A Comprehensive Forwarding Strategy in DTNs: Theory and Practice

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***Abstract*—Delay tolerant networks (DTNs) are featured by unpredictable mobility patterns and easily interrupted connections. Forwarding strategy has always been the research focus in DTNs, in order to improve a delivery ratio. An enormous amount of research works 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 both short-term and long-term speed. Subsequently, we propose a theoretical, multicopy delegation forwarding based on short-term and long-term speed in DTNs (DFSL-T), 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-T 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. However, DFSL-T assumes that each node could achieve the average speeds of the others, which is impractical. In order to overcome this problem, we further propose a practical strategy (DFSL-P) through exchanging and evaluating the average speeds of each other. Finally, we conduct simulations based on the synthetic mobility pattern and real trace. The results show that compared with other multicopy forwarding strategies, DFSL-T and DFSL-P achieve higher forwarding efficiency, which is the result of delivery ratio divided by forwarding cost.**

***Index Terms*—Delegation forwarding, DTNs, forwarding metric, long-term speed, multi-copy, short-term speed.**

I. Introduction

Delay tolerant networks (DTNs) [2], [3] 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 [4], deep space satellite networks [5], vehicle and pedestrian networks [6], wildlife tracking [7], and disaster response networks [8]. 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 problems to be addressed. Therefore, forwarding metric [9] and forwarding strategy [10] 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 a *forwarding metric*. In view of the state-of-the-art researches, a variety of forwarding metrics including contact frequency [11], last contact time [12], contact duration [13], and total contact rate [14], *etc*. have been proposed to measure the nodes' forwarding abilities. In this paper, we just regard the node's speed as an example to measure the node's forwarding metric, the other factors could also be used to measure the forwarding ability according to the different network environments. 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 times plays an important role in forwarding ability in DTNs. Moreover, the short-term and long-term speed could be used to reflect transient and longstanding forwarding abilities, respectively. It is not difficult to find that short-term speed is time-varying, while 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 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 opportunities for forwarding the message to efficient nodes with high short-term speed.

Fig. 1 compares 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 (1 m/s) of node A is lower than that (7 m/s) of node B, while the long-term speed (6 m/s) of node

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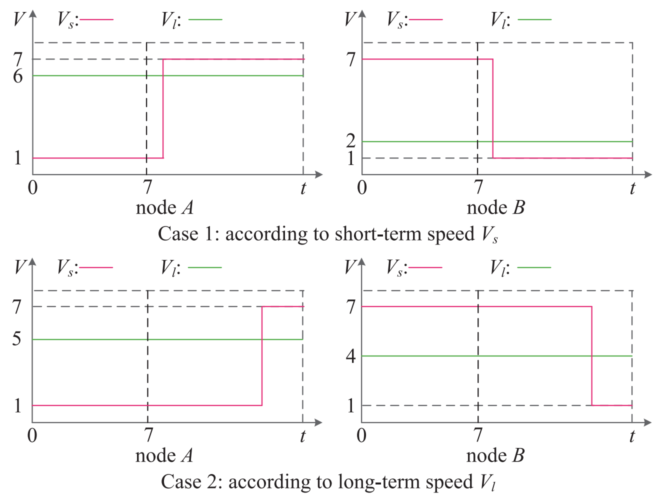

Fig. 1. The descriptions of two cases that the forwarding decisions are made according to short-term and long-term speed, respectively (V_s: short-term speed, V_l: long-term speed, node A encounters node B at the 7th second). In case 1, according to the short-term speed, node A with the short-term speed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

A is higher than that (2 m/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 (7 m/s), while that of node B reaches low level (1 m/s), which indicates that we have made a wrong forwarding decision. Similarly, in Case 2, the long-term speed (5 m/s) of node A is higher than that (4 m/s) of node B, while the short-term speed (1 m/s) of node A is lower than that (7 m/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 speeds 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 speeds.

To solve the second problem, how to decide the forwarding strategy, we use delegation forwarding [15] 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 [16]), the forwarding cost becomes unacceptable. Delegation forwarding is proposed to balance the trade off; it selects efficient relays to assist in delivering messages. Through the combination of the proposed forwarding metric and delegation forwarding, we first achieve a theoretical multi-copy delegation forwarding based on short-term and long-term speeds, which is referred to as DFSL-T. Secondly, we further propose a practical forwarding strategy, which is called DFSL-P. Simulation results show that DFSL-T and DFSL-P not only improve delivery ratio, but also reduce forwarding cost.

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

1) We present a mapping function from short-term and long-term speeds to a quantified forwarding metric, which could be used to reflect the actual forwarding ability. We also design an efficient and low-cost estimation of short-term and long-term speeds.
2) Through the combination of the forwarding metric and Delegation Forwarding (DF) [15] strategy, a theoretical, multi-copy delegation forwarding (DFSL-T) based on short-term and long-term speeds is proposed in DTNs.
3) In order to effectively obtain and evaluate the average speeds of other nodes, we further propose a practical strategy (DFSL-P) through exchanging and evaluating the average speeds of each other.
4) We conduct extensive simulations based on synthetic mobility pattern and real trace. The results show that, compared with other multi-copy forwarding strategies, DFSL-T and DFSL-P achieve a higher 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 speeds is presented in Section III, which includes both the theoretical and practical strategies. In Section IV, we evaluate the performances of DFSL-T and DFSL-P through extensive simulations. We conclude the paper in Section V.

II. Related Work

According to the different concerns [17]–[27], regarding the forwarding-based routing protocols, the existing researches in DTNs can be divided into the following two aspects: *forwarding metric*, which aims to determine which one is better between the message holder and the encounter, and solves the problem of whether to forward messages to the encounter; *forwarding strategy*, which attempts to decide how many message copies should be replicated or forwarded to the encounter, and then solves the problem of how to control the number of message copies in order to improve the delivery ratio while reducing the forwarding cost.

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 [15]. A destination-specific forwarding metric varies depending on the destination of a message. For example, FRESH [28] 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, have no relationship with the different destinations, and hence, are regarded as destination-independent. On the other hand, the forwarding metrics could also be time-varying or time-constant. A time-varying forwarding metric varies along with time (e.g., move speed, contact frequency). However, a time-constant forwarding metric remains unchanged (e.g., social relationship, total contact rate).

In this paper, speed is regarded as 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. A mapping function from the short-term and long-term speeds to a quantified forwarding metric is necessary. Therefore, we propose a forwarding metric which utilizes the occasional encounter with a node in high short-term speed to forward the message while avoiding forwarding the message to an encounter in low long-term speed.

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 further 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 [29] 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 [30] is proposed to limit the maximum number of message copies and to adopt a binary splitting method to disseminate message copies into the network; the process then continues until any message holder encounters the destination. Zheng and Wu [31] 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 flooding strategies and conditional flooding strategies. The flooding strategy aims to improve the delivery ratio without considering other constraint conditions. Therefore, the routing protocols in this category are usually purely theoretical. Epidemic [16] utilizes every contact opportunity to increase the probability that a message will 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 usually unusable in a real network environment. Conditional flooding strategy does not restrain the total number of message copies. Rather, it conditionally chooses the message to replicate, therefore, it attempts to avoid the waste of network resources by employing efficient nodes. In Delegation Forwarding [15], 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. In this way, it reduces the forwarding cost while achieving a higher delivery performance. Gao *et al*. [32] propose a novel method to improve data forwarding by taking advantage of transient social contact patterns; they also propose appropriate forwarding metrics to choose suitable nodes for forwarding the message.

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 the problem description. Next, we determine a forwarding metric reflecting the node's actual forwarding ability. Finally, combining forwarding metric and delegation forwarding strategy, a multi-copy delegation forwarding based on short-term and long-term speeds is proposed.

A. Mobility Model

The short-term and long-term speeds are used, respectively, to reflect transient and permanent forwarding abilities. Meanwhile, how to map the short-term and long-term speeds into the actual forwarding ability is an important problem.

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, with each node repeating its own behavior as follows: by selecting a destination arbitrarily and by 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. The two phases include the process of moving to the destination, and the process of staying at the destination. They are referred as the active phase and rest phase, respectively. At the beginning of the active phase, a node should perform 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 that the node rests for). The above mobility model matches that of our daily habit. We choose a walking speed to reach a destination, and then we stay there to have a rest or to address some issues. The faster we walk, the longer the amount of time we need to rest for is. In conclusion, the improved random-waypoint mobility pattern is suitable for assisting the research in terms of forwarding metric and forwarding strategy. Moreover, we also assume that the network resources (buffer, energy, bandwidth, etc.) are sufficient.

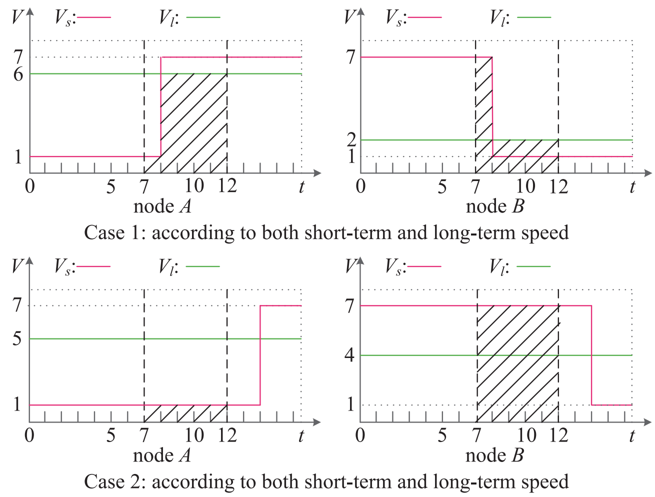

Fig. 2. A detailed example of the forwarding strategy utilizing both short-term and long-term speeds in DTNs (V_s: short-term speed, V_l: long-term speed. Node A encounters node B at the 7th second, and its expected time to encounter another node with a higher forwarding ability is the 12th second. The shaded area represents the forwarding ability, which is referred to as forwarding metric).

B. Problem Description

As 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 the long-term speed (V_l) are both important in terms of measuring the node's forwarding ability; We should determine a reasonable forwarding metric. 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 problems. (1) The short-term speed reflects the transient forwarding ability, while the long-term speed indicates the permanent average forwarding activity; we should 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 the long-term speeds. Neither of the above decisions alone can 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 (1)).

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

However, many mapping functions could be used to determine the forwarding metric. Analysis reveals that neither short-term nor long-term speeds could obtain the optimal result because 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 in order to measure the forwarding ability. Fig. 2 is a detailed example of the forwarding metric utilizing both short-term and long-term speeds. 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 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 5 m/s, and the node B's average speed is 3 m/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 1 m/s, and the average speed of node B is 7 m/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 efficient nodes with the higher forwarding metric among all the ever-encountered nodes. To summarize, we first present a theoretical multi-copy delegation forwarding based on short-term and long-term speed in DTNs. Furthermore, we propose a practical forwarding strategy by exchanging and evaluating the average speeds of each other. The simulation results show that, compared with other multi-copy forwarding strategies, the proposed forwarding strategies achieve a higher forwarding efficiency. The main notations used in this paper are illustrated in Table I.

C. Forwarding Metric in Theory

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 can 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 ε 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 (2) and (3), respectively.

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

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

As 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 noting that, in the rest phase, $V_s = 0$.

Then we take the long-term speed V_l, which does not change during the whole lifetime and which reflects the node's permanent activity level, into consideration. As shown in Table I, the

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
ω	A constant specific [33] to the random-waypoint model
ε	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	Upper bound of the uniform distribution of V_e
V_d	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
α	The proportion between V_e and T_r, $T_r = \alpha V_e$
λ	Parameter in exponential distribution of intermeeting times
λ_m	Parameter in exponential distribution of minimum intermeeting times
T_m	Mathematical expectation of the minimum intermeeting times, $T_m = \frac{1}{\lambda_m}$
λ_e	Parameter in exponential distribution of minimum intermeeting times to meet another node whose speed is higher than message holder
T_e	Mathematical expectation of the minimum intermeeting times for meeting another node whose speed is higher than message holder
F_a	The forwarding metric in the active phase
F_r	The forwarding metric in the rest phase

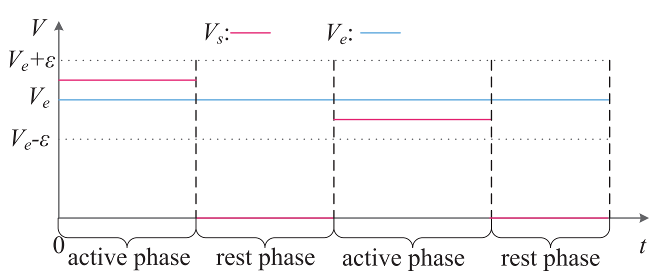

Fig. 3. An example to illustrate the changes of V_s and V_e during the active and rest phases.

expected active duration is $T_a = E(t_a)$, and the expected rest duration is $T_r = \alpha V_e$ (the expected rest duration is in direct proportion to the expected short-term speed). So the expected V_l is expressed as follows:

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

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

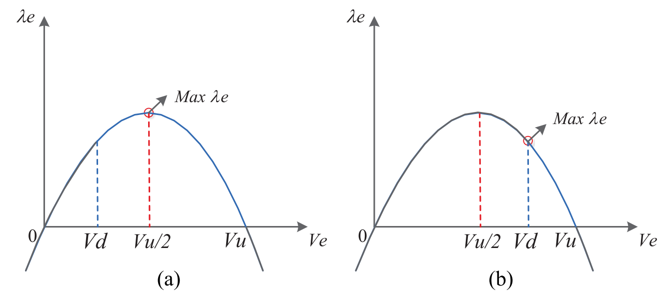

Fig. 4. The maximum value of λ_e in two situations. (a) $V_d <= V_u/2$. (b) $V_d > V_u/2$.

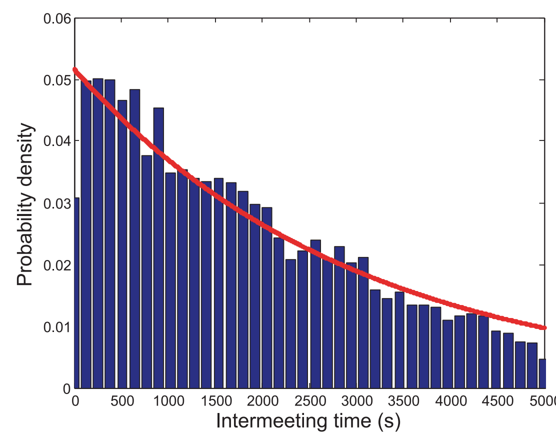

Fig. 5. The intermeeting time's distribution under the improved random-waypoint mobility pattern.

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, the minimum intermeeting time, and the efficient intermeeting time, as follows:

Definition 1: Intermeeting time 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 is the minimum elapsed time from the end of the previous contact to contact with any other node.

Definition 3: Efficient intermeeting time is the minimum elapsed time from the end of the previous contact to contact another node with a higher forwarding ability.

According to recent research [33], intermeeting times tail off exponentially in many popular mobility patterns. 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. 5, the intermeeting times approximately follow an exponential distribution: $f(x) = \lambda e^{-\lambda x}$ $(x \geq 0)$, where λ 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 λ.

Next, we take the following situation into consideration: the average speed in the active phases 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 [34], the expectation of relative speed can be calculated numerically through (5).

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

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 (5): $E(V_r) = \frac{4V_e}{\pi}$. On the basis of the research result in [34], the parameter in the exponential distribution of intermeeting times can be expressed as (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.

$$\lambda = \frac{2\omega dE(V_r)}{L^2} = \frac{8\omega dV_e}{\pi L^2} \tag{6}$$

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 λ. Therefore, the minimum intermeeting time is defined as follows: $T_m = Min_{i\in\{1,2,3\ldots,N-1\}}T_i$; it follows an approximate exponential distribution with the parameter λ_m, which is shown as (7). The mathematical expectation of the minimum intermeeting times is expressed as (8).

$$\lambda_m = N\lambda = \frac{8N\omega dV_e}{\pi L^2} \tag{7}$$

$$T_m = \frac{1}{\lambda_m} = \frac{\pi L^2}{8N\omega dV_e} \tag{8}$$

Our purpose is to find a reasonable time slice, which could be used to calculate average speed. The average speed is further used as a forwarding metric to measure actual forwarding ability. In this paper, we consider that the efficient intermeeting time 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. We attempt 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 $[V_d, V_u]$. So the parameter λ_e in the exponential distribution of efficient intermeeting times can be expressed as (9). Furthermore, T_e (i.e., the expectation of efficient intermeeting times) is achieved by (10).

$$\lambda_e = \frac{V_u - V_e}{V_u - V_d}\lambda_m = \frac{V_u - V_e}{V_u - V_d}\frac{8N\omega dV_e}{\pi L^2}, \tag{9}$$

$$T_e = \frac{1}{\lambda_e} = \frac{V_u - V_d}{V_u - V_e}\frac{\pi L^2}{8N\omega dV_e}, \tag{10}$$

where two functions of variable V_e coexist: $\frac{V_u - V_d}{V_u - V_e}$ and $\frac{\pi L^2}{8N\omega dV_e}$. Along with the increase of V_e, $\frac{\pi L^2}{8N\omega dV_e}$ 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, it becomes clear that a higher V_e leads to a 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. It is worth noting that, T_e is different from Intermeeting time and Minimum intermeeting time, which are defined by Definitions 1 and 2. Intermeeting time means the time slot between the two consecutive meeting for a pair of nodes, while Minimum intermeeting time is the time slot for a node to meet any other node. Efficient intermeeting time means the time slot for a node to meet a better node, where "better" means that the node is with a higher forwarding ability.

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 $\frac{\pi L^2}{8N\omega dV_d}$, 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 because the speed of the message holder is the highest. In conclusion, the method we used to calculate T_e actually makes sense.

Next, we consider the maximum value of λ_e in (9). The change trend of function λ_e in (9) is the same as that of $(V_u - V_e)V_e$. Moreover, the variation range of V_e is from V_d to V_u. In order to achieve the maximum value of λ_e, we should consider the following two situations: $V_d <= V_u/2$ and $V_d > V_u/2$, which are shown in Fig. 4. When $V_d <= V_u/2$, λ_e achieves maximum value when $V_e = V_u/2$. When $V_d > V_u/2$, λ_e achieves maximum value when $V_e = V_d$.

The above theoretical result is reasonable because larger V_e does not always get shorter efficient intermeeting time. This is because a node with larger V_e rarely encounters a node with a higher forwarding ability. Therefore, when V_d is sufficiently low, $V_e = V_u/2$ leads to a shortest efficient intermeeting time. When V_d is sufficiently high, $V_e = V_d$ leads to the shortest efficient intermeeting time.

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 $T_a \le t_i$, 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 $T_e \le T_a - t_i$, which means that the node will be in the active phase during the efficient intermeeting time, we regard the short-term speed as the average speed. When

$T_a > t_i$ and $T_e > T_a - t_i$, it 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:

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

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

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

According to the above analyses, for each node, if the parameters V_s, V_l, T_a, T_r, T_e and t_i are achieved, it could calculate the forwarding metric, DFSL-T 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, then V_l and T_e could be calculated through (4) and (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. Forwarding Metric in Practice

In Section III-C, a forwarding metric in theory is proposed, and DFSL-T is further formulated to address the message delivery problem in DTN. However, it is not difficult to find that, when calculating $E(V_r)$ in (5), we assume that $V_a = V_b = V_e$ because we could not achieve other nodes' expectations of V_s. In order to achieve a practical forwarding metric, in this section we try to collect the average V_e of all the nodes and to calculate (5) using the average V_e of all the nodes instead of the previous V_e.

The collection process is shown in Fig. 6, in which two nodes exchange each other's missing records. Each node could calculate the average V_e of all the nodes in the records. The forwarding metric, in practice, is achieved. DFSL-P is further proposed based on the forwarding metric in practice.

Next, the overhead is discussed, as shown in (10), the expectation of efficient intermeeting time is $T_e = \frac{V_u - V_d}{V_u - V_e} \frac{\pi L^2}{8N\omega d V_e}$. Assume that the total time is T, the average communication overhead for a node is T/T_e, then the total communication overhead is similar to $NT/T_e = NT \frac{V_u - V_e}{V_u - V_d} \frac{8N\omega d V_e}{\pi L^2}$. Therefore, the total communication overhead is $O(N^2)$.

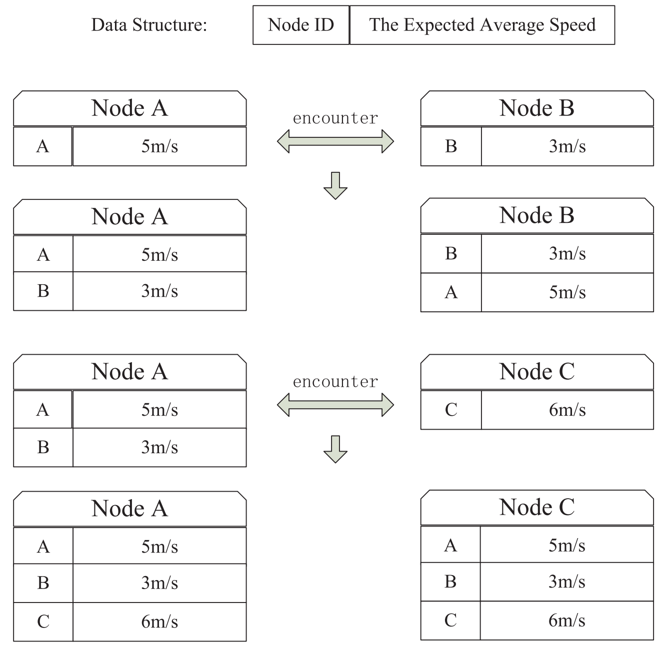

Fig. 6. The exchange process to collect V_e of each other.

E. Multi-Copy Delegation Forwarding

In the previous subsections, we obtain the node's forwarding metric calculated through F_a when the meeting time is in the active phase. However, when the meeting time is in the rest phase, the forwarding metric is achieved by F_r. Therefore, each node has a forwarding metric, which represents its forwarding ability. So far, the first problem presented in Section I is solved; we could judge the nodes' forwarding abilities and determine which node is better according to the forwarding metric. Next, we attempt to make a forwarding strategy in order to decide how to disseminate 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 a message to a node with a higher forwarding metric. The second one is Epidemic forwarding strategy, which replicates a message to every encounter. The Single-copy forwarding strategy uses the fewest network resources, however, its delivery ratio could not be guaranteed. The Epidemic forwarding strategy on the other hand, could achieve the highest delivery ratio when network resources are sufficient, but it also spends the highest forwarding cost. Therefore, the above forwarding strategies could not achieve 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 with the forwarding metric and delegation forwarding, we propose our theoretical and practical forwarding strategies based on short-term and long-term speeds (DFSL-T and DFSL-P) 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

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

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 that of both node i's current forwarding metric and that of the highest forwarding metric existing in the threshold H_i.

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

Proof : It is well known that the upper bound of Delegation Forwarding's forwarding cost [15] 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 and 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: $E[C_{\text{delegation}}] \lesssim \frac{5}{3}\sqrt{N}$. 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 $E[C_{\text{no-delegation}}] \lesssim \frac{N}{2}$. Compared with the Delegation Forwarding algorithm, in 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. Because we could not control the changes of the forwarding metric, there is a probability of $1/2$ that node j's forwarding metric is higher than node i's current forwarding metric.

TABLE II
SIMULATION PARAMETERS FOR TESTING PROPOSED FORWARDING METRIC

Parameter	Value
Simulation time	5000 s, 6000 s, $\cdots$ 9000 s, 10000 s
Simulation area	3000 m $\times$ 3000 m
Number of nodes	60, 80, 100, 120, 140
Number of messages	100
Transmission speed	250 kBps
Message size	50 kB
Buffer size	50 MB
Transmission range	10 m, 15 m, 20 m, 25 m, 30 m
TTL	5000 s, 6000 s, $\cdots$ 9000 s, 10000 s
α	0.5

TABLE III
SIMULATION PARAMETERS FOR TESTING PROPOSED FORWARDING STRATEGY

Parameter	Value
Simulation time	3000 s, 4000 s, $\cdots$ 6000 s, 7000 s
Simulation area	3000 m $\times$ 3000 m
Number of nodes	100, 110, 120, 130, 140
Number of messages	100
Transmission speed	250 kBps
Message size	50 kB
Buffer size	50 MB
Transmission range	10 m, 15 m, 20 m, 25 m, 30 m
TTL	3000 s, 4000 s, $\cdots$ 6000 s, 7000 s
α	0.5

According to the above analyses, the expectation forwarding cost of DFSL satisfies $E[C_{DFSL}] \approx \frac{E[C_{\text{delegation}}]}{2} \lesssim \frac{5}{6}\sqrt{N}$. Theorem 1 is proved.

IV. Performance Evaluation

A. Simulation Setup

To demonstrate the performance of DFSL-T and DFSL-P, we carry out simulations under the improved random-waypoint mobility pattern and two real traces: pmtr [35] and roma/taxi [36]. In order to verify the efficiency of the proposed forwarding metric, seven single-copy forwarding strategies (DFSL-O, DFSL-T, DFSL-P 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-T uses the theoretical forwarding metric proposed in this paper, and DFSL-P uses the practical forwarding metric. 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, six forwarding strategies (Single-Copy (SC), Spray And Wait (SAW) [30], DFSL-T, DFSL-P, Utility-Based (UB), and Epidemic (EP)) are implemented in order to compare their performances. UB

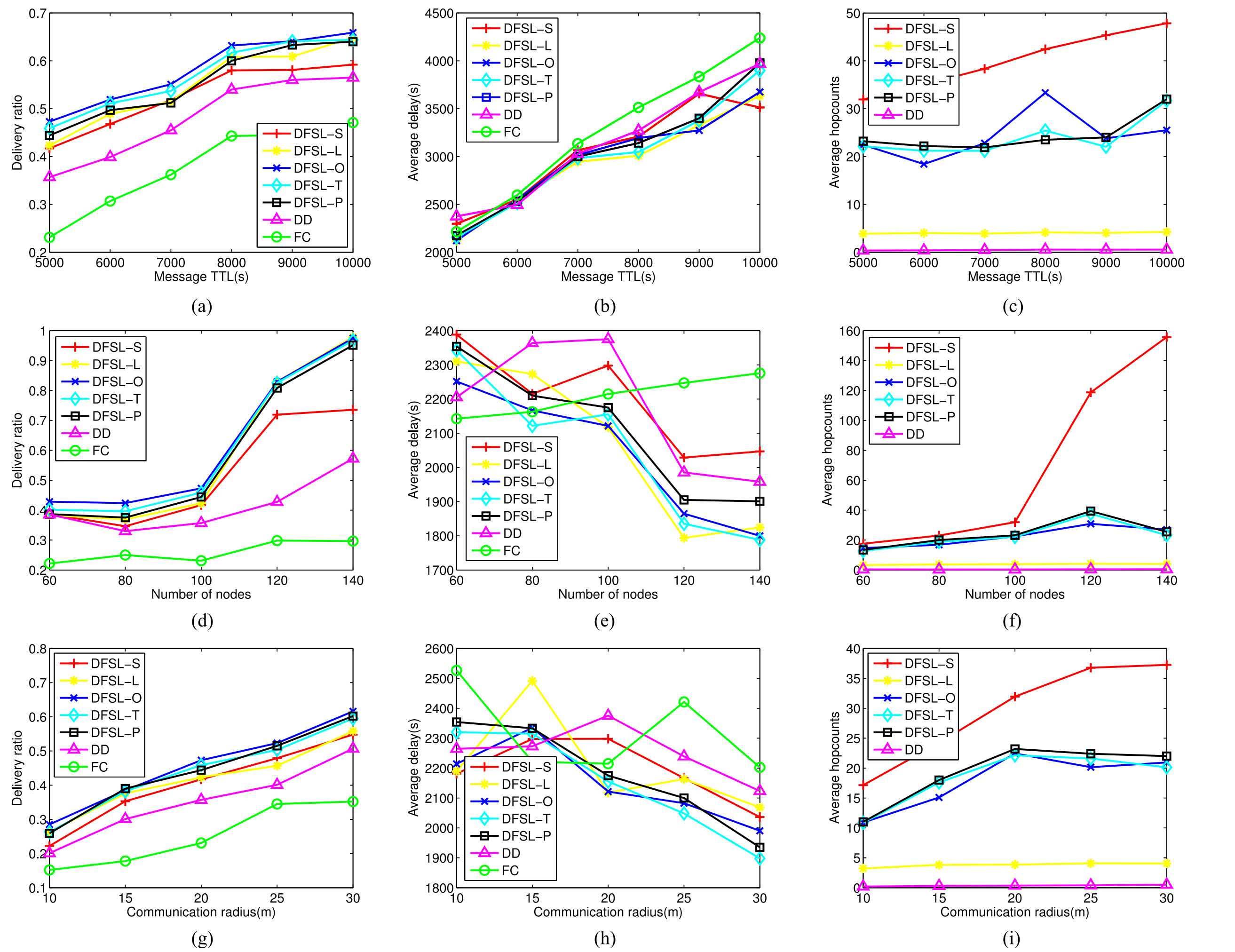

Fig. 7. Delivery ratio, average delay and average hopcounts as a function of message TTL, number of nodes, and communication radius under the improved random-waypoint mobility pattern.

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

For the first set of simulations, we set the number of nodes to 100 and the communication radius to 20m. The trends of delivery ratio, average delay, and average hopcounts as a function of message TTL are shown in Fig. 7(a)–(c).

Fig. 7(a) shows the changes of delivery ratio over message TTL from the 5000 s to the 10000 s. 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 because 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 noting that DFSL-T and DFSL-P, proposed in this paper, do an excellent job in terms of delivery ratio. However, the results are less than, however close to, the results of DFSL-O. In addition, the delivery ratio of DFSL-T is obviously higher than the that of DFSL-S and

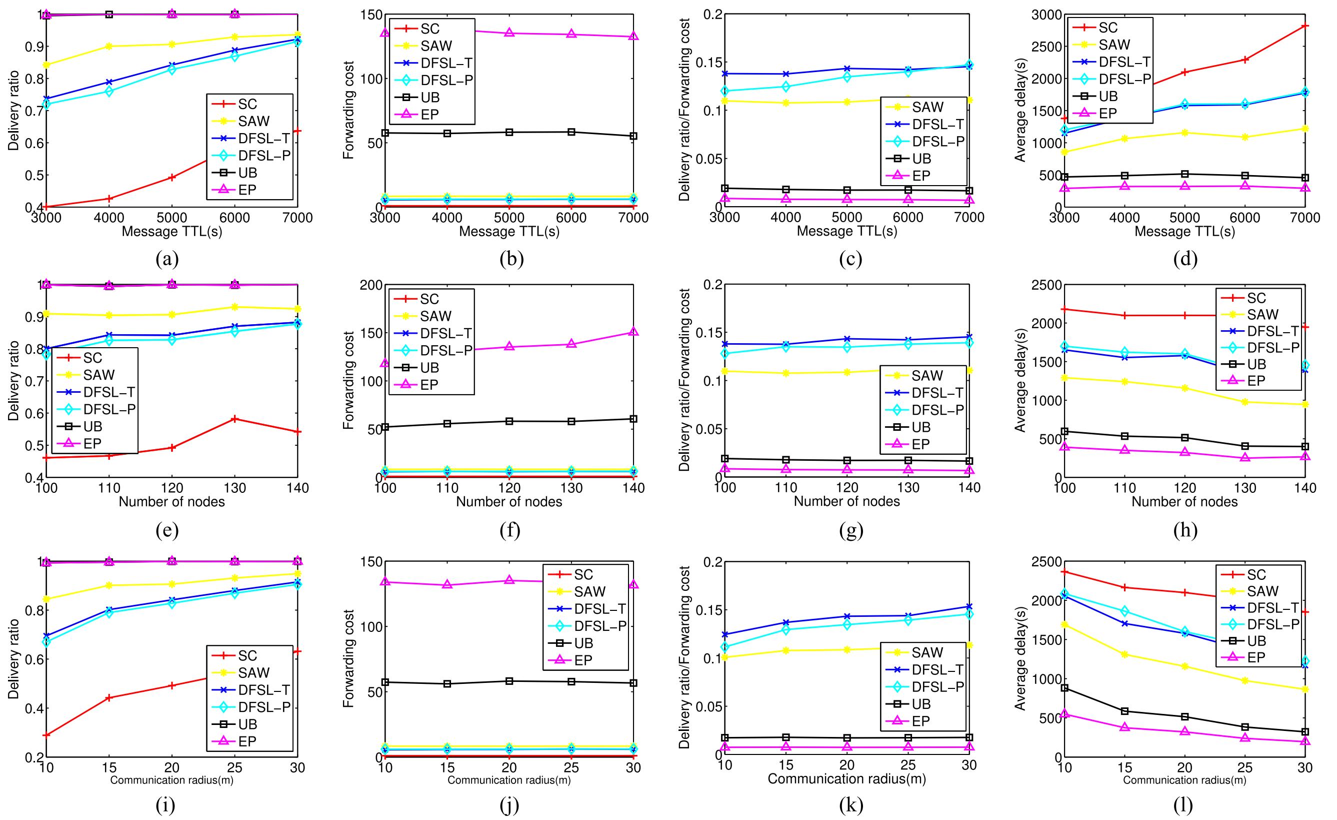

Fig. 8. Delivery ratio, forwarding cost and forwarding efficiency as a function of message TTL, number of nodes, and communication radius under the improved random-waypoint mobility pattern.

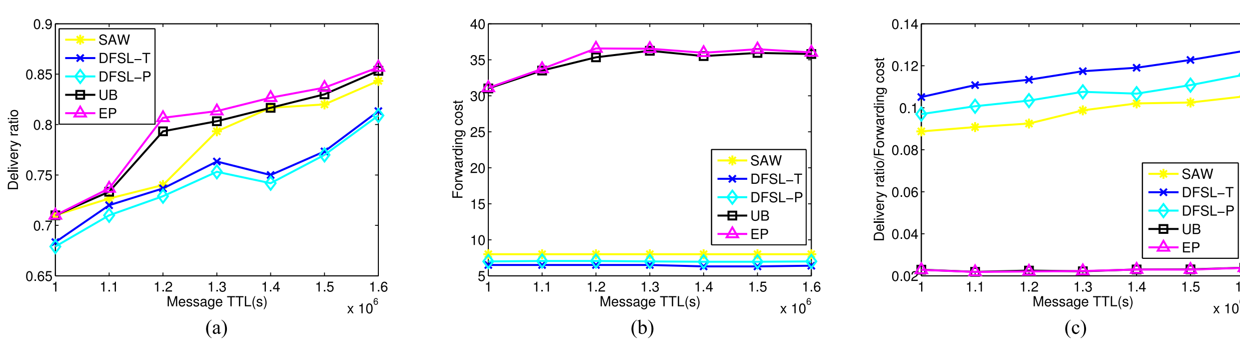

Fig. 9. Delivery ratio, forwarding cost and forwarding efficiency as a function of message TTL under the pmtr real trace. (a) Delivery ratio. (b) Forwarding cost. (c) Forwarding efficiency.

of DFSL-L, which further proves that the proposed forwarding metric is effective. Therefore, simply using the short-term speed or long-term speed as the forwarding metric could not obtain the optimal delivery performance. Moreover, we are pleased to find that DFSL-P achieves a similar delivery performance to DFSL-T.

Fig. 7(b) describes the variation trend of average delay as a function of the message TTL. It is easy for us to see that DFSL-T and DFSL-P get lower average delays to deliver a message in terms of different message TTLs. Fig. 7(c) provides some important data regarding average hopcounts performance; it is a very pleasant surprise that DFSL-T and DFSL-P achieve better performances regarding average hopcounts compared to other routing protocols. The better performances are mainly caused by the reasonable forwarding metric and forwarding algorithm.

Next, the changes of delivery ratio, average delay, and average hopcounts as a function of the number of nodes are shown in Fig. 7(d)–(f). Then, the change trends of delivery ratio, average delay, and average hopcounts are plotted as a function of communication radius in Fig. 7(g)–(i). We omit a detailed description because its shape is similar to that of previous figures.

C. Simulation Results in Terms of Forwarding Strategy

Random waypoint: In this section, we use the same simulation environment as that of Section IV-B. In order to exclude the interference of the forwarding metric, the proposed forwarding

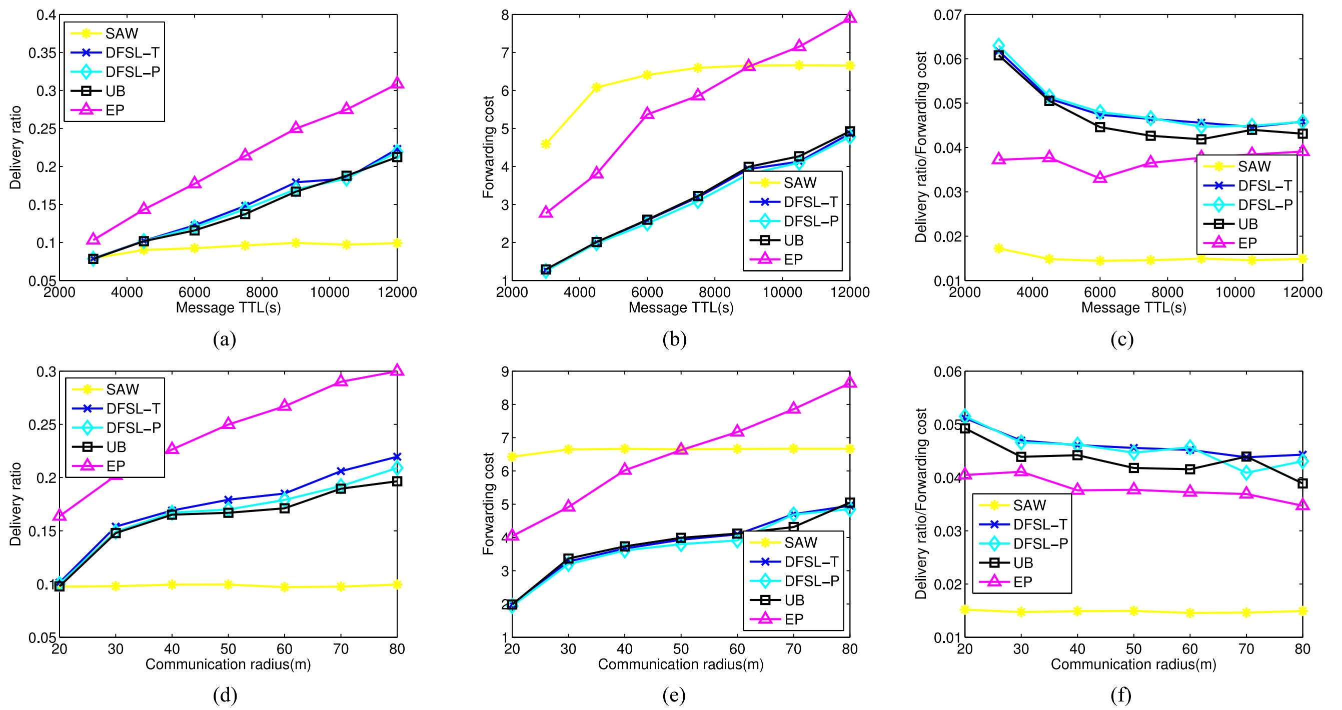

Fig. 10. Delivery ratio, forwarding cost and forwarding efficiency as a function of message TTL and communication radius under the roma/taxi real trace.

metric is used in different forwarding strategies. Then, six forwarding strategies are implemented to show the efficiency of DFSL.

As seen in Fig. 8(a)–(d), SC achieves the lowest delivery ratio, the lowest forwarding cost, and highest average delay, while EP obtains the highest delivery ratio, the highest forwarding cost, and lowest average delay, which matches our previous judgements. What's more, as shown in Theorem 1, the upper bound of DFSL's forwarding cost is $\frac{5}{6}\sqrt{N}$, which means that the forwarding cost's upper bound of DFSL in our simulation approaches 9. The simulation results show that the forwarding cost of DFSL-T 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 noting that DFSL-T achieves the highest forwarding efficiency compared to other forwarding strategies with regard to different message TTLs. Moreover, we are pleased to find that the forwarding efficiency of DFSL-P is close and similar to that of DFSL-T.

Fig. 8(e)–(h) show the changes of delivery ratio, forwarding cost, and average delay as a function of the number of nodes. Is is worth noting that, forwarding cost appears a growth trend along with the increase of node number in Fig. 8(f). It is easy to understand because more nodes lead to more forwarding relays, which increase the forwarding cost. However, the changes of average delay appear as a downtrend in Fig. 8(h), which is mainly because more nodes leads to a quicker delivery process.

Fig. 8(i)–(l) describe the variation trends of delivery ratio, forwarding cost, and average delay as a function of the communication radius. Is is worth noting that, larger communication radius leads to quicker delivery process and also results in lower average delay.

To conclude, compared with the other routing protocols, DFSL-T achieves the highest forwarding efficiency with regard to different message TTLs, numbers of nodes, and communication radius under random-waypoint scenario.

Pmtr: In order to further prove the applicabilities of DFSL-T and DFSL-P, we conduct simulations under the pmtr [35] real trace, which contains mobility traces from 44 mobile devices at University of Milano. Five multi-copy forwarding strategies are implemented to show the efficiency.

As seen in Fig. 9, DFSL-T achieves the highest forwarding efficiency, regarding different message TTL in the pmtr real trace, which further proves that DFSL-T utilizes a small number of nodes to achieve a very high delivery ratio. In conclusion, no matter the synthetic mobility pattern or the real trace, DFSL always achieves the best performance.

Roma/taxi: In order to further verify the efficiency of the proposed forwarding metric, we also conduct extensive simulations under the roma/taxi real trace, which contains mobility traces of taxi cabs in Rome, Italy. Roma/taxi contains GPS coordinates of approximately 320 taxis collected over 30 days.

We first study the influence on delivery ratio caused by message TTLs, the simulation results are shown in Fig. 10(a)–(c). As seen in the Fig. 10(a), the delivery ratio shows an increasing trend along with the growth of message TTL for all five routing methods. However, the rates of growth for the five methods are different. Epidemic routing achieves the fastest growth rate, which is reasonable. Moreover, SAW achieves the lowest delivery ratio, and the increasing trend is also not obvious. The above phenomenon illustrates that longer message TTL could not affect the delivery ratio when the messages are sprayed adequately. As seen in Fig. 10(c), DFSL-T and DFSL-P still achieve better delivery ratio compared to other forwarding metrics under different message TTLs.

Secondly, we conduct simulations to study the changes of delivery ratio along with communication radius in Fig. 10(d)–(f). The simulation results show that a larger communication radius leads to a higher delivery ratio, which is also easy to understand. Fig. 10(f) shows that DFSL-T and DFSL-P still achieve a better delivery ratio than other routings under different communication radiuses.

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 on its own. 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 a message while avoiding forwarding the message to an encounter in low long-term speed. Furthermore, taking delegation forwarding into consideration, we propose a theoretical multi-copy Delegation Forwarding based on Short-term and Long-term speed in DTNs (DFSL-T). However, DFSL-T assumes that each node could achieve the average speeds of the others, which is impractical. In order to overcome this problem, we further propose a practical strategy (DFSL-P) through exchanging and evaluating the average speeds of each other. We conduct simulations under the improved random-waypoint mobility pattern and two real traces: pmtr and roma/taxi. The simulation results show that both DFSL-T and DFSL-P achieve higher forwarding efficiencies.

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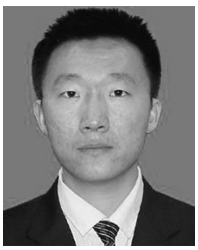

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