Research of Routing Protocols in Mobile

Delay Tolerant Networks

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Residual Contact Time with Location Information)

Summary

Delay Tolerant Network (DTN) has been emerged to support the network connectivity of disruptive networks such as disaster networks, mobile wireless networks with low connectivity, Interplanetary Internet, etc. In DTN, the main research issue is how to cope with a long delay caused by the network disconnections among mobile nodes. In the early works, it has been shown that it is sometimes possible to use routing protocols for Mobile Ad hoc Networks (MANET) to provide an end-to-end data delivery services in such environments. However, if the networks seriously suffer from the low network connectivity, the routing protocols for MANET cannot provide the communication service along the end-to-end path because keeping the end-to-end path is difficult in such disrupted networks. Even in such cases, the routing protocols for DTN can support the communication services using the opportunistic contacts of mobile nodes to extend the network connectivity in the mobile wireless networks with low connectivity.

In this dissertation, we have focused on the review of several routing protocols for DTN as related works to motivate the problems of early studies and we proposed a novel routing protocol to use mean residual contact time which can reduce the delivery latency of the routing protocols in mobile DTN. The simulation results support that the proposed method can improve the performance of routing protocols for DTN. In addition, we introduce a new metric which can show in what situations the proposed method provides more efficient data delivery service. Variation Metric can be used to characterize these situations in the degree of different contact interval among mobile nodes.

Acknowledgement

Chapter 1

Introduction

1.1. Backgrounds

As wireless networks and mobile devices have been developed, there are diverse requirements to provide the communication services. When a mobile user exchanges their information among others, the user wants to use the available communication services for sending and receiving data. However, wireless networks suffer from the network disruption caused by the limits of radio range due to the dynamic mobility of mobile nodes, sparse deployments of AP (Access Point),

energy depletion, etc [1][2]. Even in such environments, the users want to send data via the available network service depending on the applications despite of delays.

For these reasons, DTN (Delay Tolerant Networks) have been emerged to support the communication to cope with the delay of the network disruption in the intermittent connected networks such as disaster network and MANET (Mobile Ad hoc Networks) with the low network connectivity. Fig. 1.1 shows an example of DTN. In Fig. 1.1-(a), there are three separated wireless networks connected by the network infrastructure. If a user can use the network infrastructure, the user has no problem to send data from separated network A to network B. However, if the user cannot use the network infrastructure due to the network disruptions mentioned above, the user cannot send data from network A to network B. As shown in Fig. 1.1-(b), the one of the simple solutions that copes with the low connectivity between separated networks A and B is to use mobile objects as a data carrier to deliver

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data from network A to network B. Depending on the applications, DTN

can provide the users with the communication services within the

tolerable delays.
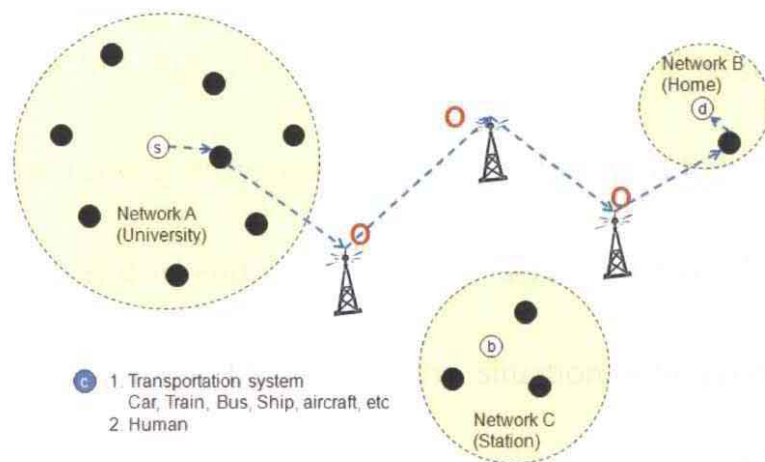
(a) Mobile wireless networks with network infrastructures
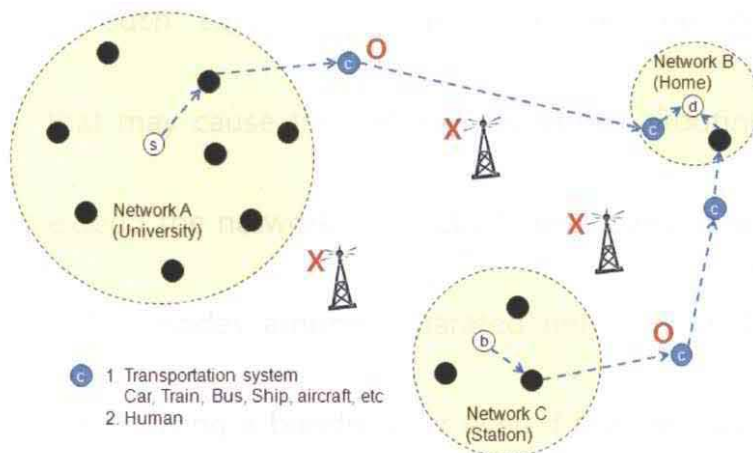
(b) Mobile wireless networks with the network disruption

Figure 1.1 An example of DTN.

1.2. Motivation

To motivate the research challenges and problems of DTN, we consider the networks consisting of mobile and wireless nodes without fixed backbone infrastructure. In such environments, it is sometimes possible to use routing protocols for MANET (Mobile Ad hoc Networks) to provide an end-to-end data delivery service; however, MANET routing protocols cannot be used in the situation with seriously low connectivity, because routing protocols for MANET are basically used to support the communication service along an end-to-end connected path. Even in such cases, DTN can overcome the low network connectivity that may cause the network disruption. Routing protocols for DTN can extend the network connectivity by means of opportunistic contacts of mobile nodes among separated networks. In DTN, nodes can deliver data by using a bundle layer even if they do not have to be connected through a connected multi-hop path [3].

Fig. 1.2 shows an example of routing method for DTN. In Fig. 1.2,

when a source node has data to deliver and meets with another mobile
node 1, the source node just forwards the data to node 1. After node 1
receives the data, node 1 save the data into the bundle layer of node 1
until the data is successfully delivered to a destination node. After that,
when node 1 meets with node 2, node 1 sends the data to node 2 at a
certain time. Finally, when mobile node 2 meets with the destination
node, node 2 sends the data to the destination. The way of data
delivery scheme like this, it is usually called as SCF (Store, Carry, and
Forwarding) in DTN. By using a repeated multi-hop forwarding, some of
data can successfully arrive at the destination even if the mobile nodes
do not have the connected end-to-end path among low connected
networks.
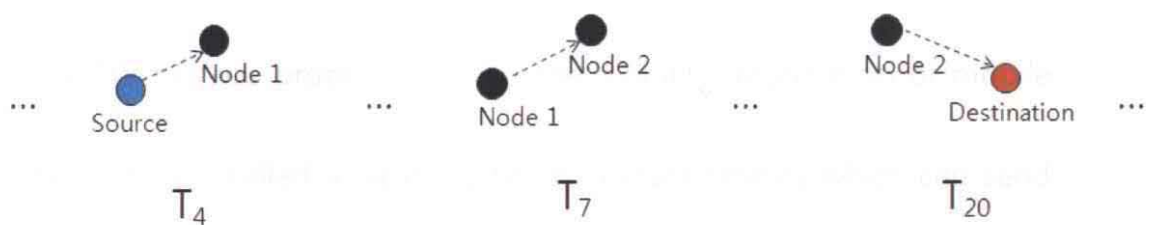
Figure 1.2 An example of routing method for DTN.

To realize the routing protocols of DTN, there are early works to propose several efficient routing protocols that use simple schemes to deliver data. One of the simplest ways among them is to use flooding repeatedly [4]. However, it has been desired to reduce these redundant transmissions in DTN because Flooding needs a lot of redundant transmissions [5]. There were early studies that propose several efficient routing protocols to reduce the redundant transmissions [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].

However, the early works have the disadvantages because they just focused on reducing the redundant flooding although the mobility information is important to utilize the contact behaviors of mobile nodes. Nectar was proposed to use the mobility information of mobile nodes, which is called a Neighborhood Contact History which can send messages to neighborhoods of destination [8]. Nectar showed the use

of the Neighborhood Index to improve the performance of routing protocols for DTN. 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 models 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 contact interval as one of the mobility information and try to use this metric for routing in DTN.

1.3. Objectives

The main objectives of this dissertation are to review several prominent routing protocols for DTN and to provide an efficient routing protocol to cope with the disadvantages of early works through diverse evaluations. Especially, we focused on the variant contact interval of mobile nodes in DTN. The contact interval can be defined as the time difference between a previous contact and a current contact for a given pair of nodes. When a mobile node has different contact schedule to another nodes, the contact interval may be different from each other. In such cases, there could be the variance of the contact interval among mobile nodes. In the early works, especially Prophet proposed a concept of a probabilistic routing protocol that utilizes the history of contact encounters. However, the contact encounters is just considered as the mean contact interval of past history in Prophet. If mobile nodes have the variant contact interval, sometimes the mean contact interval causes longer delay for message delivery as the performance

degradation in Prophet.

In this dissertation, we propose the routing protocol that reflects the variance of contact interval using a metric MRCT (Mean Residual Contact Time). MRCT can describe the exact waiting time to reduce delivery latency considering 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 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.

1.4. Organization of Dissertation

The dissertation is organized as follows. Fig. 1.3 shows the structure of the dissertation. Chapter 1 introduces the background and objective of the dissertation. Chapter 2 explains the related works to compare with the advantages and disadvantages. Several prominent routing protocols are explained in Chapter 2. Chapter 3 describes the problem statement as the motivation of the dissertation. The proposed routing protocol is explained in Chapter 4 and Chapter 5 shows the performance evaluation of the proposed routing protocol in the various scenarios. Chapter 6 shows the performance evaluation in a practical scenario using the proposed method. Finally, we conclude the dissertation in Chapter 7.

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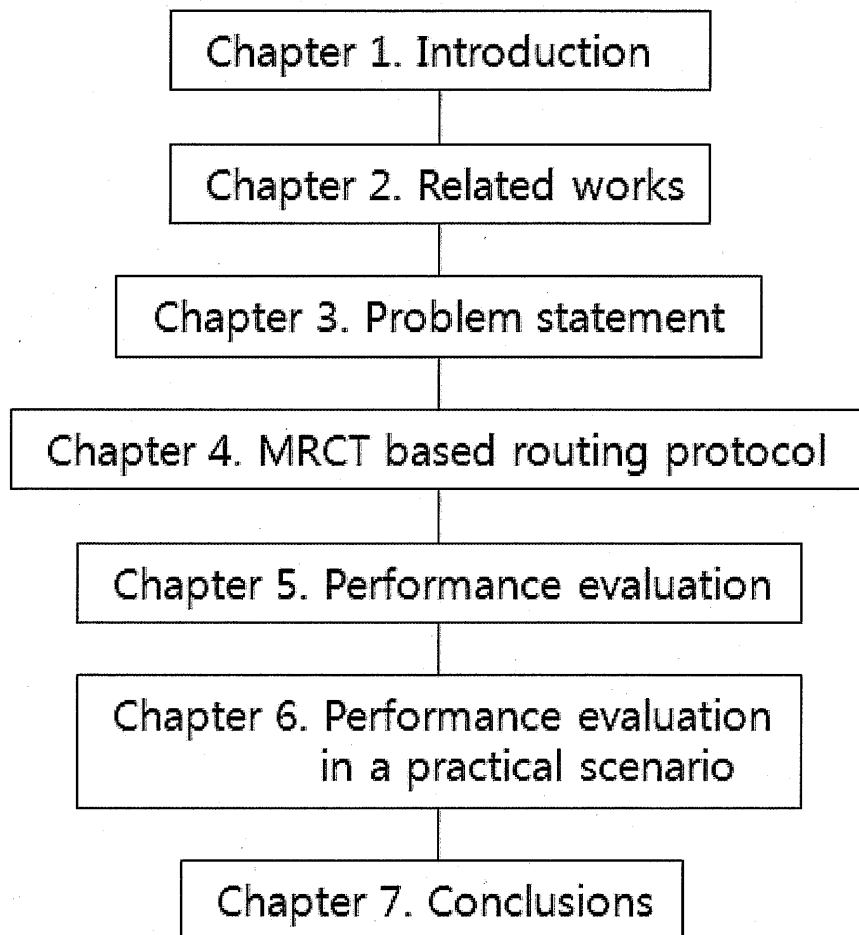
Figure 1.3   Structure of the dissertation.

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Chapter 2

Related Works

2.1. Mobility Models

Routing protocols for mobile and wireless networks are very dependent with the mobility models. There are several mobility models to emulate the characteristic of our movement patterns and to evaluate routing protocols in the mobility models. The contact behaviors of mobile nodes among mobility models are different and it can affect the performance of routing protocols. Therefore, a novel mobility model is required to well describe the realistic mobility patterns of our daily life.

In this section, we introduce one of basic mobility model, called RWP

(Random Waypoint) and the proposed mobility model to explain the

difference between two models.

2.1.1. Simple Random Mobility

In the mobility models for mobile and wireless networks, the simple

random mobility like RWP (Random Waypoint) was used to evaluate the

performance of routing protocols for MANET [1]. In the RWP model,

nodes randomly choose a destination with a random speed and a

direction. After the nodes choose the destination and a speed, nodes

start to leave for the destination. When the nodes arrive at the

destination, the nodes stay at the destination for a while and choose

the new destination continuously. Fig. 2.1 shows the movement of RWP

mobility model.
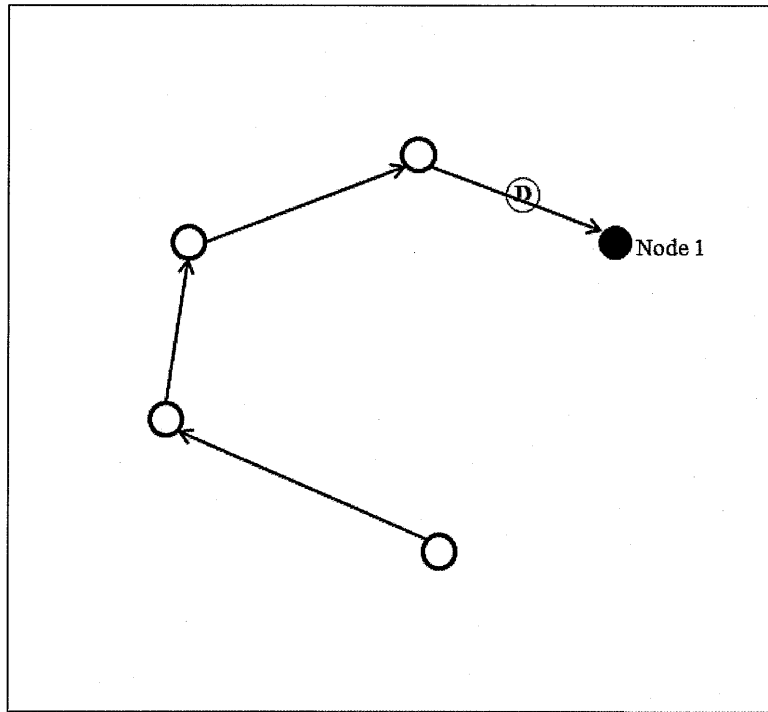
Figure 2.1 Random Way Point mobility model.

However, RWP model is likely to be unrealistic because we usually do not move our visiting places at random. In our daily life, before we start our trip we have some moving schedule with a goal for efficient movements. For example, when we visit somewhere, we usually know the visiting places, and we can make a schedule which efficiently visits to the places based on the user preference such as a minimum transfer, a minimum delay, a minimum cost, etc. Therefore, it is desirable to

model the mobility to mimic the realistic mobility model in our daily life in some better way.

2.1.2. User Preference Mobility

In this dissertation, we propose the user preference mobility model which can emulate the realistic mobility model in our daily life. In the proposed mobility model, the visiting schedule can be decided by the user preference in terms of time, place, and occasion. The contacts among users frequently occur in such places based on not random but the personal preference. Therefore, we propose a novel mobility model emulating the reality in our daily movements, and we consider such environments in the evaluation of routing protocols for mobile DTN with opportunistic contacts.

Fig. 2.2 and Table 2.1 show an example of our daily mobility model. There are several places that we usually visit in one day. John, Sato, and Kim have their own visiting schedule including a staying time

as shown in Table 2.1. In this example, we can expect that they have different time schedule based on their user preference which can affect the contacts among John, Sato, and Kim. This model is defined as the user preference mobility model in the dissertation.
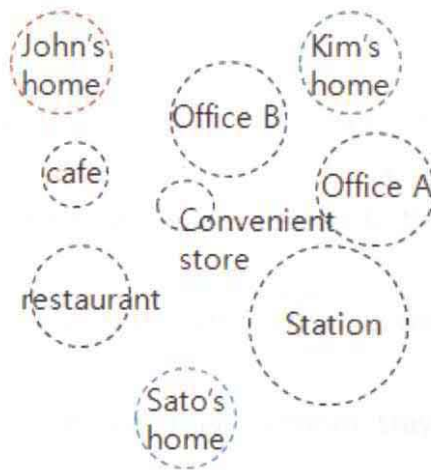

Figure 2.1 Visiting places in our daily life.

Table 2.1 Visiting schedule for each person.

	Station	Convenient Store	Office A	Office B	Restaurant	Cafe
JOHN	5 min	10 min	3 hour	30 min	1 hour	30 min
KIM		5 min	4 hour		30 min	2 hour
SATO	10 min	3 min		6 hour	1 hour	30 min

In addition, we showed the basic model to help readers to easily understand the proposed mobility model. Here, we introduced the simplified version of the proposed mobility model. Fig. 2.2 shows the simple version of the user preference mobility model. As shown in Fig. 2.2, 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 a probability P_{BA} and region C with a 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.
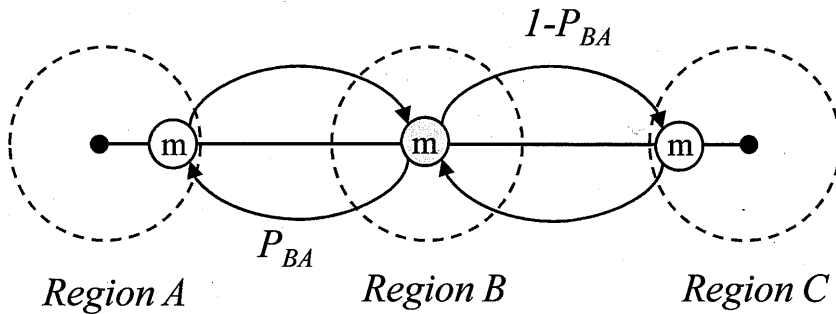

Figure 2.2 The simplified version of user preference mobility model.

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(Tict)* can classify the variance of contact model. The contact pattern becomes more variant if *MRCT / E(Tict)* 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(Tict)* and *MRCT* can be computed as follows:

$$E(T_{ict}) = -\frac{T_B + 2T_{BC} + P_{BA}(T_A + 2T_{AB} - 2T_{BC} - T_C) + T_C}{-1 + P_{BA}}, \qquad (2.1)$$

$$
\begin{aligned}
MRCT = {} & \\
& T_C - [\{T_B{}^2 + 2P_{BA}(T_{AB} - T_{BC})(T_A + T_{AB} - T_{BC}) \\
& + 2T_B T_{BC} + 2T_{BC}{}^2 + P_{BA}(T_A{}^2 + 2T_A(T_{AB} + T_B + T_{BC}) \\
& + 2(T_{AB}{}^2 + 2T_{AB}(T_B + T_{BC}) - T_{BC}(T_B + 2T_{BC}))\} / \\
& \{(-1 + P_{BA})(T_B + 2T_{BC} + P_{BA}(T_A + 2T_{AB} - 2T_{BC} - T_C) \\
& + T_C)\}].
\end{aligned}
\qquad (2.2)
$$

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}.

2.2. Routing Protocols

2.2.1. Epidemic

Epidemic routing protocol supports the eventual delivery of messages to arbitrary destinations without the knowledge of the underlying network [2]. The periodic pair-wise connectivity is required to exchange the message delivery. Epidemic routing protocol works as follows. Each node maintains a buffer consisting of messages that it has originated as well as that it is buffering on behalf of other nodes (i.e., hash table is indexed by a unique identifier regarding to each messages). Each node stores the summary vector that indicates which entries in their hash tables are set. When two nodes come into the communication range of one another, the node exchanges the summary vector with each other. After the node compares the summary vector with other nodes, the node requests the messages to other nodes if the messages are not existed in the buffer of the node. Fig. 2.3

shows the operation of Epidemic routing protocol.
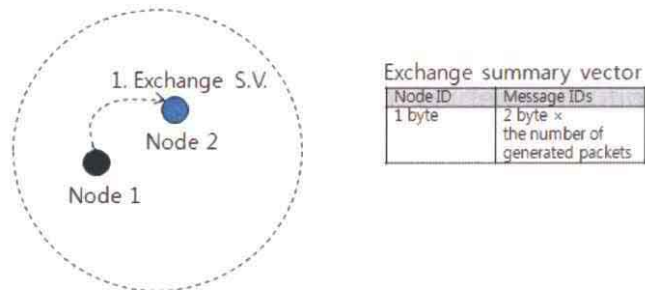
(a) Exchange message ID in the summary vector
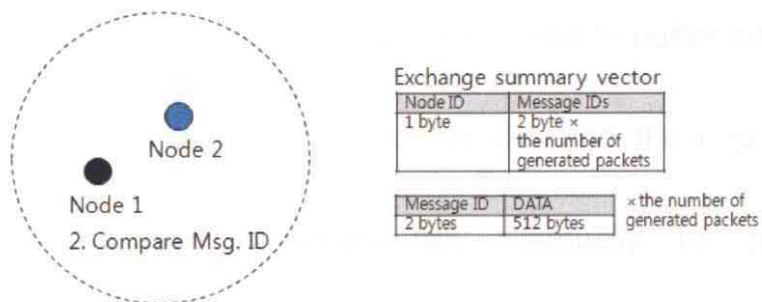
(b) Compare the message ID between buffer and received S.V.
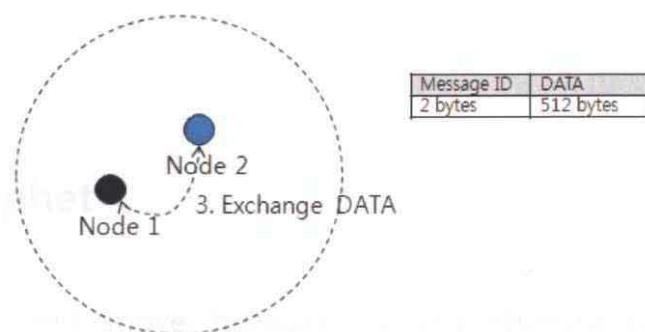
(c) Exchange DATA that do not exist in the buffer

Figure 2.3 The operation of Epidemic.

The main contribution of Epidemic routing protocol is to maximize

message delivery rate and to minimize message latency in the partially

connected ad hoc networks. In addition, Epidemic routing protocol tries

to minimize the total resource consumed in message delivery due to

the flooding of messages. Epidemic routing protocol can reduce the

redundant message forwarding in use of the summary vector. However,

message delivery rate is regulated by the available buffer size and the

hop count of the message. If the buffer size and the hop count are

sufficiently large, the messages will eventually be propagated

throughout the entire network. Otherwise, message delivery rate may

be limited by the metrics.

2.2.2. Prophet

As mentioned above, 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 of

routing protocols. Prophet (Probabilistic Routing Protocol using History of Encounters and Transitivity) proposed the estimation-based forwarding method that adopts the use of contact probability [3]. 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.

Prophet used delivery predictability as a metric, which can approximate the contact probability. 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. (2.3) and (2.4), 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.

$$P_{(1,2)} = P_{(1,2)old} \times \gamma^k, \quad (2.3)$$

$$P_{(1,2)} = P_{(1,2)old} + (1 - P_{(1,2)old}) \times P_{init}. \quad (2.4)$$

Prophet also considers the update for multi-hop forwarding from node 1 to node 3 via intermediate node 2 by using Eq. (2.5), where $\beta \in [0,1]$ is a scaling constant.

$$P_{(1,3)} = P_{(1,3)old} + (1 - P_{(1,3)old}) \times P_{(1,2)} \times P_{(2,3)} \times \beta. \quad (2.5)$$

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 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 [4]. In [5], 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.

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.

2.2.3. Nectar

Nectar protocol uses an opportunistic contact to calculate a Neighborhood Index and spread messages in a controlled manner [6]. During the contact period of nodes, nodes first start the transmission of

messages whose destination is the node that established the contact, then exchange information about the neighborhood (Neighborhood Index), and eventually forward other messages. The spread of the Neighborhood Index allows the knowledge of network topology by utilizing mobility information. Nectar protocol uses the mobility information as a movement-based heuristic. This heuristic considers the realistic mobility scenario that nodes' past contact history among neighbor nodes. Consequently, Nectar can increase the message delivery probability and reduces traffic on the network in a controlled way to a neighborhood of a destination.

The Neighborhood Index is based on recent contacts' history. If nodes frequently contact to neighbors of the destination, the nodes have a high Neighborhood Index. When the first contact between nodes i and j occurs, the Neighborhood Index to each other is assigned to 1, and while nodes i and j are within radio range, the Neighborhood Index and the contact counter are increased in a linear fashion. After

that, nodes i and j update the Neighborhood Index for the destination

that are not within radio range. Suppose that node j has a better

Neighborhood Index to node d than node i. In this case, the node's i

Neighborhood Index to node d ($N_{(i', d)}$) will be computed by the

following procedure. The Neighborhood Index is the division of

Contact$_{(j, d)}$ and two metrics: a distance metric and an aging metric. The

distance metric is calculated by adding 1 to Hops$_{(j, d)}$ counter, which

represents the amount of hops between j and d. The amount of time

slots that nodes j and d are out of radio range raised by an aging

constant (σ) defines the aging metric. The Neighborhood Index formula,

shown in Equation (2.6), favors the delivery of messages to neighbors

that are near from a destination and have been in contact recently.

$$N_{(i',d)} = \frac{Contact_{(j,d)}}{(Hops_{(j,d)} + 1) \times (TS - ts\_update + 1)^{\sigma}} \quad (2.6)$$

In addition, if node i has already a route to node d, and node j has a

better Neighborhood Index to node d, $N_{(i', d)}$ will be updated in a

weighted fashion. With this approach, the Neighborhood Index

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calculation mitigates the impact of new information, and prevents nodes from dramatically altering a known Neighborhood Index with data that may have a limited validity. The Neighborhood Index is changed, however the associated value is reduced, allowing another neighbor, with a better Neighborhood Index, to be the next hop, as shown in Equation (2.7):

$$N_{(i,d)} = \begin{cases} N_{(i',d)}, & \text{if node d is unknown} \\ \frac{(N_{(i,d)} \times \omega) + N_{(i',d)}}{\omega + 1}, & \text{otherwise.} \end{cases}$$

(2.7)

Nectar also has an advantage of increase in the delivery rate with a movement based heuristic in the constrained resource environments. They proposed the past contact's history of nodes by using the Neighborhood Index. However, the performance of Nectar can be varied with the metric that controls how nodes frequently forward the messages. The relationship between the delivery rate and redundant message forwarding is a tradeoff in Nectar. Furthermore, Nectar has the similar concept of Prophet that uses the contact probability, which does not consider the variance of the contact interval of mobile nodes. When

a node calculates the Neighborhood Index, the value is just increased

or decreased in a linear fashion based on constant value regardless of

the varied contact interval.

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Chapter 3

Problem Statement

3.1. Variance of Contact Interval

When a mobile node has a contact for a given pair of nodes, the contact occurs in some intervals. The contact interval can be defined as the time difference between previous contact time and current contact time. For example, if node 1 meets with node 2 at time T_1 = 3:00 and node 1 meets again with node 2 at time T_2 = 3:30, the contact interval is 30 minutes for a given pair of nodes 1 and 2.

As mentioned in Chapter 1, the contacts of mobile nodes strongly

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depend on the mobility model in the networks. Based on the mobility model, the contact interval may be uniform or be varied. If the contact interval is varied and the variance of the contact interval is large, the delivery latency of the routing protocols for DTN can be affected by the irregular contact interval. However, the variance of contact interval of mobile nodes was not well considered in the previous works. They focused on the use of the contact history with some probabilistic way in the RWP mobility model to evaluate their routing protocols. If the contacts of mobile nodes have different characteristics with large variance of contact interval, the performance of routing protocols is degraded as the variance of the contact interval increases.

In this dissertation, we define the mobility model to emulate more realistic mobility model which can have the large variance of the contact interval. Recall the definition of user preference mobility model; we can observe that the variant contact interval occurs in our daily life. Fig. 3.1 shows a simple example to remind our assumption. In Fig 3.1,

there several visiting places for John, Sato, and Kim. They visit those

places based on their visiting schedule. They can meet with each other

in some places or cannot meet in other places. As a result, the contact

behaviors between two persons are different as shown in the bottom of

Fig. 3.1. John and Kim have different contact encounters and contact

interval to Sato.
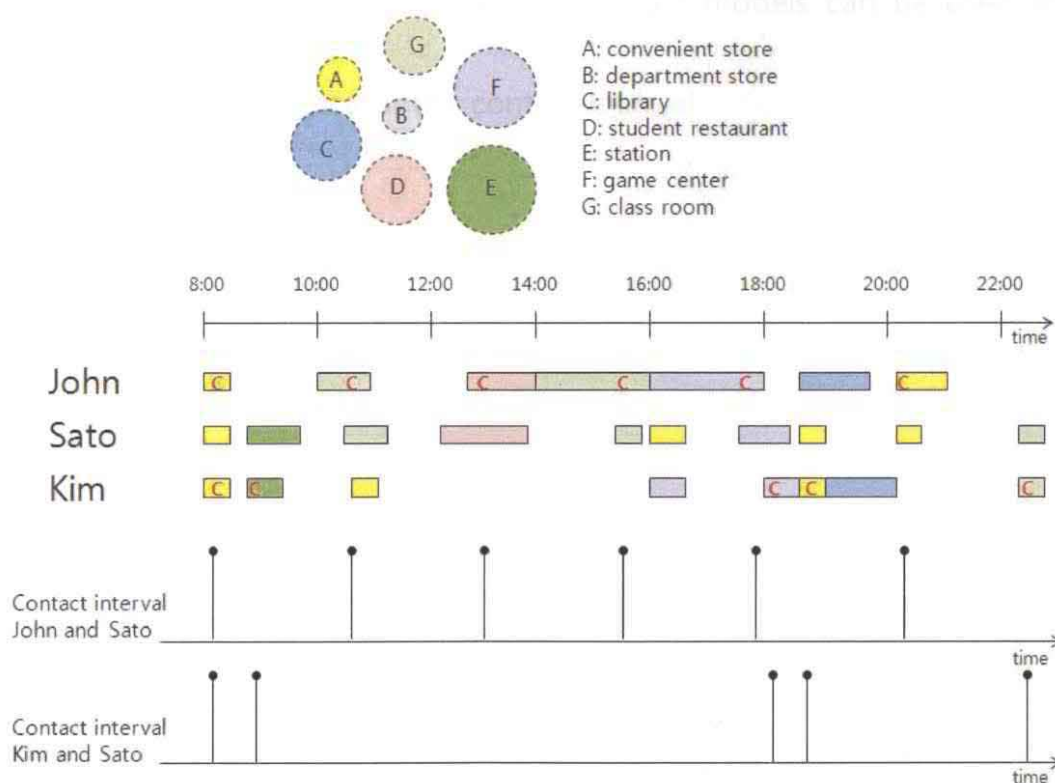
Figure 3.1 Different contact behavior between nodes in user

preference mobility model

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Additionally, in the simplified version of the proposed mobility model, the variance of the contact interval can be defined as the function of visiting probability and staying time to a certain place. 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 dissertation, these two contact models can be used to differentiate the variance of the contact interval.

3.2. Problem of Prophet

With the consideration for the variant contact interval, there may be problems in the previous works. As mentioned, Prophet selects a node with high contact probability in the uniform contact model with small variance. In such environment, the contact probability of the node becomes high when the mean contact interval becomes small because the contact probability stands for the mean number of contacts in a unit time. However, because Prophet does not distinguish the variance of the contact interval in the time variant contact model, the performance of Prophet has to be degraded as the variance of the contact interval increases. It is sure that 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.

For example, there are two contact models with the same mean

value of the contact interval (500 sec) as shown in Fig. 3.2. However, the variance of the contact interval is quite different. Fig. 3.2-(a) shows the uniform contact model of node 1 that periodically contacts to the destination. In this contact model, the contact interval of node 1 is uniform. In contrast, Fig. 3.2-(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 [1], we can compute the mean residual contact time (MRCT) as

$$MRCT = \frac{E(T_{ict}^{2})}{2E(T_{ict})}, \quad (3.1)$$

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. 3.2, 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 sec^2 for node 1 and $E(T_{ict}^2)$ =

570000 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

3.1 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 [2]. Namely, Prophet cannot distinguish

the above two nodes with different variances. As a result, the

performance of Prophet may be 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.
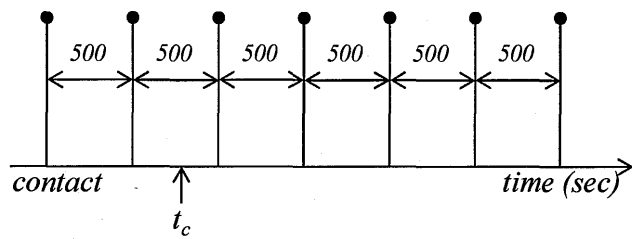
(a) The uniform contact interval of node 1
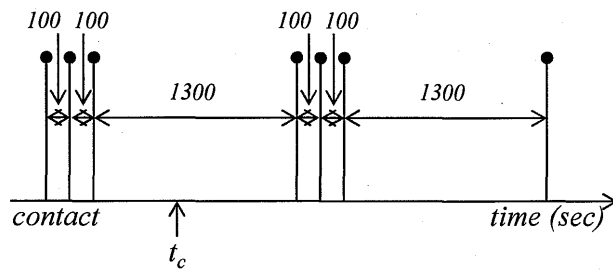
(b) The variant contact interval of node 2

Figure 3.2 The different contact interval.

Table 3.1 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

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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 3.1, 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 3.1 also shows the complete values of Case 2. In Table 3.2, we show the five cases depending on the combined set of the mean value of the contact interval and the mean residual contact time.

Table 3.2 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

In this dissertation, 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 3.2, 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.

3.3. Classification of the Relative Contact Interval

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 the previous section, 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 3.2. 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. (3.2).

$$VM_2(i, j) = \max\left\{\frac{MCI_i \times MRCT_j}{MCI_j \times MRCT_i}, \frac{MCI_j \times MRCT_i}{MCI_i \times MRCT_j}\right\}. \quad (3.2)$$

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. (3.2). 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 3.2.

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:

$$VM_{all} = \frac{\sum_{1 \leq i < j \leq n} VM_2(i, j)}{\frac{n(n-1)}{2}}. \quad (3.3)$$

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.

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Chapter 4

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.

4.1. Operation of MRCT based Routing Protocol

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). The all values are stored in the routing table of a node as shown in Fig. 4.1.

Node ID	MRCT	Last contact time (LCT)	Number of encounters(NC)	Sum of contact interval $\Sigma(CI)$	Sum of the square of contact interval $\Sigma(CI^2)$
2	500	11000	9	10000	4100000
3					
9					

Node ID	MRCT	Last contact time (LCT)	Number of encounters(NC)	Sum of contact interval $\Sigma(CI)$	Sum of the square of contact interval $\Sigma(CI^2)$
2	1875	13000	10	12000	4500000
3		...	...	...	...
9		...	...	...	...

Figure 4.1 Routing table of node 23.

4.2. Message Format

Similar to Epidemic and Prophet, MRCT based routing protocol also uses the routing information for updating routing table and for exchanging messages that is unseen in the buffer [1][2]. The message format of MRCT routing protocol consists of 2 parts: message ID and node ID+MRCT value. The 2 bytes unique message ID is originated by source node and whenever the messages are forwarded to other nodes, the message ID is used to reduce the redundant forwarding of the same message. This 2 bytes message ID is also used in Epidemic and Prophet for the same purpose. In addition to the message ID, MRCT based routing protocol uses MRCT table including node ID and MRCT value for each node. The node ID is 2 bytes and MRCT value is 4 bytes, totally 6 bytes. Fig. 4.2 shows the message format of MRCT routing protocol.

Exchange summary vector & MRCT

Node ID	Message IDs	MRCT
1 byte	2 byte × the number of generated packets	6 byte × the number of other nodes

Message ID	DATA
2 bytes	512 bytes

× the number of generated packets

Figure 4.2 Message format of MRCT routing protocol.

When a node meets with other nodes, these two lists are exchanged before exchanging messages. In the case of Epidemic, 2 bytes message ID list is only used for message exchange [1]. Prophet and MRCT use two types of lists for message exchange including the comparison of the contact information. Node ID and contact probability are used for Prophet [2], node ID and MRCT for MRCT based routing protocol. Commonly, the routing information can be considered as the overhead for data message. However, in this case, the total size of routing information is relatively smaller than that of data message. It has shown that the traffic volume of the routing information does not greatly affect the increase of the total traffic volume in the routing

protocol.

In the dissertation, we used 512 bytes for data message and 6 bytes routing information x the number of nodes in the network. In the simple model, we generated 10 packets and 3 nodes. The total size of data messages is 5120 bytes and the total size of routing information is 20 bytes for Epidemic, 38 bytes for Prophet and MRCT based routing protocol. Even in the realistic model, we generated 200 packets for data message and 50 nodes. The total size of data message 10240 bytes and the total size of routing information is 100 bytes for Epidemic, 400 bytes for Prophet and MRCT based routing protocol.

4.3. MRCT Calculation

Based on the contact information, a node calculates MRCT before the node forwards message to other nodes. 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, $CI^2_{12} = 41000000$ 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, $CI^2_{12} = CI^2_{12,old} + (T_{10} - LCT_{12,old})^2 = 45000000$ 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. (3.1). 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 4.1.

Table 4.1 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^2s / 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.

4.4. Buffer Management Scheme

MRCT based routing protocol adopts the buffer management scheme which can reduce the redundant forwarding of the delivered messages to the destination as used in [3]. Considering the constrained resources of a node, the buffer management scheme can increase the delivery rate by removing the delivered messages in the buffer. In the buffer management scheme, when a node delivers a packet to the destination, the destination sends an acknowledgement 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. In the dissertation, we performed two different scenarios with and without considering the limited buffer size in the evaluation. Chapter 5 shows the effect of the buffer management scheme in the routing protocols.

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Chapter 5

Performance Evaluations

We performed simulations to evaluate the proposed routing protocol compared to Prophet with diverse parameter sets using *ns-2* [1]. 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 [2]. 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 5.1.

Table 5.1 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

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. 2.2. 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} = 0.3, T_A, T_B, and T_C are listed in Table 5.2. 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. (3.2). 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.

Table 5.2 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

To evaluate the proposed protocol, we performed comparisons using Epidemic and diverse Prophets with different parameter set. Epidemic simply forwards data to every contacting node [3]. As

mentioned in Chapter 2, Prophet approximates the contact probability

by using the parameters such as P_{init}, β, and γ in Eqs. (1), (2), and (3) [4].

The performance of Prophet is dependent with the parameter set.

Hence, we choose five parameter sets to classify the performance of

Prophet. Table 5.3 describes the parameter set used in the simulation.

Table 5.3 The parameter set of PROPHET.

	β	P_{init}	γ
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. 5.1 shows the delivery latency of the routing protocols as a

function of VM. Fig. 5.2 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

[4]-[7]. 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.

For references, we show the total traffic volume for both the data packets and the routing information in Fig. 5.3 and the total traffic volume for only the routing information in Fig. 5.4. From these figures, we can confirm that the traffic for data packets is the 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. 5.1, Epidemic shows the lowest delivery latency because Epidemic forwards data to every node. In Fig. 5.2, Epidemic shows the largest number of forwarding than other methods due to the repeated forwarding. In the analysis of diverse Prophets, we observed that Prophet has the tendency to decrease the delivery latency according to the increase of forwarding as shown in Fig. 5.1 and Fig. 5.2. $Prophet_5$ 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.
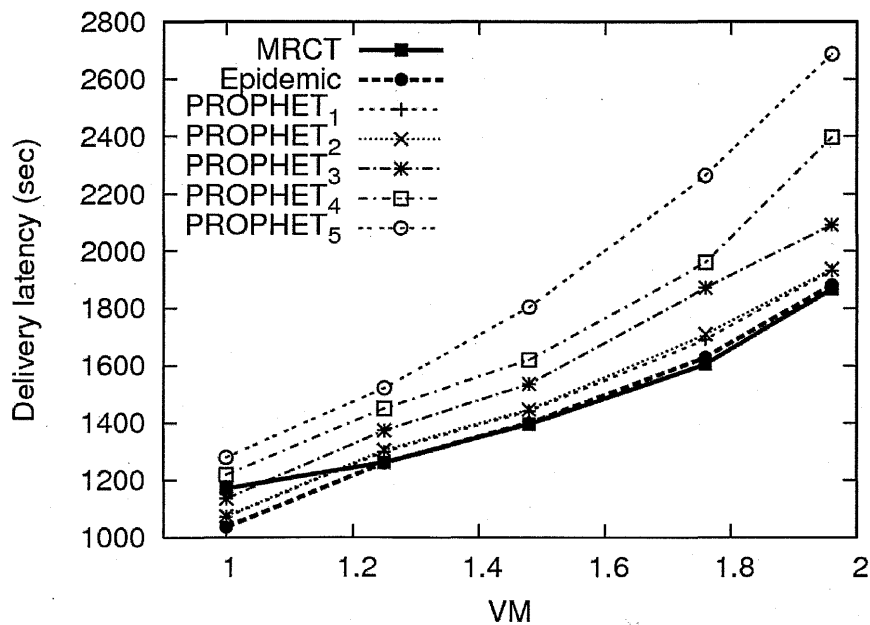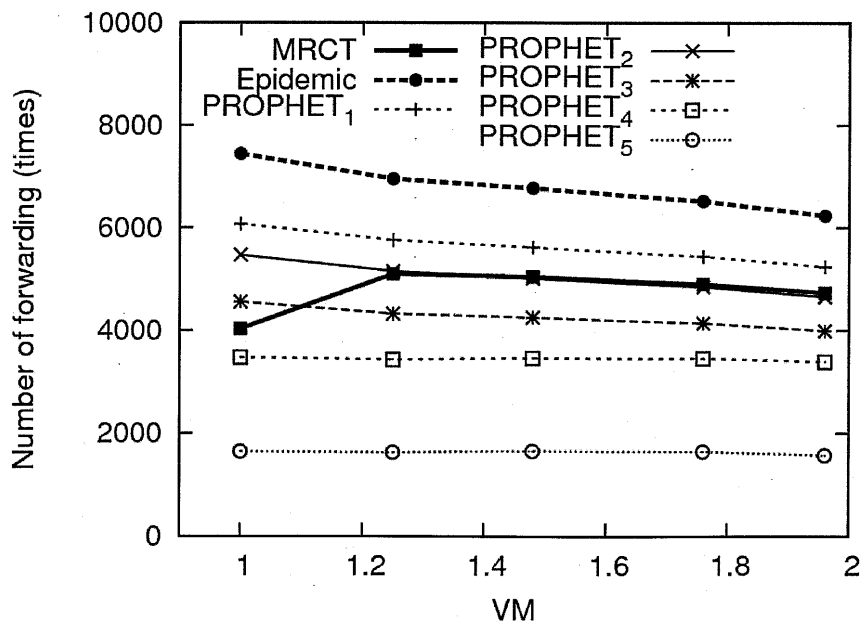

Figure 5.1 Delivery latency.
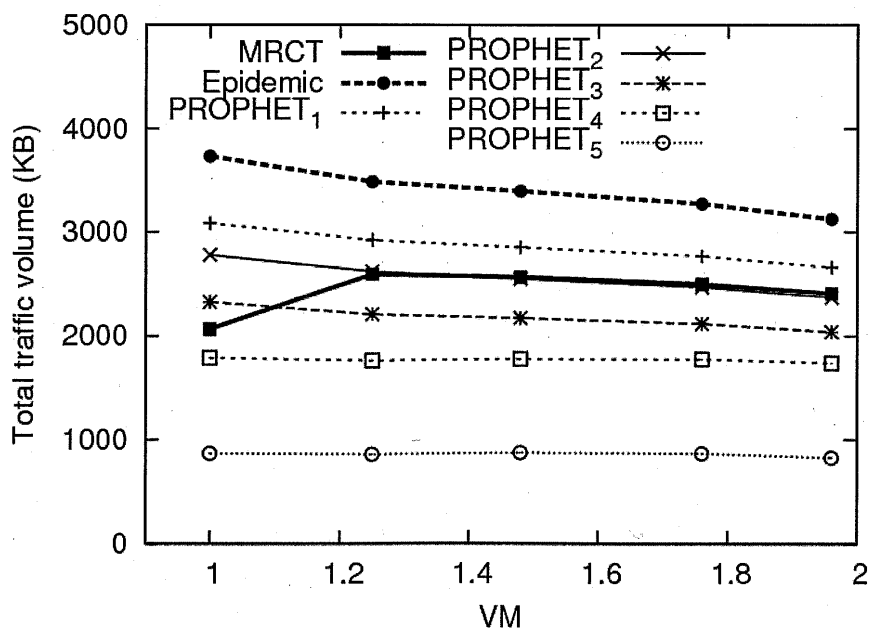
Figure 5.2 The number of forwarding.

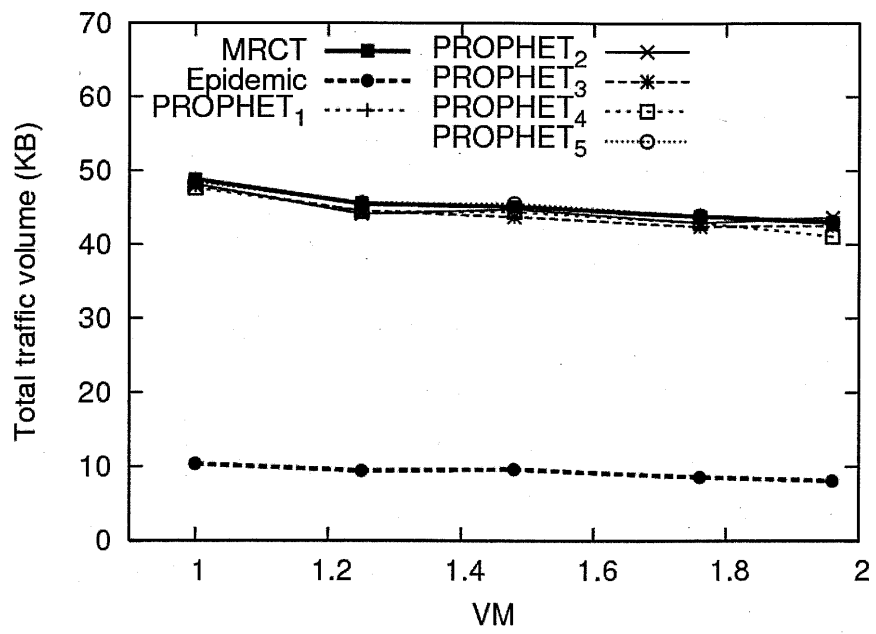**Figure 5.3** The total traffic volume.

Fig. 5.4 The total volume of the routing information.

5.3. Performance Comparisons 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 Chapter 2. Here, we call this generalized model as the realistic model. Fig. 5.5 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 9×9 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. 5.5, 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.
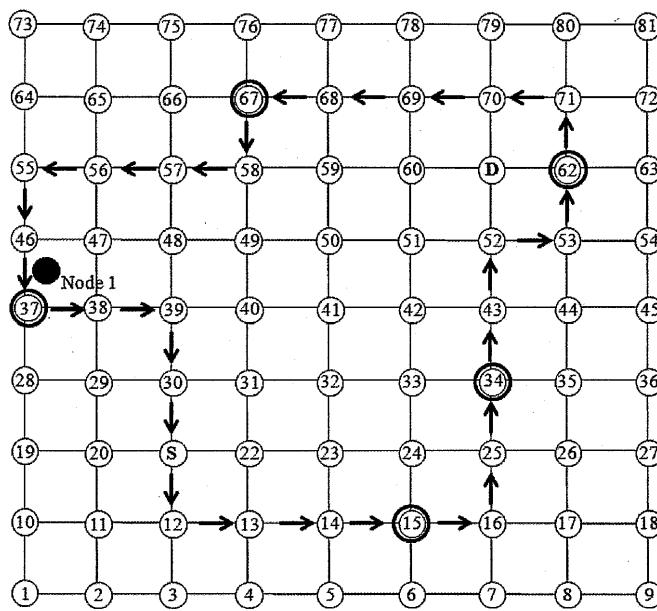

Figure 5.5 The topology of the realistic model.

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 5.4. Vehicles are also classified into five groups as shown in Table 5.4. For both pedestrians and vehicles, one group has 5 mobile nodes. Therefore, the total number of mobile nodes is 50 in the network. Table 5.4 describes the detail parameters used in the simulation.

Table 5.4 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		

According to the above assumption, we evaluate the routing protocols in the realistic model. First, we assume that we have the 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 the buffer management scheme in the limited buffer scenario.

5.3.1. Unlimited Buffer Scenario (Ideal Case)

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 5.5.

Table 5.5 The parameter set of PROPHET.

	β	P_{init}	γ
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. 5.6 shows the comparison of delivery latency of routing protocols.

Fig. 5.7 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

Section 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}, β, and γ. 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.
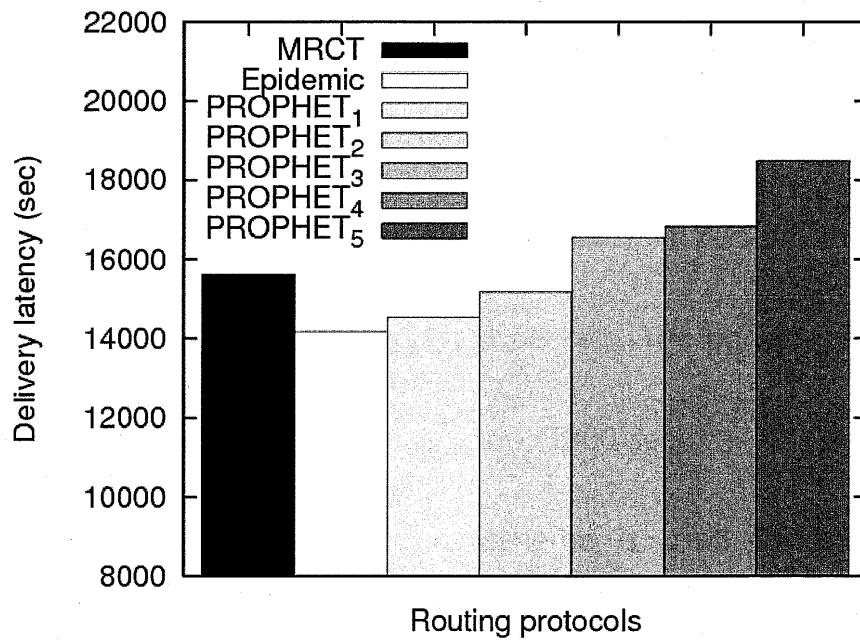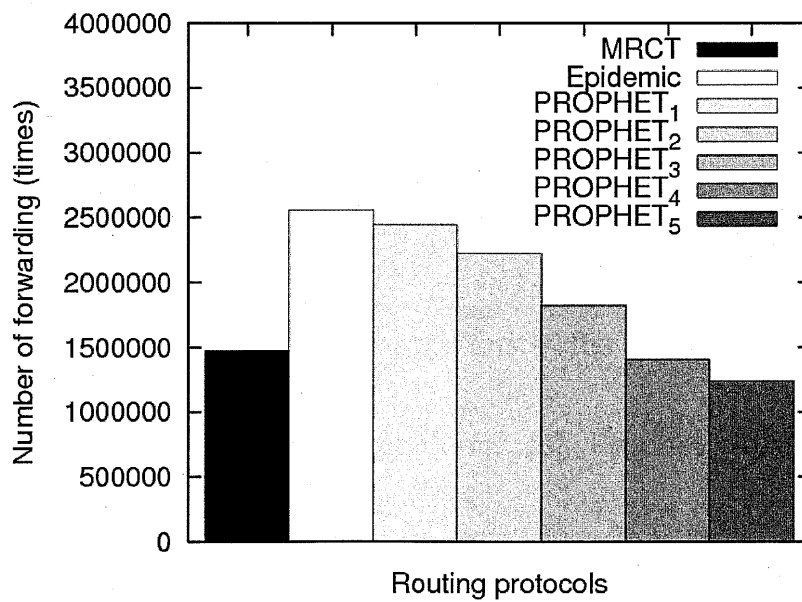
Figure 5.6 Delivery latency.

Figure 5.7 The number of forwarding.

5.3.2. Limited Buffer Scenario (General Case)

In this section, 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 [7], the buffer management scheme is used to 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 [3], Prophet [4], Nectar [5], Advanced Prophet (Prophet-$_{ADV}$) [6], MRCT with the buffer management scheme (MRCT-$_{BM}$), and Prophet with the buffer management scheme

(Prophet-$_{BM}$) [7]. We use the three parameter sets for Prophet, Prophet-$_{ADV}$ and Prophet-$_{BM}$. The parameter sets are same as the values of Prophet$_1$, Prophet$_4$, and Prophet$_5$ in the first analysis. Besides Prophet, Nectar also has parameters that affect the performance [5]. Among them, the range of metric (*MinEpidemicLevel, MaxEpidemicLevel*) is especially 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 [5]. We define Nectar$_1$, Nectar$_2$, and Nectar$_3$ as Nectar with parameters (1, 4), (2, 4), and (4, 8), respectively.

Fig. 5.8 shows the delivery rate of all routing protocols. Fig. 5.9 shows the delivery latency and Fig. 5.10 describes the number of forwarding. In Fig. 5.8, MRCT, Epidemic, Prophets, and Prophets-$_{ADV}$ have the lower delivery rate compared to MRCT-$_{BM}$ and Prophets-$_{BM}$. Prophet-$_{ADV}$ has the low delivery rate about 25 % because Prophet-$_{ADV}$ focuses on addressing routing jitter and does not consider the buffer

management. The delivery rate of MRCT-$_{BM}$ and Prophets-$_{BM}$ 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 Nectar$_1$, Nectar$_2$, and 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-$_{BM}$ and Prophets-$_{BM}$ can increase the delivery rate even though the buffer size is limited.

Fig. 5.9 and Fig. 5.10 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-$_{BM}$ and Prophets-$_{BM}$. As shown in Fig. 5.9 and Fig. 5.10, MRCT-$_{BM}$ and Prophet$_4$-$_{BM}$ 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-$_{BM}$ in the second scenario. The performance of Prophets-$_{BM}$ 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

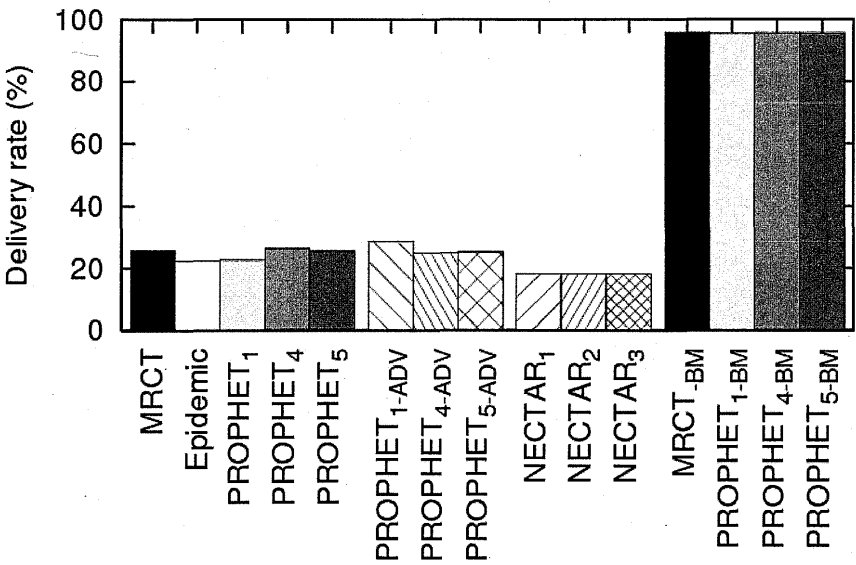delivery latency and relatively small overhead in all cases.

Figure 5.8 The delivery rate.
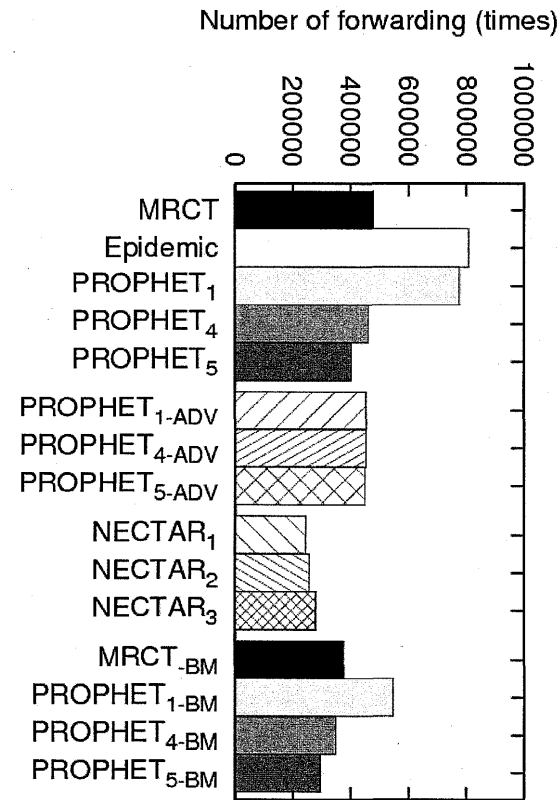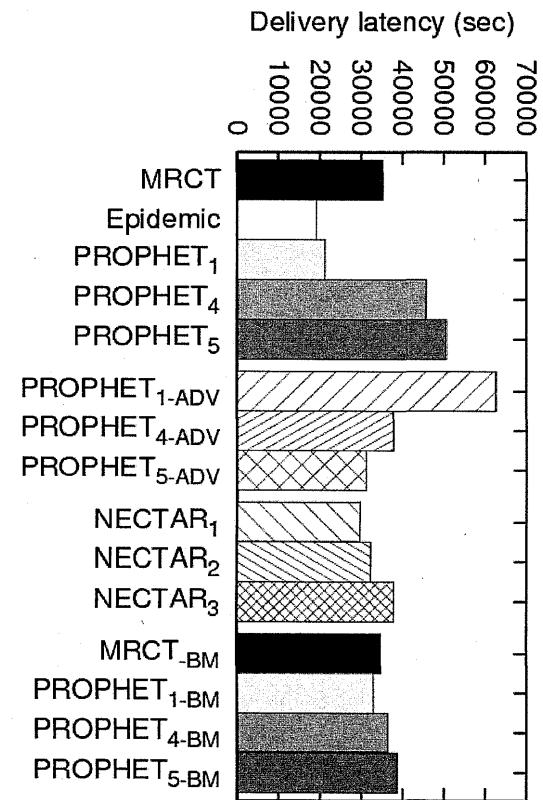
Figure 5.10   The number of forwarding.

Figure 5.9   The delivery latency.

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Chapter 6

Practical Scenario (MRCT+LI: Mean Residual Contact Time with Location Information)

6.1. Backgrounds

In this section, we show the performance evaluation in a practical scenario as an application of the MRCT based routing protocol in our daily life. As mentioned before, DTN introduces the use of opportunistic

communications in message delivery service. The early studies have

considered the routing methods as the stochastic estimation to identify

the contact in the random mobility. We also showed the advantage of

the routing protocol to use MRCT (Mean Residual Contact Time) that

describes the opportunistic contact period. However, the stochastic

approaches still have the inaccuracy in the estimation of the contacts of

mobile nodes. In the following sections, we introduce the practical

application using the advanced MRCT routing protocol that improve the

inaccuracy of the stochastic approaches by using the exact location

information of mobile nodes.

6.2. Introduction

DTN (Delay Tolerant Network) has been proposed to extend the network connectivity of the mobile and wireless networks. One typical example of DTN is MANET (Mobile Ad hoc Networks). DTN considers the MANET that suffers from some disruption caused by the limit of wireless radio range, energy discharge, break down, noise, etc. In such environment, a node stores data until the node can forward the data to intermediate nodes in opportunistic communication [1].

To support the characteristics of DTN, early works proposed diverse routing protocols to maximize the use of the opportunistic contact among nodes. Epidemic [2] and Spray and Wait [3] proposed to control the number of message copies when two nodes meet with each other. Prophet [4] introduced the stochastic method to utilize the contact probability of the nodes. CM Spray and Wait [5] proposed the hybrid routing to combine the advantages of flooding and stochastic method. MRCT [6] proposed the routing protocol to estimate the residual

contact time in the time variant mobility model.

Although they proved that the stochastic method can provide efficient routing to overcome the opportunistic behavior of DTN, early works have a limitation in accuracy of estimation for the message delivery schedule. Moreover, nowadays there are many novel applications which can estimate the mobility information of mobile nodes in the aids of the cheap and portable networking devices. For example, recent portable devices are equipped with GPS (Global Positioning System) and navigation software in our daily use. Hence, we may easily know to where each device moves if we can obtain the detailed information from the devices. It is expected that if a node uses location information to a certain destination, the node can more accurately estimate the time of contact and the message delivery time.

With this as backgrounds, we introduce the MRCT+LI (Mean Residual Contact Time with Location Information) routing protocol to provide the efficient estimation of the message delivery time for DTN.

The proposed method uses the route information that shows the

feasibility of the navigation information in aid of location based

message delivery service as a practical example in DTN.

6.3. MRCT+LI: Mean Residual Contact Time with Location Information

In our day life, we generally know the location information of our current position and the destined place, and we can make use of the transportation systems which can efficiently reach to the place with the shortest time. Moreover, the most of visiting places have user preference. The preference is different from each other in terms of time, place and occasion. The opportunistic contact frequently occurs in such place based on the personal preference. In such environments, the contact and contact interval are considered as important metrics for the routing protocols in DTN.

Recently, we proposed MRCT (Mean Residual Contact Time) routing protocol, which can estimate the residual contact time among nodes when a node has no information of the network [6]. Even in that case, the estimation of the message delivery time still has inaccuracy because

nodes use only the history of the contact time. However, if we use the navigation information, the contact time of nodes on the place can be more accurately estimated by the speed of mobile nodes and the distance between the current position and the location of the places. Such an improvement of the accuracy of the contact time can make the routing protocol more effective in the DTN. To do this, we propose MRCT+LI (Mean Residual Contact Time with Location Information) routing protocol that uses the navigation information. The proposed MRCT+LI routing protocol uses the route and location information to compute the contact time which can decide the message delivery latency. It is expected that navigation information can increase the accuracy of the estimation of MRCT to compute the exact message delivery time.

The operation of MRCT+LI routing protocol is as follows. First, if a node has the route information for a travel destination and the node has the message destination in the route, the node estimates the

message delivery time as the length of the route from the current

position to the message destination divided by the node's speed.

Otherwise, the node estimates the message delivery time from the Eq.

(6.1), where T_{ict} is a contact interval [6]. Note that $E(T_{ict})$ and $E(T_{ict}^2)$ are

calculated from only the history of the past contact.

$$MRCT = \frac{E(T_{ict}^{2})}{2E(T_{ict})}, \quad (6.1)$$

Second, the node exchanges the message delivery time to decide the

forwarding to the other node whenever the node has the contacts to

other nodes. After the node compares the received message delivery

time, the node forwards data to the other node with the lower message

delivery time to the destination.

The detail operation of the forwarding decision algorithm is

explained as follows. When node 1 meets with node 2, node 1 firstly

checks whether node 2 use the valid route information including the

message destination. If node 2 has the message destination in the

route information and node 1 does not have the destination in the

route information, node 1 sends data to node 2. In addition, the proposed method uses the directional information in the forwarding decision. If both node 1 and node 2 do not have the message destination in the route information, node 1 checks whether the direction to the destination is front or not. If node 1 is moving toward the message destination, node 1 never forwards data to node 2 because node 1 can deliver the data to near the message destination without forwarding. Otherwise, node 1 compares the message delivery time with the value of node 2, and node 1 forwards the data to node 2 when node 2 has the lower message delivery time.

6.4. Evaluation

We evaluated the proposed routing protocol in the vehicular DTN
with 802.11b MAC protocol within *ns-2* [7]. Fig. 6.1 shows the grid
topology used in the simulation. There are 25 places that may be
considered as the preference place of mobile nodes and one message
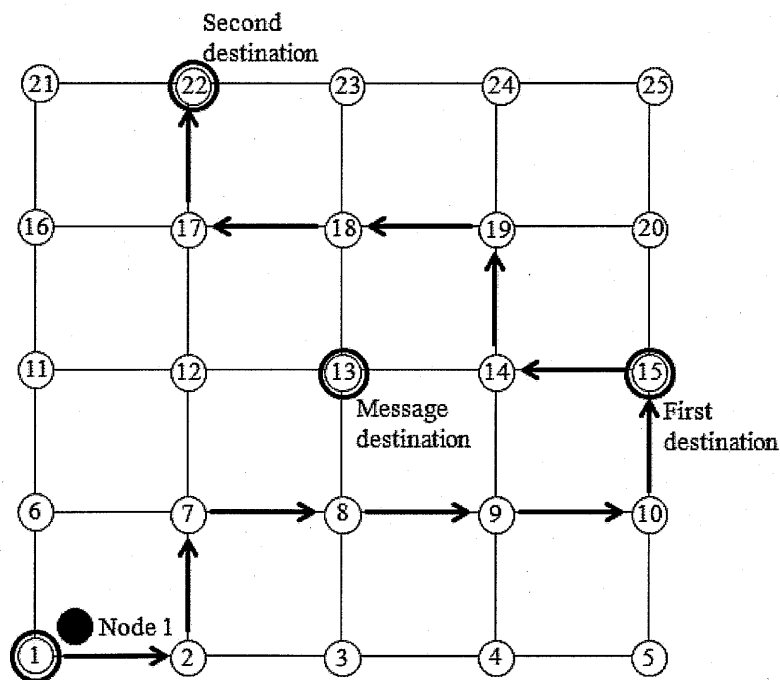destination is located at the center of topology.

Figure 6.1 Topology used in the evaluation.

Each node has some preference places and moves between these

preference places. In the example in Fig. 6.1, node 1 has three preference places (1, 15, and 22), and place 1 is a current staying position of node 1 at a certain time. Before node 1 starts the travel, node 1 selects a place among its preference places except for the current place (places 15 or 22 in this case) as the first destination. Suppose that place 15 is chosen as the destination, node 1 moves toward the destination along the randomly selected route among all shortest routes between places 1 and 15. After node 1 arrives at the first destination (place 15) and stays for a while, node 1 selects the second visiting place as the travel destination from the preference places (1 or 22) and moves toward the destination. In the same manner, all nodes repeatedly visit their preference places during the whole simulation.

In the simulation, we defined two scenarios which can specify the concentration of the route selection for mobile nodes. Table 6.1 shows the list of the parameters of two scenarios. The first simulation explains

the high concentration case of the route selection. In the first scenario,

all nodes join the same group which has two preference places. Every

node decides its own route between two places and the contact of the

route becomes very concentrated. The second simulation gives the

example of low concentration scenario of the route selection by nodes.

There are five groups that use different preference places. Nodes of

each group can move along the low concentrated route. This evaluation

is expected to show the effect of using the route information including

location information in the routing protocol for DTN. The remained

parameters are shown in Table 6.2.

Table 6.1 User preference mobility scenario.

	Concen-tration	Node group	Number of nodes	Preference place
Scenario 1	High	Group 1	10	11, 15
Scenario 2	Low	Group 1	2	1, 25
		Group 2	2	6, 20
		Group 3	2	10, 16
		Group 4	2	11, 15
		Group 5	2	5, 21

Table 6.2 Simulation parameters.

Parameters	Contents
Node movement	User preference mobility
Node speed	15 m/s
Distance between regions	15 km
Mean staying time	1. Preference place: 3000 sec 2. Other place: 300 sec
Distribution of staying time	Exponential distribution
Communication range	30 m
Simulation time	10 days

Fig. 6.2 shows the delivery latency and Fig. 6.3 describes the number of forwarding in two scenarios. We evaluated three routing protocols in both scenario such as Epidemic, MRCT, and MRCT+LI. Epidemic is a simple protocol that forwards data to every contacting node. In the high concentration scenario, all methods show the low delivery latency and the high number of forwarding because the number of contacts among nodes increases when they use the concentrated routes. Epidemic has the lowest delivery latency and the

highest number of forwarding due to the simple flooding scheme. MRCT has the advantage of the lowest number of forwarding compared to other methods. The delivery latency of the proposed MRCT+LI is the almost same as that of Epidemic in the first scenario. Moreover, the number of forwarding of the proposed method is lower than that of Epidemic. The first results show that the proposed method can reduce the delivery latency in high concentration case.
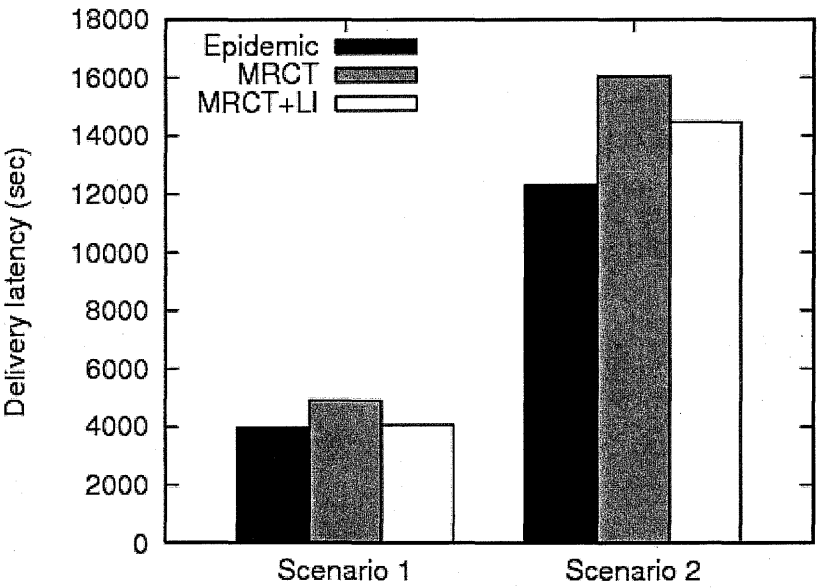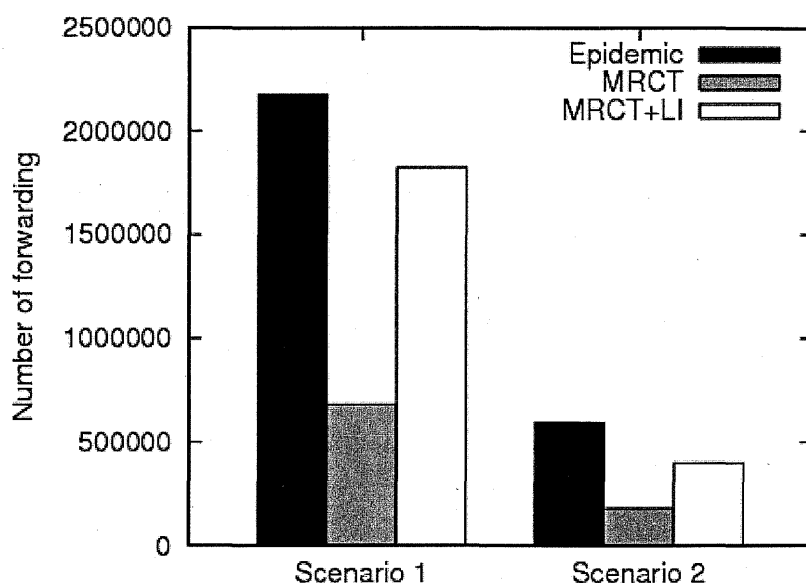

Figure 6.2 Delivery latency.

Figure 6.3 The number of forwarding.

On the other hand, the gap of the delivery latency between MRCT+LI and Epidemic is large in the second scenario although the delivery latency of MRCT+LI is smaller than that of MRCT. The difference is caused by the concentration of the route. The high concentration of the route selection stands for the high possibility that the selected route includes the message destination; therefore, the location information could be more efficient in the high concentration case.

From the simulation result, it has been shown that the route information can increase the performance of routing protocols in DTN.

However, we just introduce the use of the navigation information in the routing protocol of DTN as the simple example. The proposed method is required to consider the diverse viewpoints to adopt the navigation information in DTN.

6.5. Discussion

In this Chapter, we showed the advantage of using the navigation information in the routing protocol of DTN. The proposed MRCT+LI routing protocol uses the route information of mobile nodes with location information. We observed that if a routing protocol is aware of using the more detailed mobility information from navigation, the routing protocol can provide more efficient message delivery service with DTN. In the future work, we consider another metrics to improve the proposed routing protocol like the distance difference of mobile nodes.

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Chapter 7

Conclusions

In this dissertation, we proposed MRCT based routing protocol to cope with the performance degradation due to the variance of contact interval in mobile 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 the 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-$_{BM}$) can realize the high delivery rate unlike Epidemic, Prophet, Prophet-$_{ADV}$, and Nectar. Although Prophet with the buffer management method (Prophet-$_{BM}$) also showed the high delivery rate, Prophet-$_{BM}$ 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-$_{BM}$ kept the low delivery latency and the small number of forwarding without the additional optimization.

Appendix

Let T_{ict} be the contact interval, which is the time from the kth arrival of a mobile node at region C to the $k+1^{th}$ 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

$$\Pr\left(M = m\right) = P_{BA}{}^m \left(1 - P_{BA}\right).$$

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

$$f_{T_{ict}}(t) = \sum_{m=0}^{\infty} \Pr\left(M = m\right) f_{T_{ict,m}}(t).$$

where $f_{Tict,m}(t)$ 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 $f_{Tict,0}(t)$ can be

computed as follows:

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

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 $f_{Tict,m}(t)$ can be computed as follows:

$$f_{T_{ict,m}}(t) = \int_0^t f_{T_{ict,m-1}}(\tau)f_T(t-\tau)d\tau,$$

where $f_T(t)$ is the probability density function of $T_{stay,A} + T_{stay,B} + 2T_{AB}$ and can be computed as

$$f_T(t) = \begin{cases} 0, & t < 2T_{AB}, \\ \int_0^{t-2T_{AB}} f_A(\tau)f_B(t-\tau)d\tau, & t \geq 2T_{AB}, \end{cases}$$

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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Publications by Author

Full paper:

(1) Y-P. Kim, K. Nakano, K. Miyakita, M. Sengoku, and Y-J. Park, "A Routing Protocol for Considering the Time Variant Mobility Model in Delay Tolerant Network," IEICE Trans. Information and Systems, accepted and planned to publish, Feb. 2012.

International conferences:

(1) Y-P. Kim, J-I. Koo, E. Jung, K. Nakano, M. Sengoku, and Y-J. Park, "Composite methods for improving spray and wait routing protocol in delay tolerant networks," Proceedings of ISCIT 2010, pp. 1229-1234, Oct. 2010.

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Domestic conferences and other meetings:

(1) Y-P. Kim, K. Nakano, K. Miyakita, M. Sengoku, and Y-J. Park, "A Consideration of Message Spreading Pattern in Delay Tolerant Network," IEICE Communication Society Conference 2011, Aug. 2011, Hokkaido, pp. S46-47.

(2) Y-P. Kim, K. Nakano, M. Sengoku, and Y-J. Park, "An Experimental Analysis of Intermittent Connectivity in Delay Tolerant Networks," IEICE Communication Society Conference 2010, Sept. 2010, Osaka, pp. S117-118.

(3) Y-P. Kim, K. Nakano, M. Sengoku, and Y-J. Park, "A Simulation Study of Message Delivery in Delay Tolerant Networks, " IEEE ShinEtsu Section Conference 2010, Oct. 2010, Nagaoka, pp.205.