Submitted version

Location-Aware Utility-Based Routing for Store-Carry-Forward Message Delivery

Tomotaka Kimura*, Tsubasa Matsuura*, Masahiro Sasabe†, Takahiro Matsuda‡, and Tetsuya Takine‡
*‡Graduate School of Engineering, Osaka University, Suita 565-0871, Japan
†Graduate School of Information Science, Nara Institute of Science and Technology, Ikoma 630-0192, Japan
*{kimura, t-matsuura}@post.comm.eng.osaka-u.ac.jp, †sasabe@is.naist.jp, ‡{matsuda, takine}@comm.eng.osaka-u.ac.jp

***Abstract*—One of the most important technical problems in store-carry-forward routing is to reduce the number of message copies in networks without increasing the message delivery delay. In order to solve this problem, we focus on utility-based routing schemes, where for a message, utility of a node indicates its proximity to the destination node of the message. Utility-based routing schemes are promising when relay nodes, i.e., nodes with the message (copy), have sufficient opportunities to encounter other nodes. On the other hand, when relay nodes are in extremely sparse areas of nodes and they have few opportunities to encounter other nodes, the routing schemes do not work effectively. This observation naturally leads us to propose a *location-aware* utility-based routing scheme. The proposed scheme combines a utility-based routing scheme with location-aware probabilistic forwarding, where the forwarding probability is determined based on both node utility and node density at the contact location. With several simulation scenarios, we evaluate the performance of the proposed scheme in terms of the mean number of copies in the network and the mean message delivery delay.**

I. Introduction

Intermittently connected mobile ad hoc networks are one of the most representative environments in DTNs (Delay/Disruption Tolerant Networks) [4]. In those networks, the intermittent connectivity prevents from establishing reliable end-to-end paths between source and destination nodes. In order to solve this problem, many store-carry-forward routing schemes have been proposed so far [2]. Owing to mobility of nodes, a node happens to establish a connection to another node occasionally. The store-carry-forward routing schemes utilize this occasional connectivity to deliver a message to its destination node. Specifically, when a node receives the message, the node stores the message in the buffer, carries the message with it while moving, and then forwards it to other nodes when the node encounters them.

Epidemic Routing [10] is the pioneering work in store-carry-forward routing schemes. Even though Epidemic Routing achieves the best performance in terms of the end-to-end delivery delay, it may cause excessively many copies of messages to be disseminated over networks. In order to avoid excessive consumption of network resources such as bandwidth and buttery power of nodes without increasing the message delivery delay, many store-carry-forward routing schemes have been considered [2].

In this paper, we focus on *utility-based routing* [3], [8] in order to solve this problem. Note that utility represents the proximity among nodes. For example, suppose that nodes correspond to people with a wireless terminal such as a smartphone. People who frequently meet each other, or commute to the same office or school have high utility among them. Suppose node A with a message copy destined for node C encounters node B without the message copy. In the utility-based routing schemes, node A determines whether it forwards the message copy to node B based on utility of node B toward node C. In what follows, we call nodes with message copies *relay nodes*.

The performance of utility-based routing schemes depends on contact rates among nodes. When relay nodes encounter other nodes frequently, message copies should be forwarded to only nodes with high utility. Although relay nodes ignore opportunities of forwarding message copies to nodes with low utility, the delivery delay performance does not be degraded severely because inter-contact times among nodes with high utility are short. On the other hand, if relay nodes have few opportunities to encounter other nodes, aggressive message forwarding is suitable for keeping the message delivery capability. In general, contact rates among nodes are strongly correlated with node density, so that we can enhance the performance of the utility-based routing schemes, taking account of the node density at contact locations where two nodes encounter.

In this paper, we propose a *location-aware utility-based routing scheme*. Our scheme combines a utility-based routing scheme with a location-aware probabilistic forwarding scheme proposed in [6], [7]. In the location-aware probabilistic forwarding scheme, each node estimates a spatial distribution of node density by collecting node contact information from other nodes, and forwards a message with a probability determined by the node density distribution. In our scheme, when a relay node encounters a node with high utility, the former node always forwards the message to the latter node, which is the same operation as in utility-based routing schemes. On the other hand, when the relay node encounters a node with low utility, the former node decides whether it forwards the message based on the node density of the current location. Specifically, when the relay node is currently within a low node density area, the message copy is forwarded with a high probability. By doing so, the message delivery capability is kept even in such a low node density area.

The rest of this paper is organized as follows. Section II describes the system model. Section III explains two representative utility-based routing schemes, *PRoPHET* [8] and *Delegation Forwarding* [3]. Section IV describes the proposed location-aware utility-based routing scheme. In section V, we evaluate the performance of our scheme by simulation experiments. Finally, we conclude this paper in section VI.

II. System Model

Let $\mathcal{V}$ denote the set of nodes in a network. We assume that all nodes move in a closed region $\mathcal{A} \subset \mathbb{R}^2$, and all nodes within communication range R can communicate directly. We also assume that each node has a buffer of infinite capacity to store messages and it can know its location by means of a location measurement device such as GPS (Global Positioning System). For message m, $src(m) \in \mathcal{V}$ and $dst(m) \in \mathcal{V}$ denote the source node and the destination node of message m, respectively. In what follows, when we do not have to distinguish the original message and its copies, they are called *messages*.

III. Utility-Based Routing

In this section, we describe two representative utility-based routing schemes: *PRoPHET Routing* [8] and *Delegation Forwarding* [3].

A. Message Forwarding Procedure

Let $U_v(d) \in [0, 1]$ denote utility of node $v \in \mathcal{V}$ toward node $d \in \mathcal{V}$. Suppose that node v with message m encounters node $w \in \mathcal{V} \backslash \{src(m), dst(m)\}$ without message m. In utility-based routing schemes, node v forwards message m to node w if and only if $U_w(dst(m))$ is greater than threshold $\theta_v(m)$. Note that threshold $\theta_v(m)$ is determined by node v, depending on message m.

In PRoPHET Routing, for message m and node v, $\theta_v(m)$ is defined as $\theta_v(m) \triangleq U_v(dst(m))$. Therefore node v with a message forwards its copy to every other node with higher utility than itself. On the other hand, in Delegation Forwarding, $\theta_v(m)$ is defined as $\theta_v(m) \triangleq \tau_v(m)$, where $\tau_v(m)$ denotes the maximum utility of nodes that node v has encountered. Suppose node v generates message m. Initially, $\tau_v(m)$ is set to be $U_v(m)$. When node v encounters node w and $\tau_v(m) < U_w(m)$, $\tau_v(m)$ is updated to be $\tau_v(m) = U_w(m)$ and $\tau_w(m)$ is set to be $U_w(m)$, and nodes v and w repeat this procedure. Delegation Forwarding aims at forwarding a message only to nodes with higher utility.

B. Utility Calculation Method

Both PRoPHET Routing and Delegation Forwarding require a calculation method for utility. In this paper, we use a calculation method proposed in PRoPHET Routing [8]. Initially, utility $U_v(k)$ ($k \in \mathcal{V} \setminus \{v\}$) of node $v \in \mathcal{V}$ is set to be 0. When node v encounters node w, node v first updates $U_v(k)$ as follows.

$$U_v(k) := U_v(k) \cdot \gamma^t, \quad k \in \mathcal{V} \setminus \{v\},$$

where $\gamma \in [0, 1]$ and t is elapsed time since node v encounters other nodes last time. Node v then updates $U_v(w)$ as follows.

$$U_v(w) := U_v(w) + (1 - U_v(w)) \cdot P_{\text{init}},$$

where $P_{\text{init}} \in [0, 1]$. In a similar way, node w updates $U_w(k)$ ($k \in \mathcal{V} \backslash \{w\}$). After that, nodes v and w exchange their utility values, that is, node v sends $U_v(k)$ ($k \in \mathcal{V} \setminus \{v\}$) to node w, and vice versa, and then node v updates $U_v(k)$ ($k \in \mathcal{V} \backslash \{v, w\}$) as follows:

$$U_v(k) := U_v(k) + (1 - U_v(k)) \cdot U_v(w) \cdot U_w(k) \cdot \beta,$$

where $\beta \in [0, 1]$. Similarly, node w also updates $U_w(k)$ ($k \in \mathcal{V} \setminus \{v, w\}$). Readers may refer to [8] for the rationale behind this procedure.

IV. Location-Aware Utility-Based Routing

This section describes the proposed *location-aware* utility-based routing scheme, where the forwarding probability is controlled adaptively based on the node density of contact locations.

A. Node Density Estimation

Let $I(\boldsymbol{x})$ denote the node density at location $\boldsymbol{x} \in \mathcal{A}$. Each node estimates $I(\boldsymbol{x})$ by exchanging information about contact locations with other nodes. If a network is static in terms of node density and a sufficient amount of information about contact locations is available at each node, $I(\boldsymbol{x})$ could be obtained by means of a histogram method, where the whole region is divided into many small regions and the number of contacts is accumulated in each region. Otherwise, more elaborate estimation methods are appropriate. In [6], [7], a node density estimator with a *Gaussian kernel function* is considered, where the kernel takes a form of mixed Gaussian distribution. This estimator enables us to estimate $I(\boldsymbol{x})$ with less information than that required in the histogram method. Let $I_v(\boldsymbol{x})$ denote the node density estimated by node v. In general, $I_v(\boldsymbol{x})$ is different from $I(\boldsymbol{x})$ due to estimation errors. See [6], [7] for details.

B. Procedure of the proposed routing scheme

Our scheme combines a utility-based routing scheme with a location-aware probabilistic forwarding. To do so, our scheme discriminates between high and low-utility nodes with threshold $\theta_v(m)$. Our scheme also discriminates between high and low node density areas with threshold d_v determined by each node v individually. If $I_v(\boldsymbol{x}) > d_v$, node v regards node density at location $\boldsymbol{x}$ as high. Let p_F denote forwarding probability. Kimura et al. [6] show that the single threshold d_v for controlling p_F is sufficiently effective, even though p_F can be a continuous function of $I_v(\boldsymbol{x})$ at the contact location $\boldsymbol{x}$ in general.

Figure 1 shows the procedure of our scheme, where p_{LD} and p_{HD} ($p_{\text{LD}} \geq p_{\text{HD}}$) denote the forwarding probability to low-utility nodes in low and high node density areas, respectively. Note that, as p_{LD} (resp. p_{HD}) increases, low-utility nodes have more chances of receiving messages in low (resp. high) node density areas. In particular, a large p_{LD} ameliorates the message delivery capability in low node density areas because messages will be forwarded to many low-utility nodes, as well as high-utility nodes. On the other hand, a sufficiently small

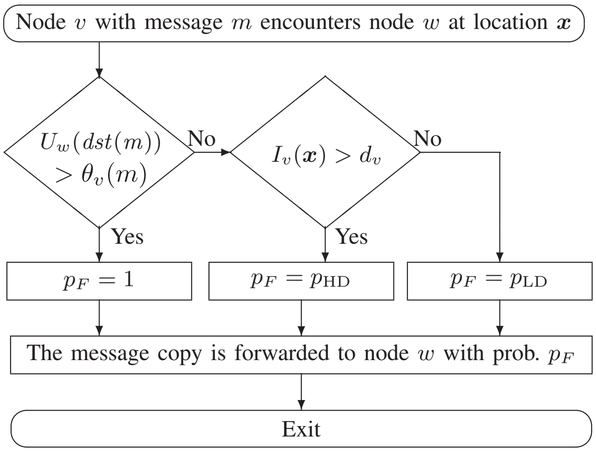


Fig. 1. The procedure of the proposed routing scheme.

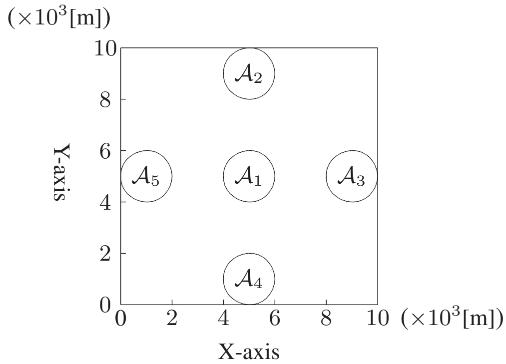


Fig. 2. Areas $\mathcal{A}_i$ $(i = 1, 2, \cdots, 5)$.

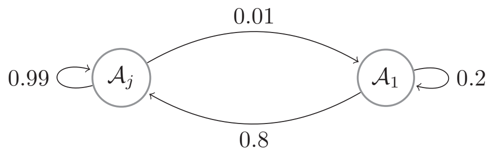


Fig. 3. State transition diagram of target locations for group $\mathcal{V}_j$ $(j = 2, 3, 4, 5)$.

$p_{\rm HD}$ implies that in high node density areas, only high-utility nodes receive messages.

When the proposed scheme is based on PRoPHET, i.e., $\theta_v(m) \triangleq U_v(dst(m))$, we refer to the proposed scheme as *Location-aware PRoPHET* (abbrev. *L-PRoPHET*). On the other hand, when the proposed scheme is based on Delegation Forwarding, i.e., $\theta_v(m) \triangleq \tau_v(m)$, we refer to the proposed scheme as *Location-aware Delegation Forwarding* (abbrev. *L-Delegation*). Note that if we set $p_{\rm HD} = p_{\rm LD} = 0$, L-PRoPHET and L-Delegation are reduced to the original PRoPHET Routing and Delegation Forwarding, respectively. If we set $p_{\rm HD} = p_{\rm LD} = 1$, both L-PRoPHET and L-Delegation are reduced to Epidemic Routing [10]. Further, if we set $\theta_v(m) = 1$, both L-PRoPHET and L-Delegation are reduced to the location-aware probabilistic routing proposed in [6], [7].

V. Performance Evaluation

We conduct simulation experiments to evaluate the performance of L-PRoPHET and L-Delegation.

A. Simulation Model

We assume that there are 100 nodes in a square area $\mathcal{A}$ of 10000 [m] × 10000 [m]. See Fig. 2. The area $\mathcal{A}$ contains five circle areas $\mathcal{A}_i \subset \mathcal{A}$ $(i = 1, 2, \ldots, 5)$ with radius 1000 [m] and center coordinates of (5000,5000), (1000,5000), (9000,5000), (5000,1000), (5000,9000), respectively. We divide the set $\mathcal{V}$ of nodes into 5 disjoint groups $\mathcal{V}_i$ $(i = 1, 2, \ldots, 5)$. Nodes in group $\mathcal{V}_1$ move only within the area $\mathcal{A}_1$ according to Random Waypoint model [1]. On the other hand, nodes in group $\mathcal{V}_j$ $(j = 2, 3, 4, 5)$ move around areas $\mathcal{A}_1$ and $\mathcal{A}_j$ according to a modified Random Waypoint model, where the target location is chosen according to a two-state Markov chain whose transition diagram is depicted in Fig. 3. Nodes in group $\mathcal{V}_j$ $(j = 2, 3, 4, 5)$ mainly stay in area $\mathcal{A}_j$ and occasionally visit area $\mathcal{A}_1$. We thus call area $\mathcal{A}_j$ $(j = 2, 3, 4, 5)$ *home region* of $\mathcal{V}_j$. Furthermore, for message m, we also refer to home regions of source node $src(m)$ and destination node $dst(m)$ as *source home* and *destination home* of message m, respectively.

TABLE I
Simulation scenarios

Scenario	Source node set $\mathcal{S}$	Destination node set $\mathcal{D}$
$\mathcal{V}_1 \to \mathcal{V}_1$	$\mathcal{V}_1$	$\mathcal{V}_1$
$\mathcal{V}_i \to \mathcal{V}_i$	$\mathcal{V}_i$ $(i = 2, 3, 4, 5)$	$\mathcal{V}_i$
$\mathcal{V}_i \to \mathcal{V}_j$	$\mathcal{V}_i$ $(i = 2, 3, 4, 5)$	$\mathcal{V}_j$ $(j = 2, 3, 4, 5,\ j \neq i)$
$\mathcal{V}_1 \to \mathcal{V}_i$	$\mathcal{V}_1$	$\mathcal{V}_i$ $(i = 2, 3, 4, 5)$
$\mathcal{V}_i \to \mathcal{V}_1$	$\mathcal{V}_i$ $(i = 2, 3, 4, 5)$	$\mathcal{V}_1$
$\mathcal{V} \to \mathcal{V}$	$\mathcal{V}$	$\mathcal{V}$

In what follows, we set $|\mathcal{V}_1| = 60$ and $|\mathcal{V}_j| = 10$ $(j = 2, 3, 4, 5)$. The moving speed of each node is 1 [m/s] and the transmission range is $R = 50$ [m]. We assume that buffer size and communication bandwidth of each node are sufficiently large so that message loss never happen. In each simulation experiment, we randomly choose one node every 50 seconds from a set $\mathcal{S}$ of candidates for source nodes, which generates a message. The destination node of each message is also chosen randomly from a set $\mathcal{D}$ of candidates for destination nodes. We consider six scenarios with different $\mathcal{S}$ and $\mathcal{D}$ as shown in Table I, where $\mathcal{V} = \cup_{i=1}^{5} \mathcal{V}_i$, and "$\mathcal{X} \to \mathcal{Y}$" represents $\mathcal{S} = \mathcal{X}$ and $\mathcal{D} = \mathcal{Y}$ $(\mathcal{X}, \mathcal{Y} \subseteq \mathcal{V})$. In any scenario, 5000 messages are generated and delivered to their destination nodes according to L-PRoPHET or L-Delegation. We set $P_{\rm init} = 0.7$, $\beta = 0.2$, $\gamma = 0.9$ in computing utility values, which are determined by preliminary simulation experiments. Each simulation experiment has a warm-up period of length 10000 [s] in which utility values are updated according to the procedure as described in subsection III-B.

For simplicity, we assume that each node v can correctly perceive whether contact location is in the high node density area $\mathcal{A}_1$ or not. In [6], [7], the accuracy of node density estimation is discussed and the location-aware routing scheme is shown to be rather robust against the estimation error. In what follows, we call $\mathcal{A}_1$ the *dense area* and the rest the *sparse area*. In addition, each routing scheme incorporates the VACCINE recovery scheme [5], where after the completion of message delivery, we delete useless message copies by spreading anti-packets according to Epidemic Routing.

B. Performance Measures

The performance of L-PRoPHET and L-Delegation is evaluated in terms of the mean delivery delay and the mean number of generated message copies. The message delivery delay T_D of a message is defined as a length of time duration from the generation of the message to its delivery to the destination node, and N_D is defined as the number of message copies generated for a message till the instant when the original message and all its copies vanish away from the network owing to the VACCINE recovery scheme. In general, there is a trade-off relationship between $\mathrm{E}[T_D]$ and $\mathrm{E}[N_D]$ [9]. In our scheme, the increase of the forwarding probabilities p_{LD} and/or p_{HD} to low utility nodes causes the decrease of $\mathrm{E}[T_D]$ and the increase of $\mathrm{E}[N_D]$.

C. Influence of probability p_{LD}

In this subsection, we fix p_{HD} to zero and investigate how p_{LD} affects the performance of our scheme. Figure 4 shows the mean delivery delay $\mathrm{E}[T_D]$ as a function of $\mathrm{E}[N_D]$. We also plot the result of Probabilistic Routing, where the forwarding probability p_F is always fixed to p $(0 < p \leq 1)$.

Figures 4(a), 4(b) and 4(c) show results of scenarios $\mathcal{V}_i \to \mathcal{V}_1, \mathcal{V}_i \to \mathcal{V}_i$, and $\mathcal{V}_i \to \mathcal{V}_j$, respectively. We observe that $\mathrm{E}[T_D]$ in L-Delegation decreases greatly with the increase of p_{LD}, in compensation for a slight increase of $\mathrm{E}[N_D]$. In particular, L-Delegation with $p_{\mathrm{LD}} = 1$ works well. This result indicates that the utility-based relay node selection is useless in the sparse area if relay nodes are selected appropriately in the dense area. Generally, there are two reasons for the performance improvement in those scenarios. One is that when source and/or destination homes are sparse areas, aggressive message dissemination over those areas definitely improves the performance because such a strategy decreases $\mathrm{E}[T_D]$ greatly, while $\mathrm{E}[N_D]$ is not affected so much due to small number of nodes in those areas. Note that this advantage mainly comes from location-aware forwarding. The other is that except for source and destination homes, message dissemination over sparse areas is suppressed. Note that nodes in $\{\mathcal{V}_2, \mathcal{V}_3, \mathcal{V}_4, \mathcal{V}_5\} \setminus \{\mathcal{S} \cup \mathcal{D}\}$ have low utility. Therefore message forwarding to those nodes is suppressed even when relay nodes encounter those nodes in the dense area $\mathcal{A}_1$. This advantage comes from utility-based forwarding. In this way, our location-aware utility-based routing scheme works well in the above scenarios.

Next we consider scenario $\mathcal{V}_1 \to \mathcal{V}_1$ in Fig. 4(d). We observe that the increase of p_{LD} has no effect on the performance of our schemes. In this scenario, utility of nodes in $\{\mathcal{V}_2, \mathcal{V}_3, \mathcal{V}_4, \mathcal{V}_5\}$ are low compared with that in $\mathcal{V}_1$. Therefore, owing to utility-based forwarding, message dissemination over the sparse areas is suppressed.

Figure 4(e) shows the result of scenario $\mathcal{V}_1 \to \mathcal{V}_i$. We observe that $\mathrm{E}[N_D]$ in our schemes increases with p_{LD}, while $\mathrm{E}[T_D]$ is rather insensitive to p_{LD}. We also observe that $\mathrm{E}[T_D]$ in L-Delegation is very large, compared with Epidemic Routing (Probabilistic Routing with $p = 1$). In L-Delegation, messages hardly be forwarded to nodes in $\mathcal{V}_1$ once a node in $\mathcal{V}_1$ with relatively high utility receives the message. On the other hand, in L-PRoPHET, messages are forwarded aggressively in the dense area $\mathcal{A}_1$, so that $\mathrm{E}[T_{\mathrm{D}}]$ is small and $\mathrm{E}[N_D]$ is large, compared with L-Delegation.

Finally, we consider the comprehensive scenario $\mathcal{V} \to \mathcal{V}$ in Fig. 4(f), where the ratio of source-destination pairs $(\mathcal{S}, \mathcal{D})$ is given in Table II. Note that the highest ratio is the improvement case and the second highest ratio is no effect case for the increase of p_{LD}. Therefore, in L-Delegation, $\mathrm{E}[T_D]$ decreases greatly with the increase of p_{LD}, while $\mathrm{E}[N_D]$ increases slightly with p_{LD}, and we conclude that aggressive message forwarding in the sparse area is effective comprehensively. Note also that $\mathrm{E}[T_D]$ (resp. $\mathrm{E}[N_D]$) in L-Delegation is twice or more (resp. half or less) as large as $\mathrm{E}[T_D]$ in L-PRoPHET, so that either routing scheme is a reasonable choice for this scenario.

D. Influence of probability p_{HD}

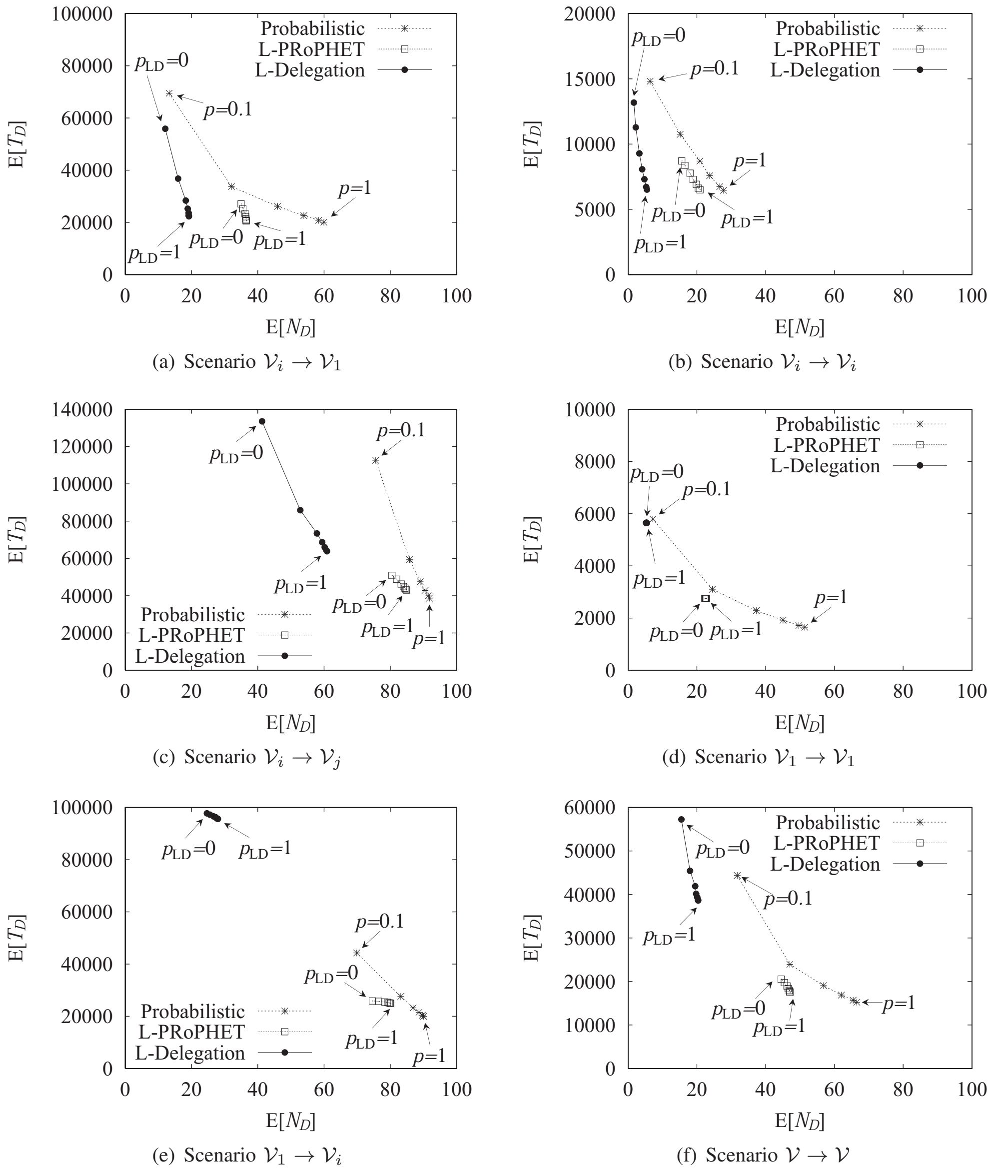
Next we consider the influence of p_{HD} on the performance, where we set $p_{\mathrm{LD}} = 1$. Recall that in the scenario $\mathcal{V}_1 \to \mathcal{V}_i$ with $p_{\mathrm{HD}} = 0$, message forwarding in the dense area $\mathcal{A}_1$ is too suppressive (resp. aggressive) in L-Delegation (resp. L-PRoPHET). We thus examine whether the increase of p_{HD} in L-Delegation improves the performance.

Figure 5 shows the mean delivery delay $\mathrm{E}[T_D]$ as a function of $\mathrm{E}[N_D]$. For the sake of comparison, we also show the performance of Location-Aware Routing (abbrev. *LA Routing*) in [6], as well as Probabilistic Routing. In LA Routing, the forwarding probability p_F is set to be one and p $(0 < p \leq 1)$ in the sparse and dense areas, respectively.

We first consider scenario $\mathcal{V}_1 \to \mathcal{V}_1$ in Fig. 5(a). We observe that message forwarding with slightly large p_{HD} in the dense area $\mathcal{A}_1$ is suitable because anti-packets can be spread quickly over the dense area as soon as messages are delivered to their destination nodes.

Figures 5(b) and 5(c) show results of scenarios $\mathcal{V}_i \to \mathcal{V}_1$ and $\mathcal{V}_i \to \mathcal{V}_i$, respectively. $\mathrm{E}[N_D]$ increases with p_{HD}, while $\mathrm{E}[T_D]$ is almost insensitive to p_{HD}. Although nodes in $\{\mathcal{V}_2, \mathcal{V}_3, \mathcal{V}_4, \mathcal{V}_5\} \setminus \mathcal{S}$ are more likely to receive messages in the dense area with the increase of p_{HD}, forwarding messages to them is meaningless in these scenarios.

Figures 5(d) and 5(e) show results of scenarios $\mathcal{V}_1 \to \mathcal{V}_i$ and $\mathcal{V}_i \to \mathcal{V}_j$, respectively. $\mathrm{E}[T_D]$ decreases and $\mathrm{E}[N_D]$ increases greatly with a slight increase of p_{HD} from 0. In general, the increase of messages in the dense area is effective for improving the delivery delay performance. Our scheme, however, causes excessive message dissemination even if p_{HD} is set to be a small positive, due to high capability of forwarding messages in the dense area.



(a) Scenario $\mathcal{V}_i \rightarrow \mathcal{V}_1$ (b) Scenario $\mathcal{V}_i \rightarrow \mathcal{V}_i$

(c) Scenario $\mathcal{V}_i \rightarrow \mathcal{V}_j$ (d) Scenario $\mathcal{V}_1 \rightarrow \mathcal{V}_1$

(e) Scenario $\mathcal{V}_1 \rightarrow \mathcal{V}_i$ (f) Scenario $\mathcal{V} \rightarrow \mathcal{V}$

Fig. 4. E$[T_D]$ as a function of E$[N_D]$ ($p_{\text{HD}} = 0$).

TABLE II
RATIO OF SOURCE-DESTINATION PAIRS $(\mathcal{S}, \mathcal{D})$ IN SCENARIO $\mathcal{V} \rightarrow \mathcal{V}$

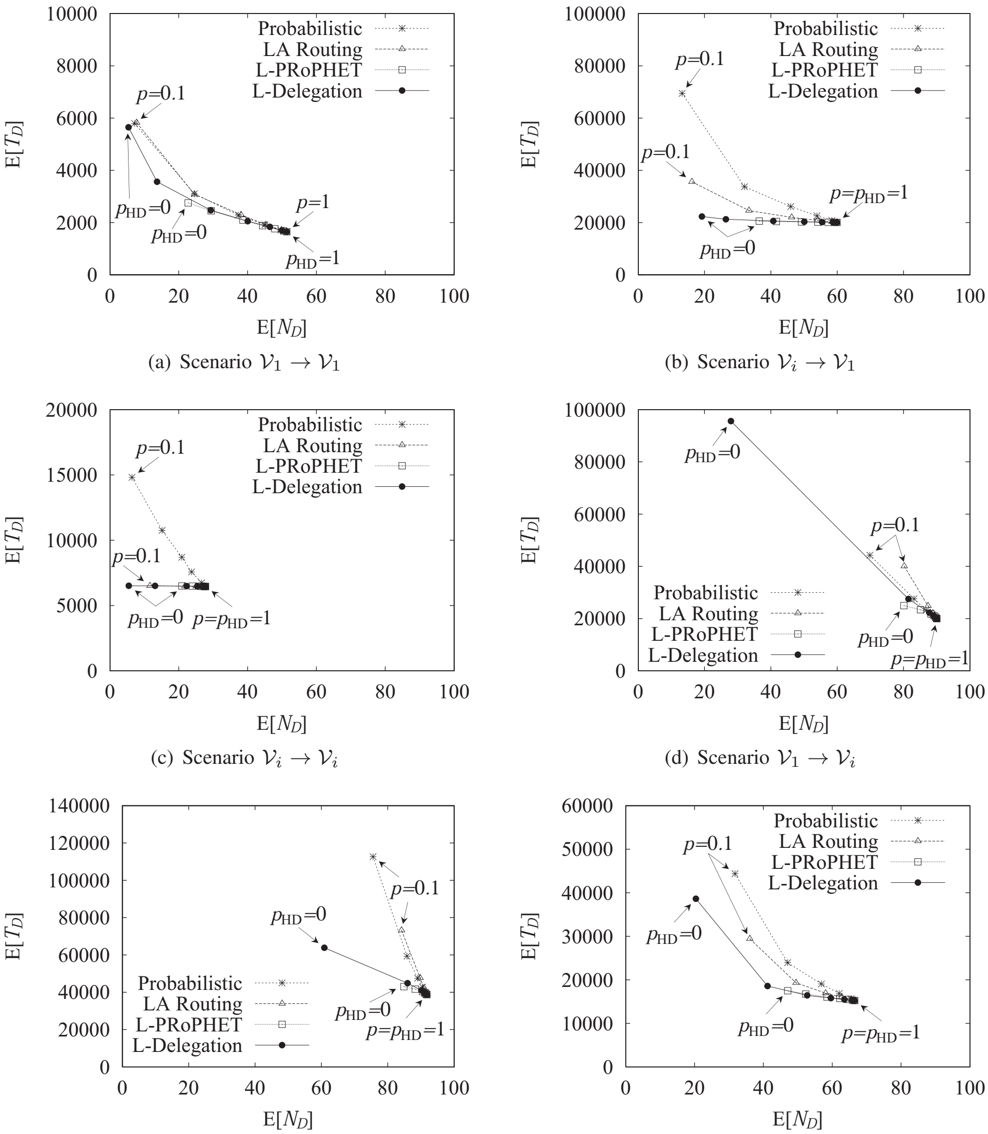
Pair $(\mathcal{S}, \mathcal{D})$	$(\mathcal{V}_i, \mathcal{V}_1)$, $(\mathcal{V}_i, \mathcal{V}_i)$, $(\mathcal{V}_i, \mathcal{V}_j)$	$(\mathcal{V}_1, \mathcal{V}_1)$	$(\mathcal{V}_1, \mathcal{V}_i)$
Ratio (%)	40	36	24

These observations indicate that more elaborate relay node selection method is required in the dense area. In particular, information about home region seems to be useful. If such information is available, the relay node selection will be operated as follows. When a relay node encounters a node that belongs to the same group of the destination node, the message is forwarded aggressively, and otherwise, message forwarding is suppressed.

Finally, we consider the comprehensive scenario $\mathcal{V} \rightarrow \mathcal{V}$ in Fig. 5(f). Our schemes outperform Probabilistic Routing and LA Routing, that is, E$[T_D]$ in our schemes is smaller than that in other routing schemes for the same E$[N_D]$. Further, the controllable range of E$[N_D]$ in L-Delegation is wider than that in L-PRoPHET. Although the performance of some source-destination pairs is not improved, L-Delegation is effective in terms of E$[N_D]$ comprehensively.

VI. CONCLUSION

In this paper, we considered the location-aware utility-based store-carry-forward routing schemes, i.e., L-PRoPHET and L-Delegation. Through simulation experiments, we showed that the utility-based relay node selection is useless in low node density areas if relay nodes are selected appropriately



(a) Scenario $\mathcal{V}_1 \to \mathcal{V}_1$

(b) Scenario $\mathcal{V}_i \to \mathcal{V}_1$

(c) Scenario $\mathcal{V}_i \to \mathcal{V}_i$

(d) Scenario $\mathcal{V}_1 \to \mathcal{V}_i$

(e) Scenario $\mathcal{V}_i \to \mathcal{V}_j$

(f) Scenario $\mathcal{V} \to \mathcal{V}$

Fig. 5. $\mathrm{E}[T_D]$ as a function of $\mathrm{E}[N_D]$ ($p_{\rm LD} = 1$).

in high node density areas. Simulation results also showed that our schemes outperform Probabilistic Routing and LA Routing. In our schemes, however, relay nodes cannot be selected appropriately in high node density areas, so that more elaborate relay node selection is required, which incorporates information about home regions. We leave it for future work.

REFERENCES

[1] C. Bettstetter, "Mobility modeling in wireless networks: categorization, smooth movement, and border effects," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 5, no. 3, pp. 55–66, Jul. 2001.

[2] Y. Cao and S. Zhili, "Routing in delay/disruption tolerant networks: A taxonomy, survey and challenges," *IEEE Commun. Surveys Tuts.*, vol.15, pp. 654–677, Second Quater, 2013.

[3] V. Erramilli, M. Crovella, A. Chaintreau, and C. Diot, "Delegation forwarding," *Proc. ACM MobiHoc '08*, 2008.

[4] K. Fall, "A delay-tolerant network architecture for challenged internets," *Proc. ACM SIGCOMM '03*, Aug. 2003,

[5] Z. Haas and T. Small, "A new networking model for biological applications of ad hoc sensor networks," *IEEE/ACM Transactions on Networking*, vol.14, pp. 27–40, Feb. 2006.

[6] T. Kimura, T. Matsuda, and T. Takine, "Probabilistic store-carry-forward message delivery based on node density estimation," *Proc. IEEE CCNC '14*, Jan. 2014.

[7] T. Kimura, T. Matsuda, and T. Takine, "Location-aware store-carry-forward routing based on node density estimation," submitted for publication, 2014.

[8] A. Lindgren, A. Doria, and O. Schelen, "Probabilistic routing in intermittently connected networks," *ACM SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 7, pp. 19–20, 2003.

[9] T. Matsuda and T. Takine, "(p, q)-epidemic routing for sparsely populated mobile ad hoc networks," IEEE J. Sel. Areas Commun., vol.28, pp. 783–793, Jun. 2008.

[10] A. Vahdat and D. Becker, "Epidemic routing for partially-connected ad hoc networks," *Duke Technical Report*, CS-2000-06, 2000.