Dynamic Replication and Forwarding Control Based on Node Surroundings in Cooperative Delay-Tolerant Networks

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Abstract—Delay-tolerant networks (DTNs) are a promising network architecture which can provide reliable multi-hop message transmission between participating mobile nodes in an unfavorable environment that is prone to link disruption and disconnection by replicating and relaying messages without any need of physical infrastructure. Additionally, DTNs can also operate as cooperative DTNs to extend the coverage of other type of networks by carrying the messages that originate from farther away base station in a multi-hop fashion to the base station. In this paper, we focus on these cooperative DTNs and propose a novel routing scheme, ring distribution routing (RDR), that controls the replication and forwarding based on the source node surroundings. This paper also analyzes the reliability and buffer efficiency in RDR. Furthermore, we show that RDR provides the reliable and immediate message delivery in any environment through extensive computer simulations.

Index Terms—Delay-tolerant networks (DTNs), routing, replication control, forwarding control

1 Introduction

With the popularization of mobile devices such as smart-phone and tablet computer, it becomes much more important to be able to provide communication services anywhere and anytime. To construct the complete static communication networks such as cellular or satellite networks, it is necessary to place much many communications infrastructures, e.g., base stations, access points or ground stations. However, it is extremely difficult because many areas such as mountain ranges or isolated islands have geographical limitations, which make optimal deployment impossible. Additionally, since constructing infrastructures in developing nations or depopulated areas is not really financially beneficial, service providers tend to have no incentive to invest in those areas. Even in urban areas or developed nations, which have a well planned deployment of infrastructures, service outage is still inevitable due to factors such as natural disasters. Ironically, in such disaster situations, the demand for communication networks greatly increases due to the need of delivering safety confirmation messages or requesting for aids. To resolve these problems, we focus our attention on DTNs [1], [2].

DTNs are used in various networks such as satellite communications [3], vehicular networks [4], [5], [6], sensor networks [7], [8], [9], [10], and are researched actively all over the world. In recent year, some researchers have discussed the way to improve the communication performance of infrastructures in other kinds of networks with DTNs to take its advantage (Cooperative DTNs). However, it has not been enough discussed yet the routing in cooperative DTNs in spite that it is critical for the communication performance of DTNs.

In this paper, we propose a novel routing scheme called RDR. Our proposed routing scheme dynamically controls the replication and forwarding strategies based on each source node surrounding environment. As a result, RDR can achieve reliable and immediate message delivery in comparison with conventional DTN routing schemes. We also analyze the reliability and buffer efficiency of RDR and other conventional DTN routing schemes. Furthermore, we conduct extensive computer simulations to evaluate the performance of RDR. These results show that RDR significantly outperforms conventional DTN routing schemes.

The remainder of this paper is organized as follows. Section 2 introduces the detail of the cooperative DTNs and their challenging issues. Section 3 proposes a novel routing scheme for cooperative DTNs, called RDR. In Section 4, we analyze the reliability and buffer efficiency in RDR. Section 5 conducts extensive computer simulations to evaluate the performance of RDR. Finally, in Section 6, we conclude this paper.

2 Conventional DTNs and Cooperative DTNs

DTNs was originally proposed as an architecture to be used in delivering messages between the planets with satellites where communication links are not always stable. Therefore, DTNs utilize the store-and-forward method where each satellite node stores the messages in its buffer while it cannot communicate with anyone. As a result, DTNs can achieve reliable message delivery in an environment where network

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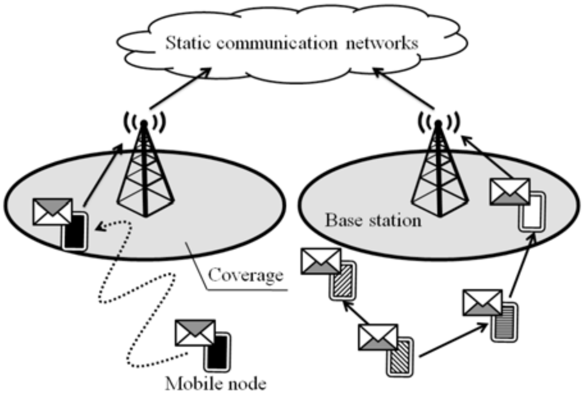


Fig. 1. Message deliveries in the cooperative DTNs.

conditions are not favorable such as when there are frequent occurrence of link disruption. Since DTNs are designed to work in an environment with many link disruptions, DTNs do not gather or make use of the route information. Another core characteristic of DTNs is that nodes replicate the original messages and distribute the replicated messages to improve their reliability. In addition to satellite links, communication between mobile devices are also prone to link instability and disruption. Thus, many researchers are applying DTNs concept to mobile device communications.

One of the well known DTN routing schemes is epidemic routing (ER) [11]. In ER, every node replicates and forwards the messages infinitely. In other words, ER attempts to distribute the created messages to all nodes in the network. Therefore, ER can achieve high reliability, provided that each node has enough buffer space. However, this is unrealistic, because the buffer is usually very limited thus causing nodes operating with ER scheme to drop messages due to buffer overflow. Direct transmission (DT) [12] is another well-known DTN routing scheme. DT is the total opposite to ER, i.e., it never replicates or forwards any messages. In DT, the source nodes carry their messages to the destination nodes by themselves. Therefore, DT rarely has any message losses, but it is difficult to ensure the success of message delivery. In addition to ER and DT, Spray and Wait (SnW) [13] was proposed as a DTN routing scheme that combines the characteristics of both ER and DT. At first, SnW limits the maximum number of replicated messages beforehand. It then limits the maximum hop counts of messages to one, i.e., only source nodes distribute their messages. Therefore, SnW achieves the reliable message delivery and fewer number of message losses simultaneously. On the other hand, SnW poses a problem that a method to specify the maximum number of messages that should be replicated is not defined.

In addition to being able to deliver messages among participating nodes without any physical infrastructure, DTNs can also operate along with other type of networks to improve the overall performance and coverage. This is referred to as cooperative DTNs which is often discussed by many researchers as a mean of virtually extending the coverage of a given network by relaying the message through DTNs. Fig. 1 shows the message delivery in cooperative DTNs to extend the coverage of infrastructures. In other words, when an infrastructure such as a base station is placed in a certain spot, nodes that are outside the communication range of the base station can send their messages to the base station via multi-hop using DTNs. In this work, we show that conventional DTN routing schemes are not ideal in cooperative DTNs because they only consider message delivery among mobile nodes [14].

TABLE 1
A List of Notations Defined and Used in Our Explanations for RDR

Notation	Definition
r	Transmission range of nodes.
d	Distance between a source node and its nearest base station.
$L_{\max}$	Maximum number of replicated messages.
N_{in}	Number of nodes in the transmission range of a source node.
N_{fwd}	Number of forwarded nodes.
$E[r]$	Expectation of the transmission distance between nodes.

Some researchers like [15], [16] attempt to resolve this problem by relaying with message porters, which have bigger buffer and higher mobility than normal nodes. [17] avoids the channel interference by controlling in medium access control (MAC) layer to improve the reliability of message distribution from a base station to nodes. The researches in [18], [19] forward the replicated messages in the direction of an optimal base station to avoid the congestions with GPS information of each mobile node. The authors in [20] propose an intelligent buffer management mechanism to collect information from a larger area in wireless sensor networks using DTNs. In [21], each node decides whether or not to replicate messages based on the received signal strength from the base stations. However, these previous works require frequent information exchanges or complex calculations to improve the reliability of message delivery. Therefore, in this paper, we propose a novel routing scheme that provides reliable message delivery with simple control mechanisms that need only the surrounding information in cooperative DTNs.

3 Ring Distribution Routing

In RDR, each source node controls the maximum number of replicated messages and the number of forwarded nodes in each message. In this section, we give the explanations on the way to calculate these numbers as replication control and forwarding control, respectively. The source and relay nodes distribute the replicated messages in accordance with these two control parameters. As a result, RDR achieves high reliability. In this section, we introduce the concept of RDR. Additionally, we give explanations on deciding two control parameters in RDR. All the notations used in our explanations for RDR are summarized in Table 1.

3.1 The Concept of RDR

In the cooperative DTNs, we assume that the destination of each source node is always a base station. Since base stations are stationary, every node can get the distance between itself and the base stations by using the shared position coordinates of the base stations and its own global positioning system (GPS). However, since the usage of GPS consumes a lot of energy, nodes should avoid using GPS as

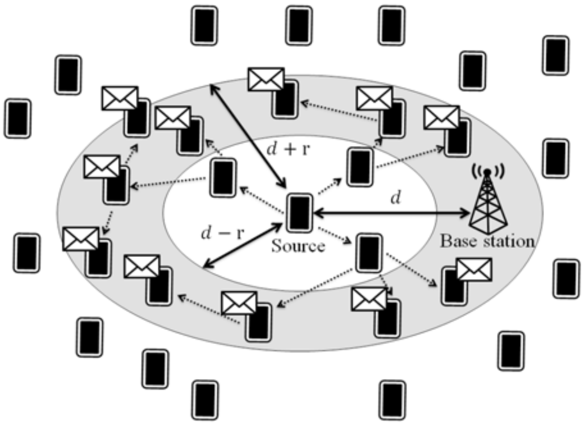


Fig. 2. Distribution of replicated messages in RDR.

much as possible. Therefore, RDR limits the usage of GPS when each node creates the messages. Moreover, RDR aims to achieve the high reliability by reducing the energy consumption to get the distance information when each source node creates a new message.

In RDR, each node does not use the GPS when it forwards messages to other nodes in order to save the energy. Therefore, RDR does not need to forward distance information among nodes. On the other hand, RDR can get the distance between each source node and base stations. By denoting r as the transmission range of nodes, it can be said that the nodes, which are in the circle with the radius of r and the center is a base station, are able to transmit the messages to the base station directly. In fact, it can be said that some nodes being a distance of $\mathbb{D}$ from the source node are at a point where they can transmit the messages to the base station directly. $\mathbb{D}$ denotes the distance between the source node and the nodes that should possess the replicated messages in RDR and it is represented as follows:

$$\mathbb{D} = \{d' \mid d - r \leq d' \leq d + r\}, \tag{1}$$

where d denotes the distance between a source node and its nearest base station. Therefore, RDR attempts to distribute the replicated messages to nodes that are in that ring area as shown in Fig. 2. Each source node in RDR controls the maximum number of replicated messages so that all nodes which are a distance of $\mathbb{D}$ possess the messages. In addition, the source node also controls the number of forwarded nodes for the message. The source node and relay nodes fairly distribute their replicated messages to nodes of the predetermined number by the source nodes. As a result, RDR achieves the ring distribution of replicated messages.

3.2 Replication Control in RDR

In RDR, each node, which is a distance of $\mathbb{D}$ from the source node, possesses one of the replicated messages. Therefore, the maximum number of replicated messages should equal to the number of these nodes which buffered the replicated message. The source node in RDR decides the maximum number of replicated messages, $L_{\max}$, from the area where these nodes exist and the node density. Let S_{ring} be the area where nodes should buffer the replicated messages. These nodes should be a distance of at least $(d - r)$ and at most $(d + r)$. Therefore, S_{ring} is calculated as follows:

$$S_{\text{ring}} = \pi(d + r)^2 - \pi(d - r)^2 = 4\pi rd. \tag{2}$$

Moreover, by putting the number of nodes that are in the transmission range of the source node to N_{in}, the node density, ρ_{est}, can be estimated as follows:

$$\rho_{\text{est}} = \frac{N_{\text{in}} + 1}{\pi r^2}. \tag{3}$$

By multiplying S_{ring} by ρ_{est}, the maximum number of replicated messages is decided from the following equation:

$$L_{\max} = \frac{4d(N_{\text{in}} + 1)}{r}. \tag{4}$$

Provided $d \leq r$, the source node does not replicate its creating message since it can transmit the message to its nearest base station directly.

3.3 Forwarding Control in RDR

In RDR, each source node controls the maximum number of replicated messages as above and the number of forwarded nodes for each created message. Also, by putting N_{fwd} as the number of forwarded nodes, each source and relay node distributes its buffered messages to N_{fwd} nodes fairly. In fact, each node forwards as many replicated messages as each other to every node. And, the nodes that are a distance of $\mathbb{D}$ from the source node reserve one replicated message for itself, and distribute other replicated messages to N_{fwd} nodes fairly. As a result, RDR achieves the ring distribution of replicated messages with very simple control, i.e., decision of number of forwarding replicated messages. In this section, we explain the way to decide the value of N_{fwd}, which is the most important parameter in this forwarding control.

In RDR, the source node distributes the replicated messages to nodes that are a distance of $\mathbb{D}$ away from its nearest base station. Here, let $E[r]$ be the expectation of the transmission distance between two nodes. The unit of hop counts, $\mathbb{H}$, between the source node and nodes that should possess the replicated messages can be represented as follows:

$$\mathbb{H} = \left\{ H \mid H \in \mathbb{I}, \left\lceil \frac{d - r}{E[r]} \right\rceil \leq H \leq \left\lfloor \frac{d + r}{E[r]} \right\rfloor \right\}, \tag{5}$$

where $\mathbb{I}$ denotes the set of natural numbers. Also, by putting the number of all nodes within h hops from a source node to $N(h)$, it is calculated as follows:

$$N(h) = 1 + N_{\text{fwd}} + \cdots + (N_{\text{fwd}})^h = \frac{(N_{\text{fwd}})^{h+1} - 1}{N_{\text{fwd}} - 1}. \tag{6}$$

In RDR, all nodes at $\mathbb{H}$ from the source node have to possess one replicated message, and the number of these nodes is calculated as follows:

$$\begin{aligned} N(\mathbb{H}) &= N\left(\left\lfloor \frac{d + r}{E[r]} \right\rfloor\right) - N\left(\left\lceil \frac{d - r}{E[r]} \right\rceil - 1\right) \\ &= \frac{(N_{\text{fwd}})^{\lfloor \frac{d+r}{E[r]} \rfloor + 1} - (N_{\text{fwd}})^{\lceil \frac{d-r}{E[r]} \rceil}}{N_{\text{fwd}} - 1}. \end{aligned} \tag{7}$$

$N(\mathbb{H})$ should be same with $L_{\max}$. Therefore, we can get the optimal N_{fwd} from (4) and (7).

TABLE 2
A List of Notations Defined and Used in Our Analysis

Notation	Definition
W	Maximum number of walks for a message in DT.
CA	Area of the coverage of the nearest base station for a source node.
ρ	Node density.
$N_{\rm in}(x, y)$	Number of nodes in the transmission range of a source node at (x,y).
S	All over the network.
$t_{\rm ttl}$	TTL.
$t_{\rm create}$	Interval of message creation.
N	Number of all nodes in the network.

As above, in RDR, the source nodes control the maximum number of replicated messages, $L_{\max}$, and the number of forwarded nodes, $N_{\rm fwd}$, by simple calculation with consideration for their surroundings, especially the distance between them and their nearest base stations. In addition, RDR achieves the ring distribution of replicated messages from the source and relay nodes forwarding in accordance with $L_{\max}$ and $N_{\rm fwd}$. As a result, RDR can provide reliable message delivery by mitigating the increase of energy consumption for usage of GPS.

4 Message Delivery Reliability and Buffer Efficiency in RDR

In this section, we analyze the message delivery ratio and the buffering ratio as the reliability and buffer efficiency, respectively. The message delivery ratio is a rate between the number of created and delivered messages. The range of message delivery ratio is from zero to one, and the value close to one represents the high reliability. The buffering ratio is a rate between the number of original messages existing in the network and the average number of buffered messages per node. The range of buffering ratio is also zero to one, and the value close to one represents to be easy to cause the message drops by the buffer overflow. To adopt any network environment, DTN routing schemes have to achieve high message delivery ratio and low buffering ratio simultaneously. Through these analyses, we show the validity of RDR. The notations summarized in Table 1 and 2 are used in our analysis.

4.1 Analysis of Message Delivery Ratio in RDR

In RDR, $L_{\max}$ nodes that are a distance of $\mathbb{D}$ from the source node possess one replicated message. Since these $L_{\max}$ nodes never forward the message to other nodes except to base stations, we regard them as the nodes utilizing DT. Therefore, we analyze the message delivery ratio in RDR with the one in DT. Actually, we had already analyzed the message delivery ratio of DT in [22]. Let $DR^{\rm dt}(d)$ be the message delivery ratio of a source node that is a distance of d from its nearest base station in DT. In [22], $DR^{\rm dt}(d)$ is calculated by following equations:

$$DR^{\rm dt}(d) = \sum_{k=0}^{W} \int\int_{CA} FP_{[(d,0),(x,y)]}(k)\ dxdy, \tag{8}$$

where W and CA denote the maximum number of walks of the source node and the area of the coverage of its nearest base station. In addition, $FP_{[(d,0),(x,y)]}(k)$ denotes the probability that the source node, which is a distance of d from its nearest base station, enters to the base station's coverage for the first time at k times walk. [22] gives all analyses of the message delivery ratio in DT to the interested readers. From (8), $DR^{\rm dt}(d)$ is a function depending on the distance between the source and destination node.

We can regard $L_{\max}$ nodes in RDR as $L_{\max}$ nodes buffering the same message in DT. Then, the message delivery in RDR is said that one of these nodes in DT succeeds to deliver the message to a base station. Therefore, the message delivery ratio in RDR, $DR^{\rm rdr}(d)$, is calculated as follows:

$$DR^{\rm rdr}(d) = 1 - \prod_{z=0}^{+\infty}\left\{1 - P^1_{\rm exist}(d, \epsilon z)\cdot DR^{\rm dt}(\epsilon z)\right\}, \tag{9}$$

where ϵ denotes a tiny value. And $P^1_{\rm exist}(d, z)$ denotes the probability that one node which possesses one replicated message of the source node being at a distance of d from a base station exists at a distance of z from the base station, and it depends on the node density and node distribution. In Fig. 3, gray zones denote areas where there are nodes buffering one replicated message. Solid and broken lines denote areas where are at a distance of z from base stations. Especially, solid lines show common areas between where there are nodes buffering one replicated message and where are at a distance of z from base stations. By assuming the uniform distribution as the node distribution, we can express $P^1_{\rm exist}(d, z)$ as follows:

$$P^1_{\rm exist}(d, z) = \begin{cases} 2\pi\rho z & (z \le r), \\ 2\rho z(\theta_1 - \theta_2) & (r < z \le 2d - r), \\ 2\rho z\theta_1 & (2d - r < z \le 2d + r), \\ 0 & (2d + r < z), \end{cases} \tag{10}$$

where

$$\theta_1 = \arccos\left(\frac{z^2 - r^2 - 2dr}{2dz}\right), \tag{11}$$

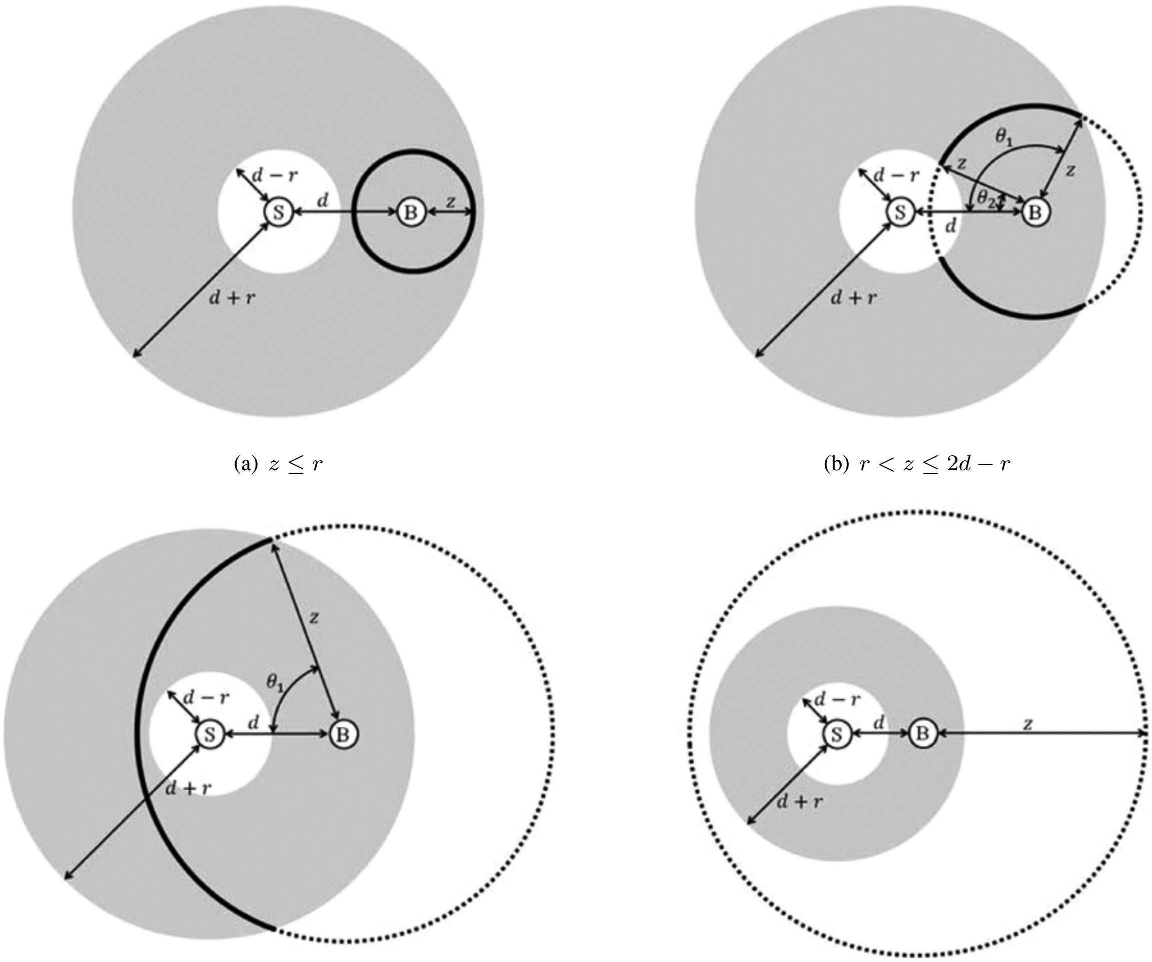
$$\theta_2 = \arccos\left(\frac{z^2 - r^2 + 2dr}{2dz}\right). \tag{12}$$

And ρ denotes the node density all over the network. From these equations, we can get the message delivery ratio in RDR.

4.2 Analysis of Buffering Ratio in RDR

The buffering ratio depends on how many messages are replicated. In RDR, each source node limits the maximum number of replicated messages for their creating messages. And the maximum number of replicated messages is calculated with the node density. In (4), $N_{\rm in}$ is a variable number relying on the node density, so we put $N_{\rm in}(x, y)$ as $N_{\rm in}$ of a source node at (x, y) in this section. Then, by putting $P^2_{\rm exist}(x, y)$ as the probability that one node exists at (x, y), the expected number of replicated messages, $M_{\rm e}$, distributed a source node in a time it creates a new message is calculated as follows:

$$M_{\rm e} = \int\int_S \frac{4d(N_{\rm in}(x, y) + 1)}{r}\cdot P^2_{\rm exist}(x, y)\ dxdy, \tag{13}$$



(a) $z \leq r$ (b) $r < z \leq 2d - r$

(c) $2d - r < z \leq 2d + r$ (d) $2d + r < z$

Fig. 3. Relationship between the areas where there are nodes buffering a replicated message of a source node that is a distance of d from a base station and where are at a distance of z from it.

where S denotes all over the network. By assuming the uniform distribution as the node distribution, we can get $P^2_{\text{exist}}(x, y)$ as follows:

$$P^2_{\text{exist}}(x, y) = \rho \Delta x \Delta y. \tag{14}$$

In DTNs, each message has Time To Live (TTL), let t_{ttl} be TTL. Then, by putting t_{create} as an interval of message creation, the average number of all messages being in the network is expressed as $(M_{\text{e}} \times t_{\text{ttl}}/t_{\text{create}})$. In other words, the number of buffered messages in each node is equal to $(M_{\text{e}}/N \times t_{\text{ttl}}/t_{\text{create}})$, where N denotes the number of all nodes in the network. Since the number of original messages created in each node is $(t_{\text{ttl}}/t_{\text{create}})$, the buffering ratio, BR can be derived by using the following equation,

$$BR = \frac{M_{\text{e}}}{N} = \int \int_S \frac{4\rho d}{r} \cdot \frac{N_{\text{in}}(x, y) + 1}{N} dx dy. \tag{15}$$

4.3 Comparing Theoretical and Simulated Results

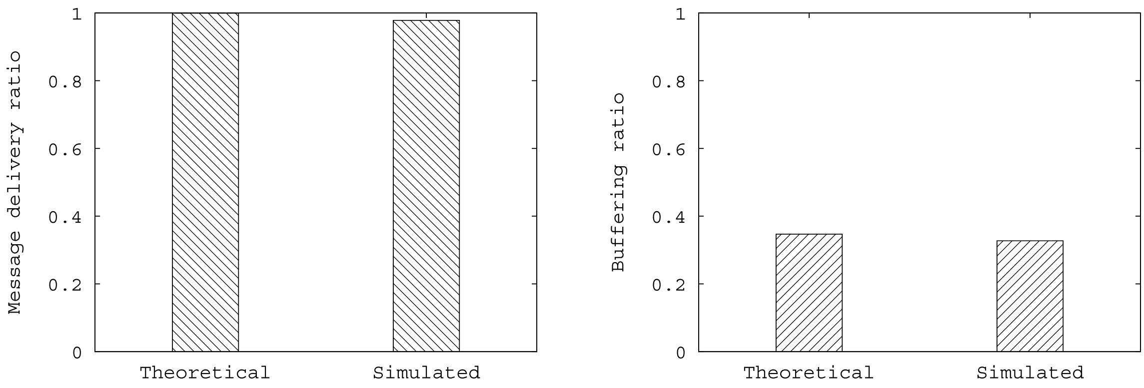
We compare the theoretical and simulated results in terms of the message delivery ratio and the buffering ratio. The simulated results are based on the simulator opportunistic network environment (ONE) [23], [24]. A base station stands at the center of the 1 km square area. We assume the situation that 500 nodes, which have a 100m transmission range, 50 Mbps transmission speed and unlimited buffer, move around following random walk mobility model [25] and exist in uniform distribution. The moving speed and duration are set to 1 m/s and 20 sec, respectively. Also, each node stops walking for 10 seconds before it starts moving again. TTL is set to 1 hour, and messages are created every 30 seconds.

Fig. 4a shows the theoretical and simulated message delivery ratios. As you can see, the simulated result is similar to the theoretical one. In addition, they are much near to 1.0. Fig. 4b shows the theoretical and simulated results in terms of the buffering ratio. The high buffering ratio represents that the messages place a high load on the network, i.e., the buffer of nodes. From Fig. 4b, we can see that the theoretical and simulated results give close agreement with each other, and RDR keeps the buffering ratio to about one-third.

From all the analysis, we can see that RDR achieves high message delivery reliability with saving the loads to the network and avoiding the message drops from the buffer of nodes.

5 Performance Evaluation

We conduct extensive computer simulations to evaluate the performance of RDR in cooperative DTNs using the simulator ONE.



(a) Message delivery ratio (b) Buffering ratio

Fig. 4. Theoretical and simulated results of RDR in unlimited buffer environment.

5.1 Simulation Environments

In this simulation, we attempt to evaluate the message delivery ratio of RDR in cooperative DTNs. Simulation parameters are set to be the same as the parameters in the Section 4.3. Number of nodes and the buffer size are varied in different scenarios. Moreover, additional parameters are added as follows. We estimate the expectation of the transmission distance between nodes to 100 m that is same with the transmission range of nodes. One of all nodes in the network creates a 500 kB message every 30 ± 5 seconds. The buffer size and node density are different every simulation scenario, and the buffer size is limited in our simulation to be closer to the real network. Also, by limiting the buffer size, we can see the effect of buffering ratio to the communication performance. The simulation time is set to 12 hours, and each simulation runs 100 times.

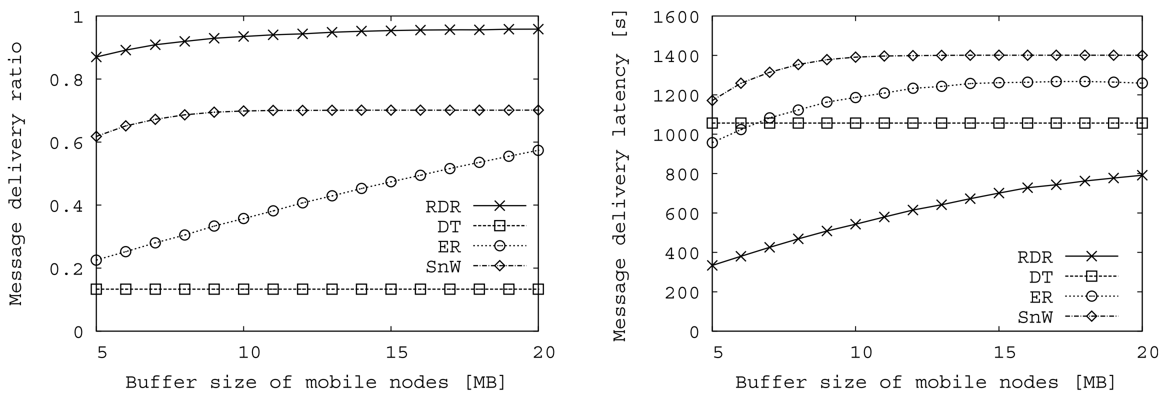
In this performance evaluation, we compare the performance of RDR with that of ER, DT, and SnW. SnW uses the same way as RDR to decide the maximum number of replicated messages since its decision of the number of replicated messages is still not determined. By comparing the performance with SnW, in fact, we can see the effect of the forwarding control in RDR regardless of the replication control. In addition, we evaluate the message delivery ratio and message delivery latency. The message delivery latency is the time required to deliver the message to a base station firstly from the message creation.

5.2 Effects of Buffer Size

At first, we conduct the simulation with varying the buffer size of nodes from 5 to 20MB. The number of nodes is set to 500 in this evaluation. Fig. 5a shows that RDR outperforms other conventional DTN routing schemes in terms of message delivery ratio regardless the buffer size of nodes. Furthermore, the message delivery ratio in RDR becomes close to 1 when the buffer size is 10MB or more. In contrast, DT and SnW stop increasing the message delivery ratios before coming close to 1. The results show that DT and SnW fail to achieve high reliability when the buffer size of nodes is limited. On the other hand, ER can increase the message delivery ratio with increasing the buffer size, but its increase is very gradual. In fact, we need a large buffer size to provide the high reliability in ER. Fig. 5b shows the relationship between the message delivery latency and the buffer size of nodes. From Fig. 5b, we can understand that RDR provides the most immediate message delivery. Therefore, it can be concluded that RDR can achieve reliable and immediate message delivery even with small buffer environment.

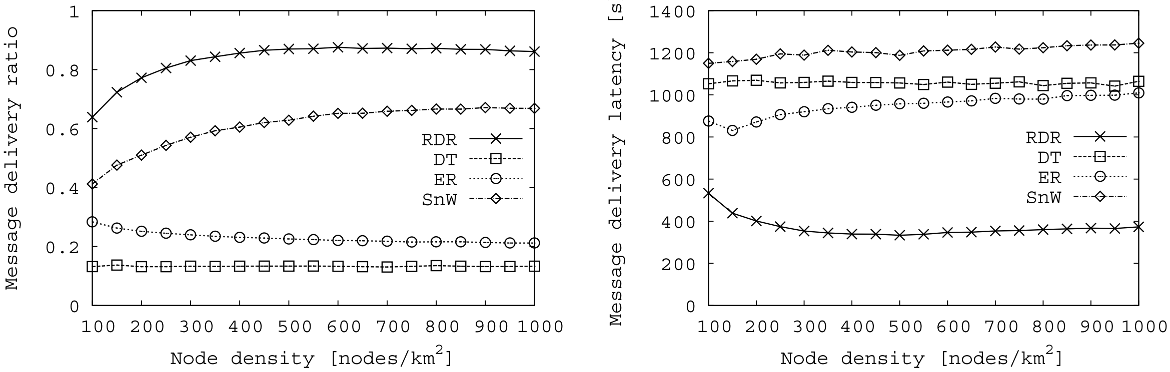
5.3 Effects of Node Density

The number of nodes is varied from 100 to 1,000 nodes/km^2. In this simulation, we set the buffer size to 5MB. Fig. 6a indicates that RDR achieves the highest message delivery ratio with any node density. Particularly, RDR always provides 20 percent higher message delivery ratio than SnW. This result confirms the difference in the forwarding policy



(a) Message delivery ratio (b) Message delivery latency

Fig. 5. Performance comparison against buffer size in limited buffer environment.



(a) Message delivery ratio (b) Message delivery latency

Fig. 6. Performance comparison against node density in limited buffer environment.

between RDR and SnW. On the other hand, since the message delivery ratio in DT depends only on the mobility of source nodes, the node density has no effect on the reliability. In contrast, the message drops in ER easily occur with an increase of node density. This is because the distribution of replicated messages with high node density can cause the congestion. Therefore, DT and ER provide the lower message delivery ratio with any node density when comparing to RDR and SnW. Fig. 6b shows the message delivery latency. As we can see, RDR cut the message delivery latency in more than half in comparison with other DTN routing schemes regardless the node density. Especially, as compared with SnW, the message delivery latency in RDR is cut in from one-quarter to one-third. From both of the graph in Fig. 6, we can see that RDR achieves the high message delivery ratio and the immediate message delivery.

In overall, the simulation results confirm that RDR can provide reliable and immediate message delivery from nodes outside the coverage of base stations because of the efficient distribution of replicated messages in any environment, even when the node density is very low and the buffer of each node is very limited. That is to say, RDR outperforms conventional DTN routing schemes in both urban and rural, and regardless of mobile devices' capacity.

6 Conclusion

In this paper, we proposed a novel DTN routing schemes, called RDR, for cooperative DTNs. In RDR, each source node controls the maximum number of replicated messages and the number of forwarded nodes. In addition, by source and relay nodes distributing the replicated messages based on these two parameters, RDR achieves the ring distribution of replicated messages to provide reliable message delivery. This paper also provides the analyses on the reliability and buffer efficiency in RDR. Furthermore, we conducted extensive computer simulations to evaluate the performance of RDR. These simulation results showed that RDR achieves reliable and immediate message delivery with efficient resource usage in any network environment.

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