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

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

Hiroki Nishiyama, Senior Member, IEEE, Asato Takahashi, Student Member, IEEE, Nei Kato, Fellow, IEEE, Katsuya Nakahira, and Takatoshi Sugiyama, Member, IEEE

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...
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].

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 researchers 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.

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

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

### 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...
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 \( d \) from the source node are at a point where they can transmit the messages to the base station directly. \( d \) denotes the distance between the source node and the nodes that should possess the replicated messages in RDR and it is represented as follows:

\[
\mathbb{D} = \{d \mid d - r \leq d \leq d + r\},
\]

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 node. 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, \( L_{\text{max}} \), from the area where these nodes exist and the node density. Let \( S_{\text{ring}} \) 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, \( S_{\text{ring}} \) is calculated as follows:

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

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

\[
\rho_{\text{est}} = \frac{N_{\text{in}} + 1}{\pi r^2}.
\]

By multiplying \( S_{\text{ring}} \) by \( \rho_{\text{est}} \), the maximum number of replicated messages is decided from the following equation:

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

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 \( N_{\text{fwd}} \) as the number of forwarded nodes, each source and relay node distributes its buffered messages to \( N_{\text{fwd}} \) 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 \( N_{\text{fwd}} \) 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 \( N_{\text{fwd}} \), 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, \( H \), between the source node and nodes that should possess the replicated messages can be represented as follows:

\[
H = \left\{ H \mid H \in \mathbb{I}, \frac{d - r}{E[r]} \leq H \leq \frac{d + r}{E[r]} \right\},
\]

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:

\[
N(h) = 1 + N_{\text{fwd}} + \cdots + (N_{\text{fwd}})^h = \frac{(N_{\text{fwd}})^{h+1} - 1}{N_{\text{fwd}} - 1}.
\]

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

\[
N(H) = N\left(\frac{d + r}{E[r]}\right) - N\left(\frac{d - r}{E[r]}\right) - 1
= \frac{(N_{\text{fwd}})^{\frac{d}{E[r]}} - 1}{N_{\text{fwd}} - 1}.
\]

\( N(H) \) should be same with \( L_{\text{max}} \). Therefore, we can get the optimal \( N_{\text{fwd}} \) from (4) and (7).
As above, in RDR, the source nodes control the maximum number of replicated messages, $L_{\text{max}}$, and the number of forwarded nodes, $N_{\text{fed}}$, 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 $L_{\text{max}}$ and $N_{\text{fed}}$. 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, $L_{\text{max}}$ nodes that are a distance of $d$ from the source node possess one replicated message. Since these $L_{\text{max}}$ 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 $DR_{\text{dt}}^i(d)$ be the message delivery ratio of a source node that is a distance of $d$ from its nearest base station in DT. In [22], $DR_{\text{dt}}^i(d)$ is calculated by following equations:

$$DR_{\text{dt}}^i(d) = \frac{W}{\rho} \int_{CA} \int_{S} FP_{[d,0],(x,y)}(k) \, dx \, dy,$$

where $W$ and $CA$ denote the maximum number of walks of a message in DT. The area of the coverage of the nearest base station for a source node.

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), $DR_{\text{dt}}^i(d)$ is a function depending on the distance between the source and destination node.

We can regard $L_{\text{max}}$ nodes in RDR as $L_{\text{max}}$ 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, $DR_{\text{dr}}^i(d)$, is calculated as follows:

$$DR_{\text{dr}}^i(d) = 1 - \prod_{z=0}^{\infty} \left( 1 - P_{\text{exist}}^1(d, \varepsilon) \cdot DR_{\text{dt}}^i(d) \right),$$

where $\varepsilon$ denotes a tiny value. $P_{\text{exist}}^1(d, z)$ 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 $P_{\text{exist}}^1(d, z)$ as follows:

$$P_{\text{exist}}^1(d, z) = \begin{cases} 2\pi \rho z & (z \leq r), \\ 2\rho z(\theta_1 - \theta_2) & (r < z \leq 2d - r), \\ 2\rho z\theta_1 & (2d - r < z \leq 2d + r), \\ 0 & (2d + r < z), \end{cases}$$

where

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

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

And $\rho$ 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), $N_{i,n}$ is a variable number relying on the node density, so we put $N_{i,n}(x, y)$ as $N_{i,n}$ of a source node at $(x, y)$ in this section. Then, by putting $P_{\text{exist}}^2(x, y)$ as the probability that one node exists at $(x, y)$, the expected number of replicated messages, $M_c$, distributed a source node in a time it creates a new message is calculated as follows:

$$M_c = \int_{S} \int_{CA} \int_{S} \frac{4d(N_{i,n}(x, y) + 1)}{r} \cdot P_{\text{exist}}^2(x, y) \, dx \, dy,$$
where $S$ denotes all over the network. By assuming the uniform distribution as the node distribution, we can get $P(x, y)_{	ext{exist}}$ as follows:

$$P(x, y)_{	ext{exist}} = \rho \Delta x \Delta y.$$  

(14)

In DTNs, each message has Time To Live (TTL), let $t_{\text{ttl}}$ be TTL. Then, by putting $t_{\text{create}}$ as an interval of message creation, the average number of all messages being in the network is expressed as $(M_e \times t_{\text{ttl}}/t_{\text{create}})$. In other words, the number of buffered messages in each node is equal to $(M_e/N \times t_{\text{ttl}}/t_{\text{create}})$, 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,

$$BR = \frac{M_e}{N} = \int \int_{S} \frac{4 \rho \Delta x \Delta y}{r} \cdot \frac{N_{\text{in}}(x, y) + 1}{N} dx dy.$$  

(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.
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 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 20 MB. 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 10 MB 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/km². In this simulation, we set the buffer size to 5 MB. 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.

![Fig. 5. Performance comparison against buffer size in limited buffer environment.](image-url)
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 graphs 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.

References


Hiroki Nishiyama received the MS and PhD degrees in information science from Tohoku University, Sendai, Japan, in 2007 and 2008, respectively. He is currently an associate professor at the Graduate School of Information Sciences, Tohoku University, Japan. He has published more than 100 peer-reviewed papers including many high quality publications in prestigious IEEE journals and conferences. He was awarded Best Paper Awards from many international conferences including IEEE’s flagship events, such as the IEEE Global Communications Conference in 2013 (GLOBECOM’13), GLOBECOM’10, and the IEEE Wireless Communications and Networking Conference in 2012 (WCNC’12). He was also a recipient of the IEEE Communications Society Asia-Pacific Board Outstanding Young Researcher Award 2013, the IEICE Communications Society Academic Encouragement Award 2011, and the 2009 FUNAI Foundation’s Research Incentive Award for Information Technology. He has served as a Co-chair for Cognitive Radio and Networks Symposium of IEEE International Conference on Communications 2015 (ICC’15), a Co-chair for Selected Areas in Communications Symposium of IEEE ICC’14, an associate editor for the IEEE Transactions on Vehicular Technology, an associate editor for Springer Journal of Peer-to-Peer Networking and Applications, and the secretary of IEEE ComSoc Sendai Chapter. His research interests cover a wide range of areas including satellite communications, unmanned aircraft system (UAS) networks, wireless and mobile networks, ad hoc and sensor networks, green networking, and network security. One of his outstanding achievements is Relay-by-Smartphone, which makes it possible to share information among many people by using only WiFi functionality of smartphones. He is a senior member of the IEEE, as well as a member of Institute of Electronics, Information and Communication Engineers (IEICE).

Asato Takahashi received the BE and MS degrees in information science from Tohoku University, Sendai, Japan in 2012 and 2014, respectively. His research interests include delay- and disruption-tolerant networks (DTNs), specifically the combination between DTNs and other infrastructure-based networks. He received the Satellite Communications Research Award from the Institute of Electronics, Information, and Communication Engineers (IEICE) in 2012. He is a student member of the IEEE.

Nei Kato received the bachelor’s degree from Polytechnic University, Tokyo, Japan, in 1986, and the MS and PhD degrees in information engineering from Tohoku University, Sendai, Japan, in 1988 and 1991, respectively. He joined Computer Center of Tohoku University as an assistant professor at 1991, and was promoted to full professor position with the Graduate School of Information Sciences, Tohoku University, in 2003. He became a strategic adviser to the President of Tohoku University since 2013. He has been engaged in research on computer networking, wireless mobile communications, satellite communications, ad hoc & sensor & mesh networks, smart grid, and pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He currently serves as a member-at-Large on the Board of Governors, IEEE Communications Society, the chair of IEEE Ad Hoc & Sensor Networks Technical Committee, the chair of IEEE ComSoc Sendai Chapter, the associate editor-in-chief of IEEE Internet of Things Journal, an area editor of IEEE Transactions on Vehicular Technology, an editor of IEEE Wireless Communications Magazine and IEEE Network Magazine. He has served as the chair of IEEE ComSoc Satellite and Space Communications Technical Committee from 2010 to 2012, the chair of IEICE Satellite Communication Technical Committee from 2011 to 2012, guest-editor of many IEEE transactions/journals/magazines, symposium co-chair of GLOBECOM’07, ICC’10, ICC’11, ICC’12, Vice Chair of IEEE WCNC’10, WCNC’11, ChinaCom’08, ChinaCom’09, Symposium co-chair of GLOBECOM’12, TPC Vice chair of TcC’14, and workshop co-chair of VTC2010. Dr. Kato received the Minoru Ishida Foundation Research Encouragement Prize in 2003. Distinguished Contributions to Satellite Communications Award from the IEEE ComSoc, Satellite and Space Communications Technical Committee in 2005, the FUNAI Information Science Award in 2007, the TELCOM System Technology Award from Foundation for Electrical Communications Diffusion in 2008, the IEICE Network System Research Award in 2009, the IEICE Satellite Communications Prize in 2011. He is a distinguished lecturer of IEEE Communications Society and a co-PI of A3 Foresight Program funded by Japan Society for the Promotion of Sciences (JSPS), NSFC of China, and NRF of Korea. He is a fellow of the IEEE.
Katsuya Nakahira received the BS and MS degrees from Kochi University, Kochi, Japan, in 1989 and 1991, respectively. He received the PhD degree in information science from Tohoku University, Sendai, Japan, in 2012. Since joining NTT Radio Communications Systems Laboratories in 1991, he has been mainly engaged in research on satellite communication network management and the development of satellite earth station equipment. His current interest is channel allocation architecture for mobile satellite communication systems. Presently, he is a senior research engineer in NTT Access Network Service Systems Laboratories. He received the IEICE Technical Committee on Satellite Communication Award in 2011.

Takatoshi Sugiyama received the BE, ME, and PhD degrees from Keio University, Minato, Japan in 1987, 1989, and 1998, respectively. Since joining NTT in 1989, he has been engaged in the research and development of forward error correction, interference compensation, CDMA, modulation-demodulation, and MIMO-OFDM technologies for wireless communication systems such as satellite, wireless ATM, wireless LAN, and cellular systems. From 1988 to 2001, he was in charge of business planning of international satellite communication services in NTT Communications Corporation. From 2004 to 2007, he was in Wireless Laboratories of NTT DoCoMo, Inc., where he worked on research and development of wireless resource management schemes, plug-and-play base stations, and wireless mesh networks. He is currently a senior research engineer, supervisor, and group leader in NTT Access Network Service Systems Laboratories, which is responsible for the research and development of intelligent interference compensation technologies and radio propagation modeling for future mobile and satellite communication systems. He received the Young Engineers Award in 1996 and the Communications Society Best Paper Award in 2011 from the Institute of Electronics, Information and Communication Engineers (IEICE). He is a senior member of the IEICE and a member of the IEEE.

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