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# A Routing Protocol for Considering the Time Variant Mobility Model in Delay Tolerant Network

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**SUMMARY** Delay Tolerant Network (DTN) has been emerged to support the network connectivity of the disruptive networks. A variety of routing methods have been proposed to reduce the latency for message delivery. PROPHET was proposed as a probabilistic routing that utilizes history of encounters and transitivity of nodes, which is computed as contact probability. While PROPHET improves the performance of DTN due to contact probability, contact probability is just one parameter reflecting the mobility pattern of nodes, and further study on utilizing contacting information of mobility pattern is still an important problem. Hence, in this paper, we try to improve routing for DTN by using a novel metric other than contact probability as mobility information. We propose the routing protocol to use mean residual contact time that describes the contact period for a given pair of nodes. The simulation results show that using the mean residual contact time can improve the performance of routing protocols for DTN. In addition, we also show in what situations the proposed method provides more efficient data delivery service. We characterize these situations using a parameter called Variation Metric.
***key words:*** *DTN, routing protocol, time variant mobility, mean residual time, delivery latency*

## 1. Introduction

DTN (Delay Tolerant Network) has been introduced to cope with the disruption of intermittently connected networks. Here, we consider the network consisting of mobile and wireless nodes without fixed backbone infrastructure. In a mobile network without infrastructure, there may be some disruption caused by the limit of wireless radio range, energy resource, attack, noise, etc [1], [2]. In such disruptive networks, it is sometimes possible to use routing protocols for MANET (Mobile Ad hoc NETwork) to provide end-to-end data delivery service; however, in a situation with seriously low connectivity, MANET protocol cannot be used because MANET protocol is basically used for communication along an end-to-end connected path. Even in such cases, DTN can support the disruption by means of the bundle layer to extend the connectivity of opportunistic contacts [3]. In DTN, source and destination do not have to be connected through a connected multi-hop path. A source node sends data to other nodes, these nodes forward the data to the other nodes, and some of these data finally arrive at the destination. One of the simplest ways to realize the routing of DTN is to use Flooding repeatedly [4]. However, Flooding needs a lot of redundant transmissions. Hence, it has been desired to reduce these redundant transmissions in DTN [5]. To do this, early works proposed several efficient routing protocols [6]–[11]. Epidemic introduced message exchanges using simple flooding scheme among nodes [6]. Spray and Wait showed the efforts to significantly reduce the overheads of flooding-based schemes [7]. NECTAR used a Neighborhood Contact History which can send messages to neighborhoods of destination [8].

Because the opportunistic contact strongly depends on the mobility patterns for each node in DTN, it has been proposed to utilize mobility information to improve the performance. PROPHET (Probabilistic ROuting Protocol using History of Encounters and Transitivity) proposed the estimation-based forwarding method that adopts the use of contact probability [9]. PROPHET defines the concept of contact probability depending on the simple random mobility model, and shows efficiency in use of mobility information for routing in DTN. In addition to the original PROPHET, there are efforts to improve the performance of PROPHET. Advanced PROPHET proposed to use the average contact probability to address routing jitter based on PROPHET [10]. In [11], authors showed the buffer management scheme to reduce the redundant forwarding of delivered packets of mobile nodes by using the exchanges of the acknowledgement ID.

As mentioned, PROPHET and PROPHET based routing protocols use the contact probability to effectively provide message delivery service in DTN. However, it has not been shown that the contact probability is the most efficient metric. Furthermore, it is not clear that contact probability is still efficient in other mobility patterns because the contact probability only depends on the number of contacts in a unit time. The contact probability does not reflect the variance of contact interval, which also affects characteristics of contacts of mobile nodes. With this as background, we define a new metric considering the mobility information and try to use this metric for routing in DTN.

In this paper, we propose the routing protocol that reflects the variance of contact interval using a metric MRCT (Mean Residual Contact Time). MRCT can describe the contact period for a given pair of nodes. Moreover, we consider a mobility model different from the simple random model [12]. In our mobility model, a mobile node stays at some places for a time interval and moves toward another

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place selected from the preference places of the node. This kind of mobility model can be seen in our daily life. The performance analysis of routing protocols was performed in the proposed mobility model. The simulation result shows the efficiency of the proposed routing protocol. In addition, we also show the basic properties of the above mobility model based on the theoretical analysis to support our proposal.

The rest of this paper is organized as follows. Section 2 explains the motivation of this paper. The user preference based mobility model is defined and analyzed in Sect. 3. Section 4 introduces the proposed routing protocol and Sect. 5 discusses the simulation results. Finally, we conclude the paper in Sect. 6.

## 2. Motivation

PROPHET used delivery predictability as a metric, which can approximate the contact probability [9]. For example, there are node 1, node 2, node 3 and destination node D. When node 1 and node 2 meet, they exchange and update the contact probabilities. If the contact probability of node 2 is higher than that of node 1; $P_{(1,D)} < P_{(2,D)}$, node 1 forwards data to node 2. The contact probability is updated by Eqs. (1) and (2), where $\gamma \in [0, 1]$ is the aging constant, $k$ is the number of time difference that have elapsed after the last aged time, and $P_{init} \in [0, 1]$ is an initialization constant.

$$P_{(1,2)} = P_{(1,2)old} \times \gamma^k, \tag{1}$$

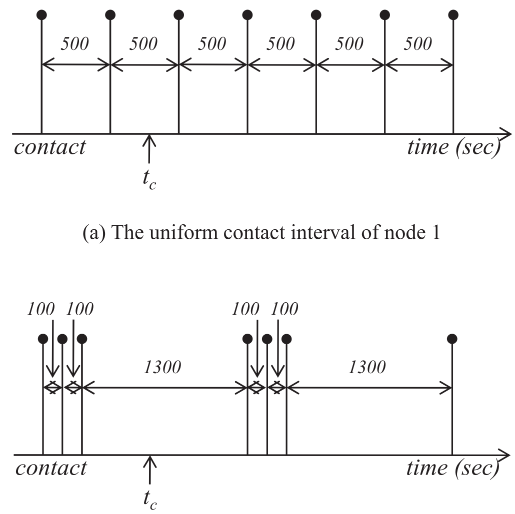
$$P_{(1,2)} = P_{(1,2)old} + (1 - P_{(1,2)old}) \times P_{init}. \tag{2}$$

PROPHET also considers the update for multi-hop forwarding from node 1 to node 3 via intermediate node 2 by using Eq. (3), where $\beta \in [0, 1]$ is a scaling constant.

$$P_{(1,3)} = P_{(1,3)old} + (1 - P_{(1,3)old}) \times P_{(1,2)} \times P_{(2,3)} \times \beta. \tag{3}$$

Although PROPHET shows the usability of the contact probability for DTN, the contact probability means the number of contact at a certain time. The contact probability is not sufficient to identify the time variant contact of DTN because the contact of DTN could be opportunistic and the contact interval can be variable with the contact model. In the paper, we define the mobility model which can have the large variance of the contact interval. When the nodes have a small variance, we say that the contact model is the uniform contact model. While, the variance of the contact interval is high, we define that the contact model is the time variant contact model. In this paper, these two contact models can be used to differentiate the variance of the contact interval.

As mentioned, PROPHET selects a node with high contact probability. The contact probability of the node becomes high when the mean contact interval becomes small because the contact probability means the mean number of contact in a unit time. However, the delivery latency of DTN depends on not only the mean contact interval but also the variance of the contact interval. Here, we give two examples which can explain the effect of the mean value and the variance of the contact interval on the performance of routing protocols for DTN.




(a) The uniform contact interval of node 1

(b) The variant contact interval of node 2

**Fig. 1** The different contact interval.

For example, there are two contact models with the same mean value of the contact interval (500 sec) as shown in Fig. 1. However, the variance of the contact interval is quite different. Figure 1 (a) shows the contact pattern of node 1 that periodically contacts to the destination. In this contact model, the contact interval of node 1 is uniform. In contrast, Fig. 1 (b) describes the large variance of the contact interval of node 2 having the time variant contact model. Consider another node 3 and suppose that node 3 contacts to both nodes 1 and 2 at the time $t_c$. Because of the difference between the variances of contact intervals for nodes 1 and 2, the residual time from $t_c$ to when node 1 contacts to the destination is different with the residual time from $t_c$ to when node 2 contacts to the destination. From the renewal theory [13], we can compute the mean residual contact time (MRCT) as

$$MRCT = \frac{E({T_{ict}}^2)}{2E(T_{ict})}, \tag{4}$$

where $E(T_{ict})$ and $E({T_{ict}}^2)$ are the mean and the second moment of the contact interval, respectively. In the example of Fig. 1, while both node 1 and node 2 have the same $E(T_{ict}) = 500$ sec, the $E({T_{ict}}^2)$ is different for each node. Namely, $E({T_{ict}}^2) = 250000\,\text{sec}^2$ for node 1 and $E({T_{ict}}^2) = 570000\,\text{sec}^2$ for node 2. As a result, the mean residual times for nodes 1 and 2 are computed as 250 sec and 570 sec, respectively. Therefore, in this case, node 3 should forward a packet to node 1 with higher priority than node 2 at $t_c$. We call the above example as Case 1. Table 1 shows the complete values of Case 1. Case 2 will be defined later.

In PROPHET, node 3 decides a node based on the contact probability and forwards a packet to the node regardless of the variance of the contact interval. Namely, PROPHET cannot distinguish the above two nodes with different variances. As a result, the performance of PROPHET may be

**Table 1** Examples of $E(T_{ict})$ and MRCT.

| | Node | $E(T_{ict})$ | MRCT | Contact pattern | Priority in PROPHET |
|---|---|---|---|---|---|
| Case 1 | Node 1 | 500 sec | 250 sec | uniform | Same |
| | Node 2 | 500 sec | 570 sec | variant | |
| Case 2 | Node 1 | 500 sec | 250 sec | uniform | Low |
| | Node 2 | 300 sec | 570 sec | variant | High |

**Table 2** The combined set of $E(T_{ict})$ and MRCT.

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| $E(T_{ict})$ | $N_1=N_2$ | $N_1>N_2$ | $N_1=N_2$ | $N_1<N_2$ | $N_1>N_2$ |
| MRCT | $N_1<N_2$ | $N_1<N_2$ | $N_1=N_2$ | $N_1<N_2$ | $N_1=N_2$ |
| Latency of PROPHET | Large | Very Large | Very Small | Small | Large |
| VM | Moderate | High | Very Low | Low | Moderate |

degraded when a node has the large variance of the contact interval. In other words, if a routing protocol is aware of differentiating the variance of the contact interval, the routing protocol can improve the delivery latency of DTN.

In the second example, if the mean contact interval of node 1 and node 2 is different and even the $E(T_{ict}) = 500$ sec of node 1 is larger than the $E(T_{ict}) = 300$ sec of node 2 as shown in Case 2 in Table 1, PROPHET tends to select node 2 regardless of the residual time of node 1 and node 2. In Case 2, the residual time for node 1 is 250 sec, and 570 sec is for node 2. In this example, the delivery latency of PROPHET increases because PROPHET tends to select node 2 based on the $E(T_{ict})$ even if the residual time of node 2 is large. Table 1 also shows the complete values of Case 2. In Table 2, we show the five cases depending on the combined set of the mean value of the contact interval and the mean residual contact time.

In this paper, we first consider the various situations with the different mean contact interval and the mean residual contact time. To do this, we introduce the metric called VM (Variation Metric) to distinguish the above five cases. While the characteristic of this metric is shown in Table 2, this characteristic will be explained in the following section. Second, we propose a new routing protocol that considers the difference between the variances of contact intervals as well as the mean number of contacts in a unit time.

## 3. Preference Based Mobility Model

In this section, we explain the preference based mobility model and the effect of the variance of the contact interval from the theoretical analysis.

### 3.1 Mobility Model for Our Daily Life

In our daily life, we usually know the visiting places, and we can make a schedule which efficiently visits to the places based on the user preference. To emulate our daily life, we propose the preference based mobility model. The proposed mobility model can show the time variant contact with the variance of the contact interval. To describe this characteristic, we first consider the following simple mobility model in this section. The generalized version of the proposed mobility model will be explained in Sect. 5.

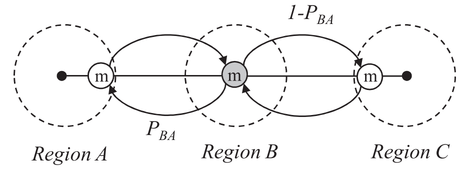



**Fig. 2** Preference based mobility model.

As shown in Fig. 2, there are three visiting regions: region A, region B, and region C. A mobile node (m) has a preference to visit region A and C with a visiting probability $P_{BA}$. When the node leaves region B, the node decides to go to region A with probability $P_{BA}$ and region C with probability $1 - P_{BA}$. Moreover, the node has exponential random staying times with mean values $T_A$, $T_B$, and $T_C$ for regions A, B, and C, respectively, and constant moving times $T_{AB}$ and $T_{BC}$ for edge AB and edge BC, respectively.

This mobility model is used to realize our daily mobility model in the uniform and time variant contact model. The contact model is defined as the contact patterns between a mobile node and a fixed node at region C. The ratio of MRCT to $E(T_{ict})$ can classify the variance of contact model. The contact pattern becomes more variant if MRCT$/E(T_{ict})$ is large from the fact that the relative standard deviation is computed by $\sigma(T_{ict})/E(T_{ict}) = \sqrt{((MRCT/2E(T_{ict})) - 1)}$, where $\sigma(T_{ict})$ is the standard deviation of the contact interval $T_{ict}$. In the proposed mobility model, $E(T_{ict})$ and MRCT can be computed as follows:

$$E(T_{ict}) = -\frac{T_B+2T_{BC}+P_{BA}(T_A+2T_{AB}-2T_{BC}-T_C)+T_C}{-1+P_{BA}}, \tag{5}$$

$$\begin{aligned} &MRCT = \\ &T_C-[\{T_B{}^2+2P_{BA}(T_{AB}-T_{BC})(T_A+T_{AB}-T_{BC}) \\ &+2T_BT_{BC}+2T_{BC}{}^2+P_{BA}(T_A{}^2+2T_A(T_{AB}+T_B+T_{BC}) \\ &+2(T_{AB}{}^2+2T_{AB}(T_B+T_{BC})-T_{BC}(T_B+2T_{BC}))\}/ \\ &\{(-1+P_{BA})(T_B+2T_{BC}+P_{BA}(T_A+2T_{AB}-2T_{BC}-T_C) \\ &+T_C)\}]. \end{aligned} \tag{6}$$

The derivations of these equations are provided in Appendix. From these equations, we found the following properties on $E(T_{ict})$ and MRCT: MRCT$/E(T_{ict})$ is always larger than or equal to 0.5, and MRCT$/E(T_{ict})$ becomes large if $P_{BA}$ is small and $T_A$ or $T_{AB}$ is large. Therefore, we can make the time variant contact model in the proposed mobility model by using small $P_{BA}$ and large $T_A$ or $T_{AB}$.

### 3.2 Characteristic of Preference Based Mobility Model

In this subsection, we consider in what situation the performance of PROPHET may be degraded and can be improved by considering the variance of contact interval in the routing protocol. As explained in Sect. 2, the five cases should be discussed because the performance of PROPHET may depend on such parameters, which are mean contact interval and mean residual contact time as shown in Table 2. For the above purpose, we introduce the metric to distinguish these five cases. We call the metric as VM (Variation Metric).

First, we define VM for the case of two nodes, node $i$ and node $j$. Suppose that the mean contact intervals of node $i$ and node $j$ are $MCI_i$ and $MCI_j$, respectively. Let $MRCT_i$ and $MRCT_j$ be the mean residual contact time of node $i$ and node $j$, respectively. VM can be computed by Eq. (7).

$$VM_2(i,j) = \max\left\{\frac{MCI_i \times MRCT_j}{MCI_j \times MRCT_i}, \frac{MCI_j \times MRCT_i}{MCI_i \times MRCT_j}\right\}. \quad (7)$$

The metric, VM can be used as an indicator that classifies the degree of mean contact interval and the variance of contact interval. In here, we recall the first example of the five cases to explain the property of the proposed metric. In the example, PROPHET selects node 1 or node 2 with the same probability because the mean contact interval is same. The residual time of node 2 is 2.28 times greater than that of node 1. As a result, selecting node 2 in PROPHET results in the 2.28 times higher delivery latency than the selection of node 1 with a certain probability. In this example, VM is 2.28 from Eq. (7). It can be seen that the performance of PROPHET is expected to be degraded by the increase of VM.

In the second example, the mean contact interval of node 1 is larger than that of node 2 but the residual time of node 1 is less than that of node 2. In this example, PROPHET selects node 2 with the higher probability than that of node 1 because node 2 has the smaller mean contact interval than node 1. The residual time of node 2 is 2.28 times greater than that of node 1. As a result, the selection of node 2 in PROPHET causes the 2.28 times higher delivery latency than that of node 1 with the higher probability compared to the first example. VM is 3.8 in this example from Eq. (7). It is expected that the performance of PROPHET is more degraded to high VM. By using the above definition, the five cases can be characterized by the degree of VM as shown in Table 2.

Next, we define the VM for more than two nodes. Suppose that there are $n$ nodes, node 1, node 2, . . . , and node $n$, other than the destination node in the network. The VM of these nodes is defined as the mean of the VMs of all pairs of two nodes as follows:

$$VM_{all} = \frac{\sum_{1 \le i < j \le n} VM_2(i,j)}{\frac{n(n-1)}{2}}. \quad (8)$$

If there are some nodes in the network and each node has different contact model, we can estimate the degree of variance to the network by using $VM_{all}$. It is expect that the performance of routing protocols is affected by $VM_{all}$ in DTN. The detail evaluation will be explained at the simulation section.

## 4. The MRCT Based Routing Protocol

The MRCT based routing protocol is proposed to reduce the delivery latency of PROPHET due to the variance of the different contact interval of DTN. Especially, the metric, MRCT is used to estimate the residual time to the next contact for a given pair of nodes. The proposed routing protocol provides the selection method based on the lower MRCT.

In the proposed routing protocol, all nodes have their own routing table to decide if a node forwards data to another contacting node. Whenever nodes meet with each other, they exchange contact information including MRCT before sending data. When a node receives the contact information, the node updates MRCT into the routing table as the latest information. After that, the node decides the forwarding based on the MRCT. The contact information consists of node ID, last contact time (LCT), and number of count (NC) for a contacting node. In addition, we need more intermediate variables to compute MRCT such as sum of the contact interval (CI) and sum of the square of the contact interval ($CI^2$).

MRCT is calculated by the smaller one of $MRCT_{DIR}$ and $MRCT_{INDR}$. $MRCT_{DIR}$ is defined as the direct residual contact time for a given contacting pair of nodes. However, when a node has no direct contact to other nodes, the indirect MRCT also can be considered for multi-hop communications. $MRCT_{INDR}$ means the sum of MRCT via the current contacting node to the neighbors in the table of the contacting node.

For example, consider three nodes: node 1, node 2, and node 3. Suppose that node 1 has the following contact information with node 2: $NC_{12} = 9$, $CI_{12} = 10000$ sec, $CI^2_{12} = 41000000\,\text{sec}^2$, and $LCT_{12} = 11000$ sec. When node 1 meets with node 2 at time $T_{10} = 13000$ sec, node 1 updates the above information as $NC_{12} = 10$, $CI_{12} = CI_{12,old} + (T_{10} - LCT_{12,old}) = 12000$ sec, $CI^2_{12} = CI^2_{12,old} + (T_{10} - LCT_{12,old})^2 = 45000000\,\text{sec}^2$, and $LCT_{12} = T_{10} = 13000$ sec. From these values, node 1 updates $MRCT_{DIR(1,2)}$ as $(CI^2_{12}/NC_{12})/2(CI_{12}/NC_{12}) = 1875$ sec. The calculation of MRCT is based on Eq. (4). This value is used to expect the residual time from an arbitrary time to the next contact between nodes 1 and 2. At this time, node 1 can also update $MRCT_{INDR(1,3)}$. At time $T_{10}$, node 1 gets $MRCT_{(2,3)}$ from node 2 and updates $MRCT_{INDR(1,3)}$ as the sum of $MRCT_{DIR(1,2)}$ and $MRCT_{(2,3)}$. At the same time, node 1 also saves the node ID of the intermediate node (i.e. node 2 in this example) for an additional information of $MRCT_{INDR(1,3)}$. However, if $MRCT_{DIR(1,2)} + MRCT_{(2,3)}$ is greater than the old value of $MRCT_{INDR(1,3)}$, and the intermediate node for the old value of $MRCT_{INDR(1,3)}$ is different from the contact node (i.e. node 2), then node 1 does not update $MRCT_{INDR(1,3)}$ because there is more efficient intermediate node than node 2. The pseudo code of the computation procedure of MRCT is explained in Table 3.

**Table 3** The pseudo code of the update for MRCT.

| | |
|---|---|
| "Update the direct $MRCT_{DIR}$ to the contact node" | |
| GET | last updated contact time for a given contact |
| CALCULATE | contact interval for each pair of contact |
| | E(T) = sum of CIs / number of contact |
| | $E(T^2)$ = sum of $CI^2$s / number of contact |
| OBTAIN | direct MRCT |
| | $MRCT_{DIR} = E(T^2) / 2E(T)$ |
| "Update the indirect $MRCT_{INDR}$ to the other nodes" | |
| OBTAIN | last updated $MRCT_{DIR}$ |
| SET | index to 0 |
| FOR | index < count_neighbor_nodes |
| CALCULATE | indirect MRCT to all neighbors of contacting node: sum of $MRCT_{DIR}$ of contacting node and minimum value of ($MRCT_{DIR(i)}$, $MRCT_{INDR(i)}$) to all neighbors of contacting node |
| OBTAIN | indirect MRCT |
| | $MRCT_{INDR} = MRCT_{DIR} + MIN(MRCT_{DIR(i)}, MRCT_{INDR(i)})$ |
| IF | is same as the last update node THEN |
| UPDATE | $MRCT_{INDR}$ as the latest $MRCT_{INDR}$ |
| ELSE IF | new $MRCT_{INDR}$ < old $MRCT_{INDR}$ THEN |
| UPDATE | $MRCT_{INDR}$ as the new obtained $MRCT_{INDR}$ |
| ENDIF | |
| INCREMENT | index |
| ENDFOR | |

After updating MRCT of each node, a node decides the forwarding based on the comparison of MRCT. When node 1 contacts node 2 and node 1 has data to send to node 3 as the destination, node 1 decides the forwarding to node 2 if $MRCT_{(2,3)}$ is less than $MRCT_{(1,3)}$. Otherwise, node 1 delivers data by itself until node 1 meets another node holding the lower MRCT.

## 5. Evaluation

We performed simulations to evaluate the proposed routing protocol compared to PROPHET with diverse parameter sets using *ns-2* [14]. The first simulation introduces the basic analysis of how the different VM affects the performance of routing protocols in the simple mobility model. The second simulation shows the validity of the proposed method based on the performance comparison with other routing protocols in the realistic mobility model.

### 5.1 Simulation Environments

The simulation environments are designed to consider a MANET example, in which pedestrians and vehicles can carry the data as nodes of DTN. All nodes follow the preference based mobility model and the nodes use 802.11b MAC protocol. The application generates packets (10 or 200 packets) from the 400000 seconds during the simulation. This preliminary time before generating packets is used to sufficiently collect the contact information in all routing protocols except Epidemic. The length of data packets is 512 bytes. On the basis of the simulation result, we have focused on comparing the performance of routing protocols with regard to the metrics: delivery rate, delivery latency, and the number of forwarding. The detail parameters are as shown in Table 4.

**Table 4** Simulation parameters.

| Simulation parameters | Contents |
|---|---|
| Node movement | Preference based mobility |
| Node speed | Pedestrian: 1 m/sec |
| | Vehicle: 10 m/sec |
| Simulation time | 10 days |
| Transmission range | Simple model: 1m |
| | Realistic model: 30 m |
| MAC protocol | 802.11b |
| Application | UDP/CBR |
| Staying time | Variable sec |

**Table 5** Simulation parameters for mobility of nodes.

| Nodes | $T_A$ | $T_B$ and $T_C$ | VM |
|---|---|---|---|
| Node 1 | 300 sec | 300 sec | - |
| Node 2 | 300 sec | 300 sec | 1 |
| | 900 sec | 300 sec | 1.25 |
| | 1250 sec | 130 sec | 1.48 |
| | 1600 sec | 70 sec | 1.76 |
| | 1800 sec | 30 sec | 1.96 |

### 5.2 Basic Analysis in the Simple Model

We perform the simulation in the simple model to examine the basic characteristics of Epidemic, PROPHET, and MRCT. This analysis can support the validity of our assumption and can show the advantages of the proposed method. In order to observe how the time variant contacts affect the delivery latency of routing protocols, the mean delivery latency is measured in the 100% delivery rate condition. We assumed that all nodes have enough buffer space with a small number of packets and the minimum interference. To realize the above assumption, buffer size is set to infinite, the application generates totally 10 packets for every 40000 sec, and the communication range of mobile nodes is set to 1 m.

The first simulation is performed at the same topology as shown in Fig. 2. There are two mobile nodes that follow the proposed mobility model, node 1 and 2. These nodes start to move their movements at region A. One static destination node is located at region C and node 2 is the source node. In the case of node 1, $P_{BA} = 0.3$ and $T_A = T_B = T_C = 300$ sec. In the case of node 2, $P_{BA}$, $T_A$, $T_B$, and $T_C$ are listed in Table 5. Node 1 is the uniform mobile node and node 2 is the time variant mobile node. The moving time between adjacent regions of each node is 300 sec. The diverse VM used in the simulation can be calculated by Eq. (7). For example, when node 2 has same $P_{BA}$, $T_A$, $T_B$, and $T_C$ as the values of node 1, VM is 1.

To evaluate the proposed protocol, we performed com-

**Table 6** The parameter set of PROPHET.

| | $\beta$ | $P_{init}$ | $\gamma$ |
|---|---|---|---|
| $PROPHET_1$ | 0.25 | 0.75 | 0.98 |
| $PROPHET_2$ | 1 | 0.75 | 0.975 |
| $PROPHET_3$ | 1 | 0.75 | 0.998 |
| $PROPHET_4$ | 1 | 0.998 | 0.999999 |
| $PROPHET_5$ | 1 | 1 | 0.98 |

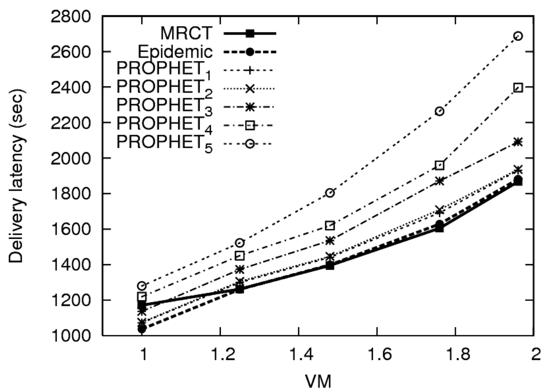



**Fig. 3** Delivery latency.

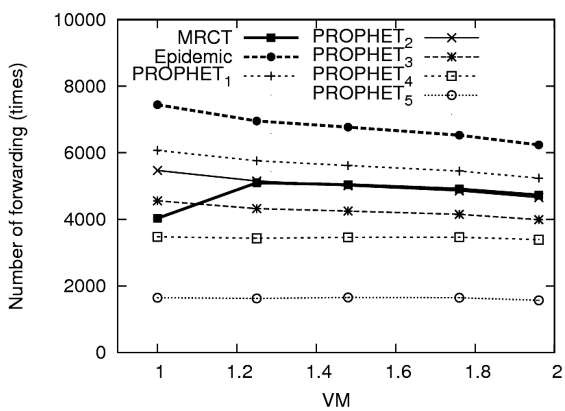



**Fig. 4** The number of forwarding.

parisons using Epidemic and diverse PROPHETs with different parameter set. Epidemic simply forwards data to every contacting node. As mentioned in Sect. 2, PROPHET approximates the contact probability by using the parameters such as $P_{init}$, $\beta$, and $\gamma$ in Eqs. (1), (2), and (3). The performance of PROPHET is dependent with the parameter set. Hence, we choose five parameter sets to classify the performance of PROPHET. Table 6 describes the parameter set used in the simulation.

Figure 3 shows the delivery latency of the routing protocols as a function of VM. Figure 4 describes the number of forwarding for each method. The number of forwarding denotes the total number of data exchanges excluding the routing information. We use this metric to evaluate how each routing protocol reduces the redundant forwarding of the same packets as the routing overhead in the same manner as in [8]–[11]. Although the exchange of routing information is also an important metric to consider the routing overhead, the total volume of the routing information is considered to be small compared with that of data packets for the following reason. In PROPHET, two nodes exchange their contact probability tables as routing information when these nodes contact with each other. The size of this table is at most the sum of (2 bytes × the total number of generated packets) and (6 bytes × the number of other nodes in the network). In the same manner, for MRCT, two nodes exchange their mean residual time tables when these nodes contact with each other, and the size of the table is same as that of PROPHET. Even for Epidemic, two nodes exchange their packet ID lists when these nodes contact with each other to reduce the redundant forwarding of the same data. The size of this list is at most (2 bytes × the total number of generated packets). On the other hand, in the case of data packets for all routing protocols, a node forwards the data packets with at most (512 bytes × the total number of generated packets) to other node when two nodes contact with each other. For example, in the simple mobility model, the size of routing information is at most 38 bytes for PROPHET and MRCT and at most 20 bytes for Epidemic, while the size of data packets is at most 5120 bytes. Because of the different size of the packets, we can expect that the traffic volume of the routing information does not greatly affect the increase of the total traffic volume in the routing protocol.

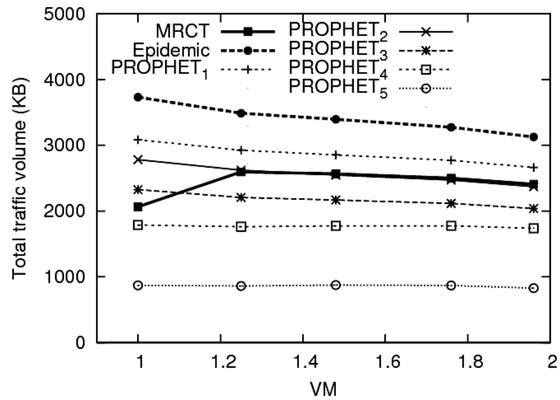



**Fig. 5** The total traffic volume.

For reference, we show the total traffic volume for both the data packets and the routing information in Fig. 5 and the total traffic volume for only the routing information in Fig. 6. From these figures, we can confirm that the traffic for data packets is dominant traffic in the total volume of the traffic. Hence, we can use the number of forwarding to evaluate not only the redundant forwarding of the same packets but also the total traffic volume including the exchanges of the routing information.

As shown in Fig. 3, Epidemic shows the lowest delivery latency because Epidemic forwards data to every node. In Fig. 4, Epidemic shows the largest number of forwarding than other methods due to the repeated forwarding. In the analysis of diverse PROPHETs, we observed

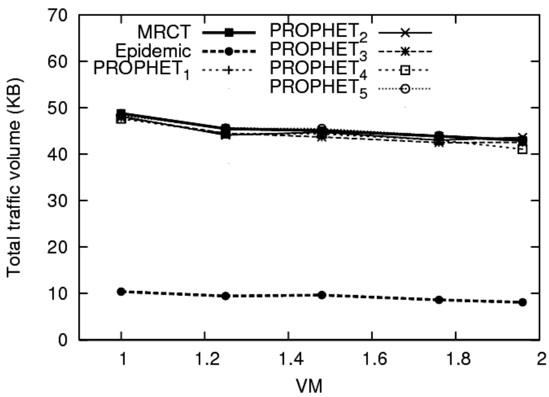



**Fig. 6** The total volume of the routing information.

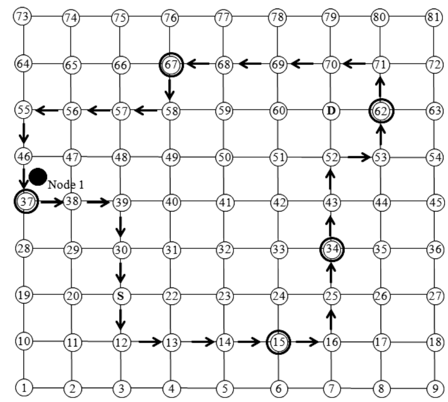



**Fig. 7** The topology of the realistic model.

that PROPHET has the tendency to decrease the delivery latency according to the increase of forwarding as shown in Figs. 3 and 4. $PROPHET_5$ has the smallest number of forwarding but the delivery latency of $PROPHET_5$ is the highest compared to other PROPHETs. As the number of forwarding of PROPHET increases, the delivery latency of PROPHETs approaches that of Epidemic (See $PROPHET_4$ and $PROPHET_3$). Finally, $PROPHET_2$ and $PROPHET_1$ show the slightly higher delivery latency than Epidemic.

$PROPHET_1$ and $PROPHET_2$ are candidates of the optimal PROPHETs in this simulation because the objective of this paper is to reduce the delivery latency. We consider $PROPHET_2$ is the optimum solution since the number of forwarding of $PROPHET_2$ is smaller than $PROPHET_1$. This means that $PROPHET_1$ stands for the limitation on decreasing the delivery latency even if PROPHET more increases the number of forwarding. However, although PROPHET can control the parameter set having better performance, it is difficult to find the optimal solution, which realizes the similar delivery latency of Epidemic with the small number of forwarding.

On the other hand, MRCT shows the almost same delivery latency as Epidemic when VM is greater than 1. At the same time, MRCT also has the similar number of forwarding to that of the optimum PROPHET ($PROPHET_2$). From the result, we can confirm that MRCT based routing protocol provides the better solution because it does not need to control additional parameters to adjust the performance like PROPHET when VM is greater than 1. When VM is 1, although MRCT shows higher delivery latency than Epidemic and some PROPHETs because MRCT is defined for the large variance of the contact interval, the delivery latency of MRCT is not much higher than other methods.

In addition, we can see the relationship of VM and the performance of routing protocols in DTN. The difference of delivery latency between Epidemic and some PROPHETs ($PROPHET_3$, $PROPHET_4$, and $PROPHET_5$) increases as VM increases although the number of forwarding of these PROPHETs does not decrease as VM increases. This result proves our expectation that the variance of contact interval affects the performance of PROPHETs.

### 5.3 Performance Comparison in the Realistic Model

The second simulation considers the performance comparison of the routing protocols in more realistic model. This model is the generalized version of the preference based mobility model defined in Sect. 3. Here, we call this generalized model as the realistic model. Figure 7 shows an example of the realistic model. There are 81 places that may be considered as the preference place of mobile nodes and one static source and destination are located at the S and D of $9 \times 9$ grid topology, respectively. Each mobile node has some preference places with a staying time at the places and moves between these preference places. In the example in Fig. 7, the bold circles mean the preference places of node 1. Before a node starts the next travel, the node randomly selects the next visiting place among the preference places of the node. After that, the node moves toward the destined place along the randomly selected route among all shortest routes between the current place and the next place. In the same manner, all nodes continuously select and visit their preference places during the whole simulation time.

Furthermore, pedestrians and vehicles are mobile nodes in this model. The speeds of pedestrians and vehicles are 1 m/s and 10 m/s, respectively. The communication range of all nodes is 30 m. The length of one segment of the grid topology is 1 km. The staying time of mobile nodes is 1 hour at the preference places, 5 minutes at other places. Pedestrians are classified into five groups in terms of the user preference. The five groups have different user preference places as shown in Table 7. Vehicles are also classified into five groups as shown in Table 7. For both pedestrians and vehicles, one group has 5 mobile nodes. Therefore, the total number of mobile nodes is 50 in the network. Table 7 describes the detail parameters used in the simulation.

According to the above assumption, we evaluate the routing protocols in the realistic model. First, we assume that we have sufficient volume of the buffer to examine the behavior of routing protocols with no effect of the limited buffer size. Second, we evaluate the routing protocols with buffer management schemes in the limited buffer scenario.

**Table 7** Simulation parameters for mobility of nodes.

| | Node Group | Preference place | Staying time | |
|---|---|---|---|---|
| | | | Preference place | Other place |
| Pedestrian Group (1 m/s) | Group 1 | 33, 16, 66, 39, 60 | 3600 sec | 300 sec |
| | Group 2 | 65, 2, 23, 43, 50 | | |
| | Group 3 | 72, 5, 9, 27, 43 | | |
| | Group 4 | 4, 1, 11, 43, 39 | | |
| | Group 5 | 29, 44, 2, 5, 57 | | |
| Vehicular Group (10 m/s) | Group 6 | 42, 11, 70, 13, 12 | 3600 sec | 300 sec |
| | Group 7 | 5, 80, 50, 15, 71 | | |
| | Group 8 | 56, 34, 50, 18, 1 | | |
| | Group 9 | 41, 4, 15, 31, 3 | | |
| | Group 10 | 34, 19, 65, 79, 78 | | |

**Table 8** The parameter set of PROPHET.

| | $\beta$ | $P_{init}$ | $\gamma$ |
|---|---|---|---|
| $PROPHET_1$ | 1 | 0.75 | 0.9999999999 |
| $PROPHET_2$ | 1 | 0.75 | 0.9999999998 |
| $PROPHET_3$ | 1 | 0.75 | 0.9999999995 |
| $PROPHET_4$ | 0.25 | 0.75 | 0.98 |
| $PROPHET_5$ | 1 | 0.75 | 0.98 |

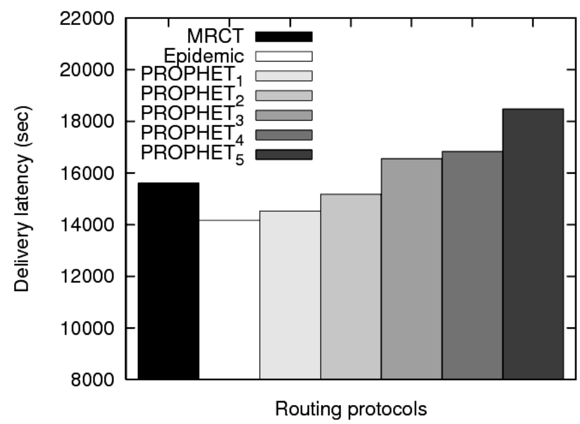



**Fig. 8** Delivery latency.

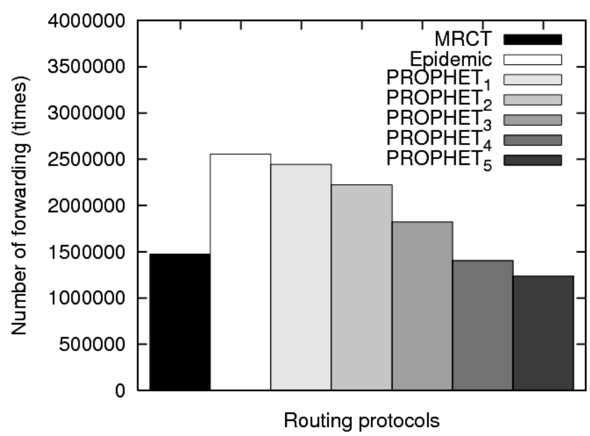



**Fig. 9** The number of forwarding.

#### 5.3.1 Consideration without the Effect of the Limited Buffer Size

In this scenario, the buffer size is defined as 100% of the number of generated packets. A node is able to store 200 packets in the buffer and we generate 200 packets in the whole simulation. The application generates a packet per 1800 sec after the preliminary time. We compare the performance of Epidemic, the five types of PROPHET, and MRCT. The parameter sets of PROPHET are different from that of the simple model because the performance of PROPHET can be affected by the network environment such as the number of nodes and topology. Here, we use five parameter sets of PROPHET in Table 8.

Figure 8 shows the comparison of delivery latency of routing protocols. Figure 9 describes the difference of the number of forwarding for each method. In this simulation, the delivery rate is 100% for all routing protocol because of the sufficient buffer size. Basically, the simulation result has the tendency similar to the result of the simple model in Sect. 5.2. Epidemic has the lowest delivery latency and the largest number of forwarding. PROPHET shows the variety of performance depending on the parameter set. In the same manner of the first simulation, PROPHET is classified by the parameter set with the different number of forwarding.

We found out the parameter set using $PROPHET_4$ as the optimum value in this simulation because the delivery latency of $PROPHET_4$ approaches Epidemic and $PROPHET_4$ has the much smaller number of forwarding than that of Epidemic. However, the parameter set is quite different from the first simulation. Whenever the network environment changes, PROPHET has to find the optimum parameter set by adjusting variables such as $P_{init}$, $\beta$, and $\gamma$. As the network environment becomes complex, the difficulty to find optimum PROPHET is considered to be more increased. This additional optimization causes the computation overhead in PROPHET. This describes the disadvantage of PROPHET. On the other hand, the proposed method shows slightly higher delivery latency with the much smaller number of forwarding than Epidemic without additional control and complexity. As a result, this simulation also supports the validity of the proposed method with the low delivery latency and small routing overhead in the realistic model if there is no effect of the limited buffer size.

#### 5.3.2 Consideration with the Effect of the Limited Buffer Size

Next, we evaluate the routing protocols in the limited buffer scenario. We assume that the buffer size is 20% of the number of generated packets. Here, we generate 200 packets in the whole simulation. Hence, the buffer size is 40 packets. The packet generation cycle is the same as the previous scenario (1800 sec).

In [11], the buffer management scheme is used to

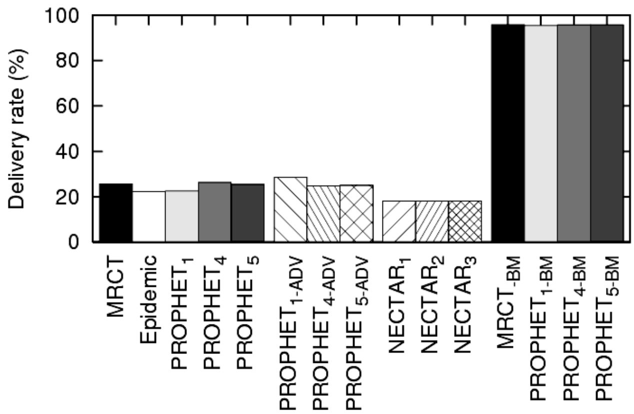



**Fig. 10** The delivery rate.

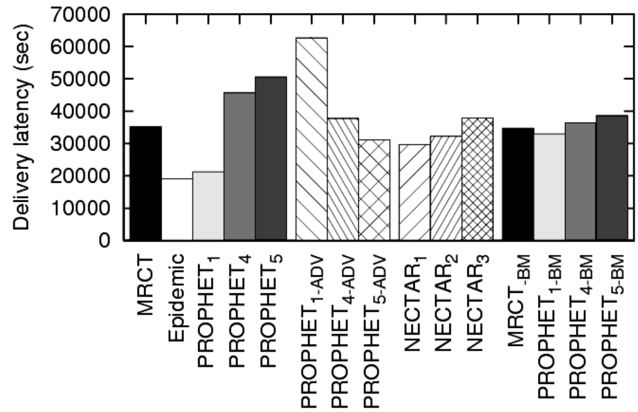



**Fig. 11** The delivery latency.

reduce the redundant forwarding of the delivered packets to the destination. In the buffer management scheme, when a node delivers a packet to the destination, the destination sends an acknowledgment of the packet to the node. After that, the node saves the packet ID with the acknowledgement and exchanges the ID list with other nodes to delete the packet in the buffer. We also apply this buffer management scheme into MRCT. We evaluate MRCT, Epidemic, PROPHET, Advanced PROPHET (PROPHET-$_{\text{ADV}}$) [10], NECTAR [8], MRCT with the buffer management scheme (MRCT-$_{\text{BM}}$), and PROPHET with the buffer management scheme (PROPHET-$_{\text{BM}}$) [11]. We use the three parameter sets for PROPHET, PROPHET-$_{\text{ADV}}$ and PROPHET-$_{\text{BM}}$. The parameter sets are same as the values of $\text{PROPHET}_1$, $\text{PROPHET}_4$, and $\text{PROPHET}_5$ in the first analysis. Besides PROPHET, NECTAR also has parameters that affect the performance [8]. Among them, especially the range of metric (*MinEpidemicLevel*, *MaxEpidemicLevel*) is used to control how frequently a node forwards packets. We use $(1, 4)$, $(2, 4)$, and $(4, 8)$ for various version of NECTAR in the simulation. Other parameters are same as the values used in [8]. We define $\text{NECTAR}_1$, $\text{NECTAR}_2$, and $\text{NECTAR}_3$ as NECTAR with parameters $(1, 4)$, $(2, 4)$, and $(4, 8)$, respectively.

Figure 10 shows the delivery rate of all routing protocols. Figure 11 shows the delivery latency and Fig. 12 describes the number of forwarding. In Fig. 10, MRCT, Epidemic, PROPHETs, and PROPHETs-$_{\text{ADV}}$ have the lower delivery rate compared to MRCT-$_{\text{BM}}$ and PROPHETs-$_{\text{BM}}$. PROPHET-$_{\text{ADV}}$ has the low delivery rate about 25% because PROPHET-$_{\text{ADV}}$ focuses on addressing routing jitter and does not consider the buffer management. The delivery rate of MRCT-$_{\text{BM}}$ and PROPHETs-$_{\text{BM}}$ almost reach 100% even though the buffer size is much smaller than the number of generated packets. However, NECTARs show only 18% delivery rate although NECTARs also have the buffer management scheme. This is because NECTAR can receive the multiple copies of the same packet and manages the packets in the buffer. When NECTAR keeps the redundant packets, there is not enough space to save new packets in the buffer. Furthermore, we also observe that there is no effect to increase the delivery rate by using different parameters in NECTAR. Namely, the delivery rate of $\text{NECTAR}_1$, $\text{NECTAR}_2$, and $\text{NECTAR}_3$ is same regardless of the parameters. On the other hand, MRCT, Epidemic, and PROPHETs have more opportunity to deliver new packets that do not exist in the buffer. A node only exchanges the packet that was previously unseen to the node in those routing protocols. For this reason, MRCT-$_{\text{BM}}$ and PROHPHETs-$_{\text{BM}}$ can increase the delivery rate even though the buffer size is limited.

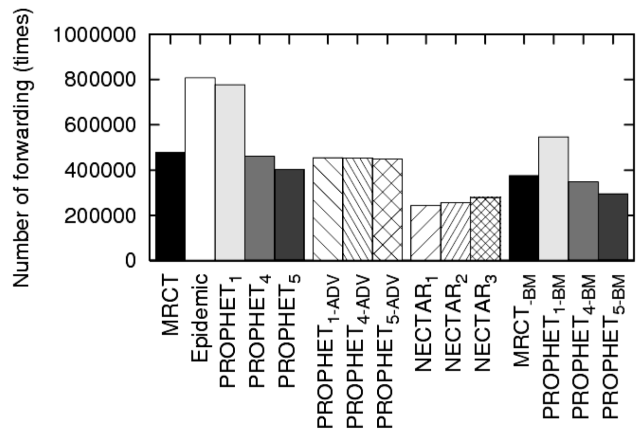



**Fig. 12** The number of forwarding.

Figures 11 and 12 show the relationship between the delivery latency and the number of forwarding, respectively. In the first analysis, Epidemic was used as the reference protocol to evaluate the delivery latency of all routing protocols in the 100% delivery rate condition. However, the delivery rate of Epidemic cannot be 100% in the second scenario because Epidemic does not have the buffer management scheme. Due to the decrease of the delivery rate, Epidemic cannot be regarded as the reference protocol to compare all methods. Therefore, the analysis is focused on the routing protocols with the high delivery rate, MRCT-$_{\text{BM}}$ and PROPHETs-$_{\text{BM}}$. As shown in Figs. 11 and 12, MRCT-$_{\text{BM}}$ and $\text{PROPHET}_4$-$_{\text{BM}}$ are considered as the efficient routing protocols with the high delivery rate, lower delivery latency and the smaller number of forwarding. As mentioned in the previous analysis, PROPHET needs the additional optimization that causes the computation overhead. Similarly, we have also observed the disadvantage of PROPHETs-$_{\text{BM}}$ in the second scenario. The performance of PROPHETs-$_{\text{BM}}$ is also varied with the different parameter set in the limited buffer scenario. On the other hand, the proposed method shows the efficiency of the performance without any optimization in the same manner as the first scenario. As a result, the proposed method is considered as the most efficient routing protocol with the high delivery late, the low delivery latency and relatively small overhead in all cases.

## 6. Conclusions

In this paper, we proposed MRCT based routing protocol to cope with the performance degradation due to the variance of contact interval in DTN. The proposed method uses MRCT as the novel routing metric. The simulation result showed the advantage of the proposed method in the simple and the realistic mobility models. Moreover, we proposed the preference based mobility model, which can realize the opportunistic contact in our daily life. Theoretical analysis introduces the time variant contact model in the proposed mobility model. We also proposed a metric called VM to specify the relative variance of the time variant contacts.

From the simulation results, we showed the advantage of the proposed routing protocol (MRCT) in the various situations. First, we showed that MRCT and PROPHET are considered as the efficient routing protocols in the scenario without the effect of the limited buffer size. From the analysis, we showed the following characteristics of PROPHET. In PROPHET, the more number of forwarding may decrease the delivery latency. However, the routing overhead also increases according to the number of forwarding. Although PROPHET can adjust the performance using optimal parameters, it causes the complexity to find the optimum solution depending on the network environment. From these characteristics, the proposed method can provide better solution with the low delivery latency and the small number of forwarding because the proposed method does not need the additional optimization.

Second, we evaluated the routing protocols in the limited buffer scenario. We implemented the buffer management scheme into MRCT to cope with the situation that a node suffered from the small buffer. The simulation results showed that MRCT with the buffer management scheme (MRCT-$_{\text{BM}}$) can realize the high delivery rate unlike Epidemic, PROPHET, PROPHET-$_{\text{ADV}}$, and NECTAR. Although PROPHET with the buffer management method (PROPHET-$_{\text{BM}}$) also showed the high delivery rate, PROPHET-$_{\text{BM}}$ still needed the additional optimization to adjust the delivery latency and the number of forwarding in the same manner as the first analysis. On the other hand, MRCT-$_{\text{BM}}$ kept the low delivery latency and the small number of forwarding without the additional optimization.

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## Appendix

Let $T_{ict}$ be the contact interval, which is the time from the $k^{\text{th}}$ arrival of a mobile node at region C to the $k+1^{\text{th}}$ arrival of the node at region C, where $k$ is a positive integer. To compute the mean contact interval $E(T_{ict})$ and the mean residual contact time $MRCT = E(T_{ict}{}^2)/2E(T_{ict})$, we analyze the probability density function of $T_{ict}$. Let $M$ be the number of arrivals of a node at region A in the contact interval. Because $M$ obeys a geometric distribution with probability $1 - P_{BA}$, we have

$$\Pr(M = m) = {P_{BA}}^m(1 - P_{BA}). \qquad (A\cdot 1)$$

Let $T_{ict,m}$ be $T_{ict}$ given that $M = m$. The probability density function of $T_{ict}$ can be computed as follows:

$$f_{T_{ict}}(t) = \sum_{m=0}^{\infty} \Pr(M = m) f_{T_{ict,m}}(t). \qquad (A\cdot 2)$$

where $f_{T_{ict,m}}(t)$ is the probability density function of $T_{ict,m}$. $T_{ict,0}$ is represented as $T_{ict,0} = T_{stay,B} + T_{stay,C} + 2T_{BC}$, where $T_{stay,B}$ and $T_{stay,C}$ are the staying times at regions B and C, respectively. Then $f_{T_{ict,0}}(t)$ can be computed as follows:

$$f_{T_{ict,0}}(t) = \begin{cases} 0, & t < 2T_{BC}, \\ \displaystyle\int_0^{t-2T_{BC}} f_C(\tau) f_B(t-\tau) d\tau, & t \geq 2T_{BC}, \end{cases} \qquad (A\cdot 3)$$

where $f_B(t)$ and $f_C(t)$ are the probability density functions of $T_{stay,B}$ and $T_{stay,C}$ and can be computed as $f_B(t) = \exp(-t/T_B)/T_B$, and $f_C(t) = \exp(-t/T_C)/T_C$. For $m \geq 1$, $T_{ict,m}$ is represented as $T_{ict,m} = T_{ict,m-1} + T_{stay,A} + T_{stay,B} + 2T_{AB}$, where $T_{stay,A}$ is the staying time at region A. Then $f_{T_{ict,m}}(t)$ can be computed as follows:

$$f_{T_{ict,m}}(t) = \int_0^t f_{T_{ict,m-1}}(\tau) f_{T'}(t-\tau) d\tau, \qquad (A\cdot 4)$$

where $f_{T'}(t)$ is the probability density function of $T_{stay,A} + T_{stay,B} + 2T_{AB}$ and can be computed as

$$f_{T'}(t) = \begin{cases} 0, & t < 2T_{AB}, \\ \displaystyle\int_0^{t-2T_{AB}} f_A(\tau) f_B(t-\tau) d\tau, & t \geq 2T_{AB}, \end{cases} \qquad (A\cdot 5)$$

where $f_A(t)$ is the probability density function of $T_{stay,A}$ and can be computed as $f_A(t) = \exp(-t/T_A)/T_A$. From these equations, we can compute $E(T_{ict})$ and $MRCT$ as Eqs. (5) and (6).

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