       **if** $F_i(t_c) < F_j(t_c)$ and $H_i < F_j(t_c)$ **then**
7:          $H_i \leftarrow F_j(t_c)$
8:          replicate $M_k$ from $n_i$ to $n_j$

---

Forwarding algorithm, in the step 6 of DFSL, when node $i$ encounters node $j$, node $i$ will replicate a message copy to node $j$ if and only if node $j$'s forwarding metric is higher than both the node $i$'s current forwarding metric and the highest forwarding metric existing in the threshold $H_i$. Due to the reason that we could not control the changes of the forwarding metric, there is the probability of $1/2$ that node $j$'s forwarding metric is higher than node $i$'s current forwarding metric. According to the above analyses, the expectation forwarding cost of DFSL satisfies $E[C_{DFSL}] \approx \frac{E[C_{delegation}]}{2} \lesssim \frac{5}{6}\sqrt{N}$. Theorem 1 is proved.

## IV. PERFORMANCE EVALUATION

### A. Simulation Setup

To demonstrate the performance of DFSL, we carry out the simulations under the improved random-waypoint mobility pattern and pmtr [21] real trace. In order to verify the efficiency of the proposed forwarding metric, six single-copy forwarding strategies (DFSL-O, DFSL, DFSL-S, DFSL-L, DirectDelivery (DD) and FirstContact (FC)) are implemented in order to compare their performances. DFSL-O utilizes the average speed of an optimal time slice to make a forwarding decision, and achieves optimal delivery performance. DFSL uses the forwarding metric proposed in this paper. However, DFSL-S makes a forwarding decision only on the basis of the short-term speed, and DFSL-L makes a forwarding decision just according to the long-term speed. For the DirectDelivery forwarding strategy, the source will not forward the message to any other node except the destination. In contrast to DirectDelivery, the FirstContact forwarding strategy forwards the message to the first available encounter. The second part attempts to test the efficiency of the proposed multi-copy delegation forwarding strategy, five forwarding strategies (Single-Copy (SC), Spray And Wait (SAW) [17], DFSL, Utility-Based (UB) and Epidemic (EP)) are implemented in order to compare their performances. UB decides whether to replicate the message copy according to the current forwarding metric, it does not consider the node's previous forwarding metric. The simulation parameters are given in Table II. While a range of

| Parameter | Forwarding Value | |
|---|---|---|
| | Metric | Strategy |
| Simulation Time | 5,000s~10,000s | 3,000s~7,000s |
| Simulation Area | 3,000m×3,000m | |
| Number of Nodes | 60~140 | 100~140 |
| Number of Messages | 100 | |
| Transmission Range | 10m, 15m, 20m, 25m, 30m | |
| TTL | 5,000s~10,000s | 3,000s~7,000s |
| $\alpha$ | 0.5 | |

data is gathered from the simulations, we take the following five main performance metrics into consideration.

(1) Delivery ratio, which is the ratio between the number of messages successfully delivered to the destination and the total number of messages generated in the network.
(2) Average delay, which is the average elapsed time of the successfully delivered messages.
(3) Average hopcounts, which is the average number of hops for all the messages in the simulation time.
(4) Forwarding cost, which is the average forwarding times for all the generated messages.
(5) Forwarding efficiency, which is the result of delivery ratio divided by forwarding cost.

### B. Simulation Results in Terms of Forwarding Metric

We set a fixed area of $3000m \times 3000m$, where 100 nodes exist, whose mobility patterns are the improved random-waypoint. They are uniformly divided into 20 groups, the expected speeds of 20 groups are 20, 22, 24, $\cdots$, $58m/s$, respectively. The offset range for the uniform distribution of short-term speed is set to $5m/s$. We vary the message $TTL$, the number of nodes, and the communication radius to examine the proposed forwarding metric.

Fig. 5-(a) shows the changes of delivery ratio over message $TTL$ from 5000s to 10000s. The data leads us to the conclusion that the delivery ratio of DFSL-O achieves the best performance in terms of different message $TTLs$. This is not strange for the reason that DFSL-O utilizes the average speed of an optimal time slice to make a forwarding decision. Maybe finding the optimal slice is a challenging problem for us, however, we can easily obtain it through plenty of simulations. It is worth noticing that DFSL proposed in this paper does an excellent job in terms of delivery ratio.

### C. Simulation Results in Terms of Forwarding Strategy

In this section, we use the same simulation environment with that of Section IV-B. In order to exclude the interference of forwarding metric, the proposed forwarding metric is used in different forwarding strategies. Then, five forwarding strategies are implemented to show the efficiency of DFSL.

As can be seen in Fig. 6, SC achieves the lowest delivery ratio and the lowest forwarding cost, while EP obtains the highest delivery ratio and the highest forwarding cost, which matches our previous judgements. What's more, as shown in Theorem 1, the upper bound of DFSL's forwarding cost is
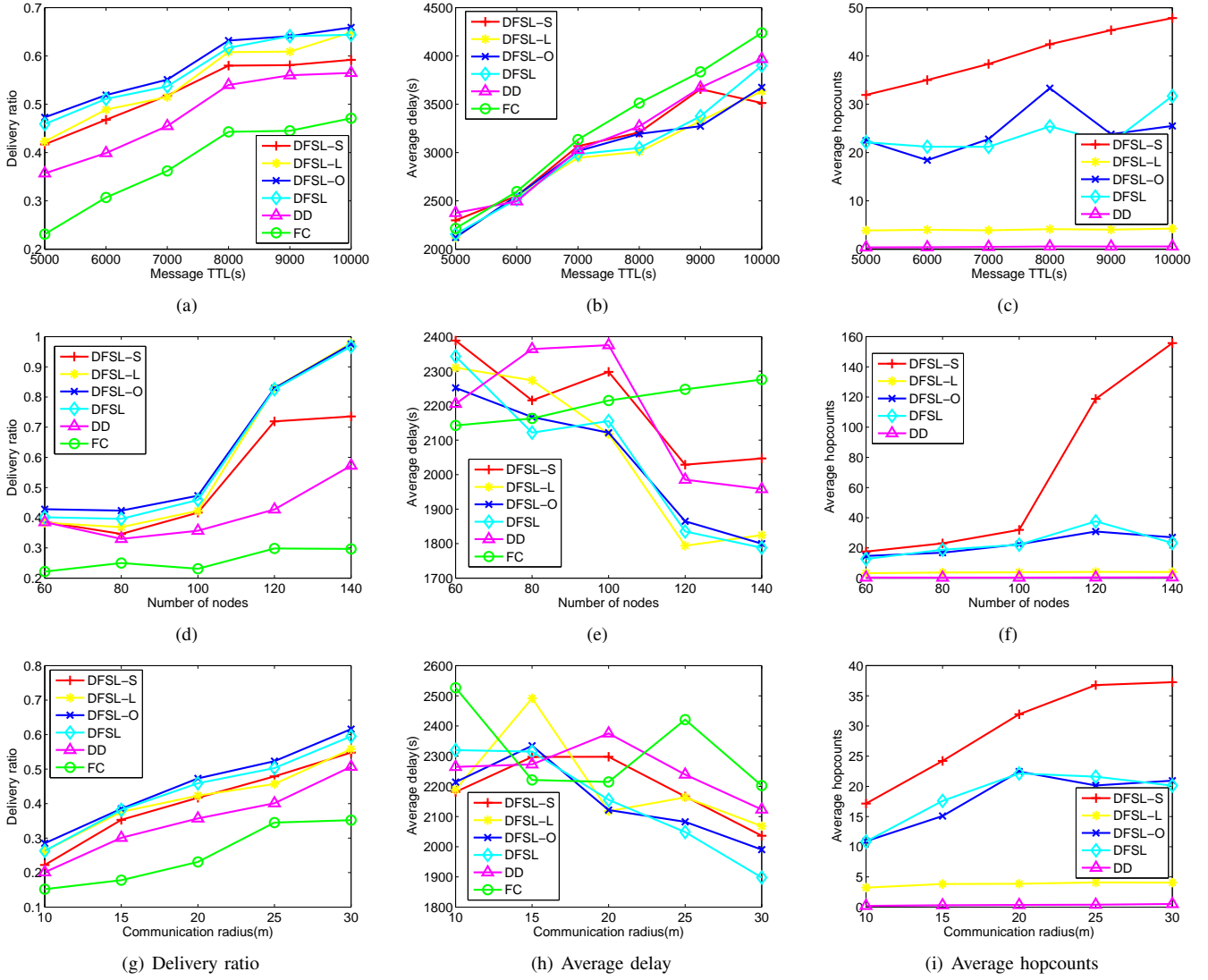
Fig. 5. Delivery ratio, Average delay and Average hopcounts as a function of message $TTL$, number of nodes, and communication radius under the improved random-waypoint mobility pattern.

$\frac{5}{6}\sqrt{N}$, which means that the forwarding cost's upper bound of DFSL in our simulation approaches to 9. And the simulation results show that the forwarding cost of DFSL is actually inferior to 9, which perfectly matches the theoretical result. Next, forwarding efficiency is defined as the result of delivery ratio divided by forwarding cost, and it could be used to measure the actual delivery performance. It is worth noticing that DFSL achieves the highest forwarding efficiency, regarding different message $TTL$, compared with other forwarding strategies.

In order to further prove the applicability of DFSL, we conduct simulations under the pmtr [21] real trace, which contains mobility traces from 44 mobile devices at University of Milano. Four multi-copy forwarding strategies are implemented to show the efficiency of DFSL. As can be seen in Fig. 7, DFSL still achieves the highest forwarding efficiency, regarding different message $TTL$ in the real trace.

## V. CONCLUSION

Forwarding metric is most important in terms of measuring the node's forwarding ability in DTNs. In this paper, we regard the node's speed as the forwarding metric by default. After analysis, neither the short-term speed, which represents transient forwarding ability, nor the long-term speed, which indicates longstanding average delivery ability, could obtain the optimal delivery performance. As a result, a comprehensive forwarding metric is presented in order to utilize the occasional encounter with a node in high short-term speed to deliver the message, while avoiding forwarding the message to an encounter in low long-term speed. Furthermore, taking the thought of delegation forwarding into consideration, we propose a multi-Copy Delegation Forwarding based on Short-term and Long-term speed in DTNs (DFSL). We conduct simulations under the improved random-waypoint mobility pattern and pmtr real trace. The simulation results show that,

(a) Delivery ratio      (b) Forwarding cost      (c) Forwarding efficiency
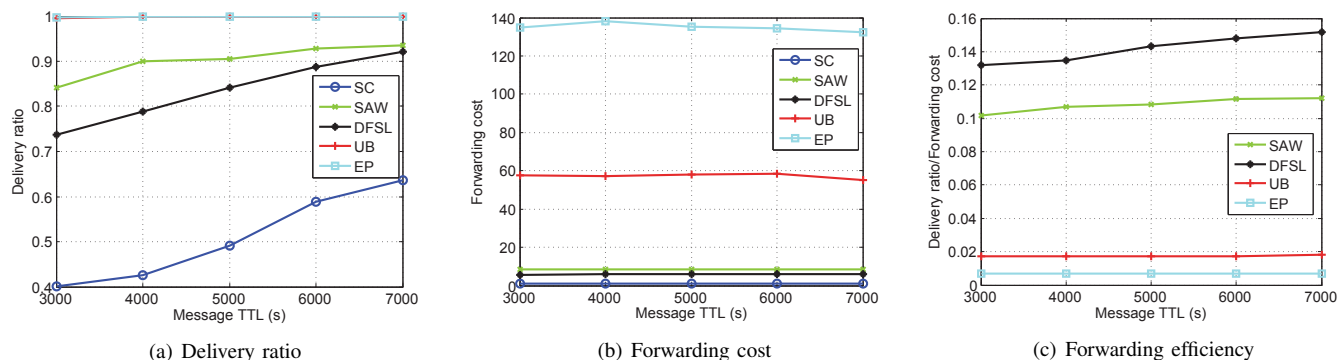
Fig. 6. Delivery ratio, Forwarding cost and Forwarding efficiency as a function of message $TTL$ under the improved random-waypoint mobility pattern.



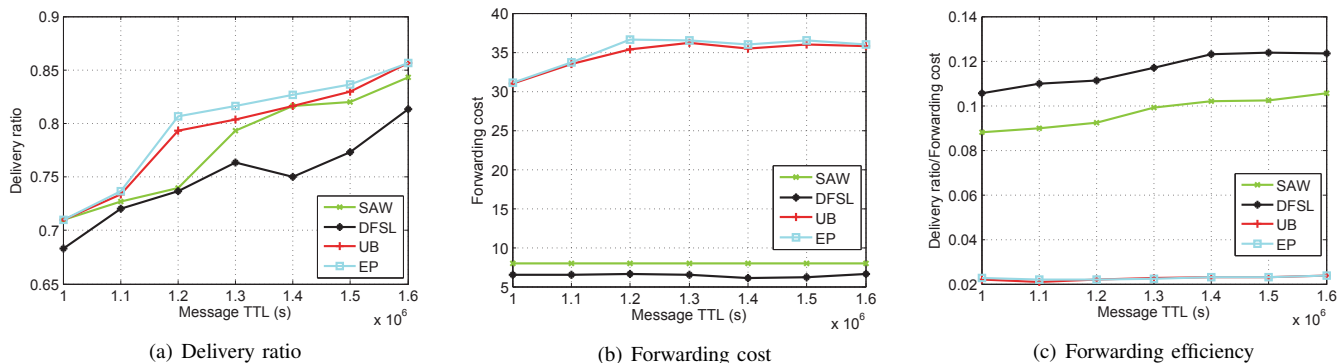(a) Delivery ratio      (b) Forwarding cost      (c) Forwarding efficiency

Fig. 7. Delivery ratio, Forwarding cost and Forwarding efficiency as a function of message $TTL$ under the pmtr real trace.

DFSL achieves the highest forwarding efficiency.

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