Fairness Issue in Message Delivery in Delay- and Disruption-Tolerant Networks for Disaster Areas

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Abstract*—Delay- and Disruption-Tolerant Network (DTN) is a promising solution which allows us to communicate to each other even in disaster areas where a large number of users lose network connectivity due to significant damages on network infrastructures by earthquakes, tsunami, tornadoes, and so on. In DTN where messages are transferred from source nodes to destination nodes through other nodes, the communication performance largely depends on the employed routing scheme which determines the feature of the message distribution over the network. A lot of researchers have dedicated their significant efforts to develop an advanced routing algorithm which is superior in terms of message delivery ratio, message deliver delay, and/or efficiency. However, they have not taken into account a criterion, i.e., the fairness in message delivery, which is much more important for users as a service in disaster areas, where DTN takes a role of the access network conveying messages from a huge number of users to a few base stations connected to external networks. In this paper, we first point out that the fairness issue is critical in disaster areas where many-to-one traffic flow exists; messages originating from users in DTN converge on the gateway. Then the performance of existing routing algorithms is evaluated through extensive computer simulations in terms of the fairness in message delivery as well as traditional criteria. The results of performance comparison show that no routing algorithm can achieve the fair message delivery ratio, and the development of advanced routing algorithm is now still an open issue.

***Index Terms*—Delay- and Disruption-Tolerant Network (DTN), relay, routing, and fairness in message delivery.**

I. Introduction

Catastrophic earthquake and tsunami struck in Japan on Mar. 11th, 2011. In disaster areas, most network infrastructures are damaged, and a huge number of people, who ardently desire to be connected with the outside by means of communication devices such as smart-phones, lose the network connectivity. Only the people within coverage areas of base stations working still are able to communicate with others.

As a solution to provide users with being outside of coverage areas with network accessibility by using only users' mobile terminals, Delay- and Disruption-Tolerant Network (DTN) [1], [2] has attracted much attention. In DTN, each mobile terminal acts as not only a source or a destination node but also a relay node transferring messages from and to neighboring nodes. Therefore, it becomes possible to deliver messages to a base station even from outside of its coverage. However, in general, DTN cannot ensure successful end-to-end message deliveries because message transmissions just relay on the users' mobility which is mostly uncontrollable and unpredictable. To tackle this issue, a lot of researches have been especially conducted in routing techniques.

In [3], DTN routing protocols have been categorized into three classes, i.e., replication based, knowledge based, coding based forwarding. The quantitative evaluation of several major routing schemes has been presented in [4]. The utilization of DTN routing techniques with specific conditions, e.g., underwater environments, have been studied in [5]. Thus although many DTN routing protocols have been developed so far, they have assumed only the cases that all nodes evenly move and message flows are randomly distributed. In other words, the performance of DTN routing schemes in disaster areas, where have a fixed base station and messages from users within its coverage as addressed in [6]-[8], has not been well studied yet.

In this paper, we focus on the performance of the many-to-one communication deployed DTN in disaster areas (Fig. 1), i.e., the message convergence from a large number of users to a base station connected to external networks. Here, Fig. 2 shows the result of a simple experiment considering disaster areas, where every node employing Epidemic Routing [9], which is one of the most famous routing algorithms in DTN, transfers messages to the same base station. We can find that the number of delivered messages differs among users. Thus, it is pointed out that the fairness in successful message delivery is a significant issue. Actually, as deeply discussed later with the performance comparison of existing DTN routing algorithms, the development of an appropriate routing scheme for disaster areas is the challenging issue.

The remainder of this paper is as follows. Section II introduces several major DTN routing schemes, and describes the feature of each of them. In Section III, we first present results of the performance comparison conducted through computer simulations, and then also discuss their performance in terms of the fairness in message delivery. Finally, we conclude our work in Section IV.

II. DTN routings and fairness issue

In this section, we introduce some famous routing schemes in DTN. DTN routings are classified as forwarding-based or replication-based routing by whether or not there are copies of

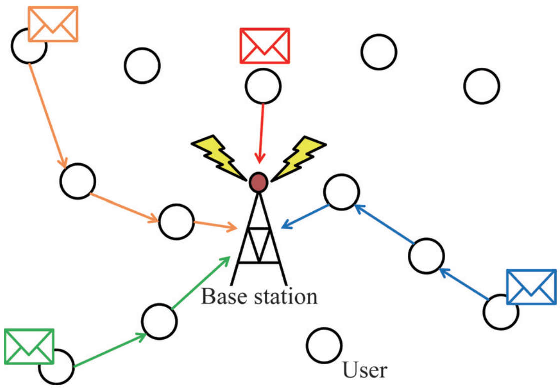

Fig. 1. An example of many-to-one communication

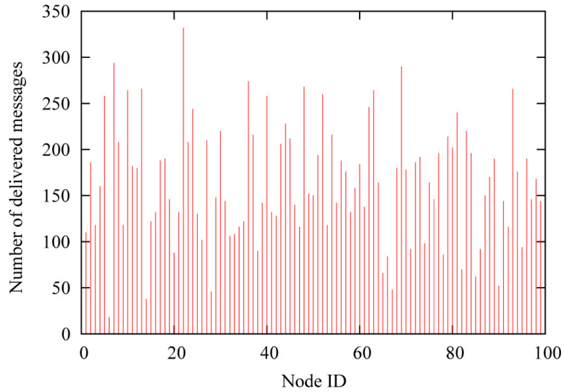

Fig. 2. The number of delivered messages for each node

the original messages [10]. Forwarding-based routing does not allow all users to replicate original messages. As a result, it can curb the consumption of network resources, such as energy and buffer, because it flows only a few messages into the network. Direct Delivery [11] and First Contact [12] are typical routing schemes categorized as forwarding-based routing. On the other hand, in replication-based routing, there is the replication of original messages. Now therefore, the redundancy of each original message increases, and users can achieve the high delivery ratio. Replication-based routing includes Epidemic Routing, Spray and Wait (SnW) [13], Binary Spray and Wait (BSW) [13], and Probabilistic Routing Protocol using History Encounter and Transitivity (PROPHET) [14]. We describe those categories and introduce routing schemes which are categorized into each class below.

A. DTN routings

1) Direct Delivery: Direct Delivery is classified as forwarding-based routing. Source nodes employing Direct Delivery can transfer their messages only to their destination nodes. Direct Delivery is the most resource-efficient routing scheme in all DTN routings because its number of message transfers is the least by not replicating and relaying.

2) First Contact: First Contact is classified as forwarding-based routing. When a node employing First Contact has messages, this node transfers messages to another node which does not have them. In First Contact, the count of forwarding is big because each node relays the next hop node continuously. Frequent forwarding may make users' devices waste electric power. However, it is insusceptible to the mobility of users are lower than Direct Delivery.

3) Epidemic Routing: Epidemic Routing is classified as replication-based routing. In Epidemic Routing, every node distributes replicated messages with no limits. In other words, all nodes forward their stored messages to every meeting node. Epidemic Routing is the most redundant in all DTN routings. In the research field of DTN, it is supposed that the delivery ratio becomes high by providing the high redundancy. So, it is thought to achieve the high delivery ratio. However, there is a fear that the considerable messages which exceed the total buffer capacity of all nodes flood into the network. If the buffer size of each node is small, each node alternates between replicating messages and dropping messages constantly. From those considerations, we can conclude that the performance of Epidemic Routing differs greatly depending on the network capacity, especially the relationship between users' buffer size and message size.

4) SnW: SnW is classified as replication-based routing. In SnW, there is a limitation of the replicas of each original message, and the limited number of replicas is L. L is a constant value and it is same at every node. SnW has two phases, spray-phase and wait-phase. In the spray-phase, a source node forwards one replica to every meeting node until the number of its replicas equals to (L-1). A source node shifts to the wait-phase when it finishes distributing replicas to other (L-1) relay nodes, and (L-1) relay nodes also do it as soon as receiving a replica from the source node. In the wait-phase, L nodes have one replica each other. Each node having the message is forbidden from forwarding to other nodes except the destination node, like Direct Delivery. SnW increases the redundancy in the spray-phase and reduces idle communications in the wait-phase. In SnW, therefore, it can provide the good delivery ratio and the resource-efficiency at the same time.

5) BSW: BSW derives from SnW. The main difference between SnW and BSW is the distributing policy in the spray-phase. In SnW, a source node transports only one replica to every meeting node. In BSW, on the other hand, every node forwards a replicated message which has the allowed number of replication. At first, the allowed number of replication for a source node is L, same as SnW. If the source node meets another node, the source node gives the right making L/2 replicas and a replicated message together to the meeting node and holds the rest of the right of replicating, L/2. Relay nodes also forward the half of the replication right. If a node is allowed replicating only one message in this repetition, it shifts to the wait-phase identical with the one in SnW. In BSW, source nodes can distribute the replicas of original messages faster than SnW, by giving their rights of replicating to other nodes. Additionally, BSW is also supposed to expand replicated messages widely than SnW.

TABLE I
THE FEATURES OF EXISTING DTN ROUTING SCHEMES

Category	Name of routing	The limited number of replicas	Selection policies of relay nodes
Forwarding-based routing	Direct Delivery	Only one	Not using relay nodes
	First Contact	Only one	A first meeting node
Replication-based routing	Epidemic Routing	Infinite	Every meeting node
	SnW	L (constant number)	Every meeting node (source node) Not using relay nodes (relay nodes)
	BSW	L (constant number)	Every meeting node (nodes having more than one replica limit) Not using relay nodes (nodes having one replica limit)
	PROPHET	Infinite	Every node having higher delivery predictability

6) PROPHET: PROPHET is classified as replication-based routing. In PROPHET, the limits for replication do not exist. Instead, every node selects next hop nodes using the history of the meeting their destination. Every node calculates odds, called delivery predictability, from contact histories of each node. The delivery predictability is increased when a node meets another node, and it is decreased in the case which a node has not met the node for a long time. When a node X having a message contacts another node Y not having the message, node X distributes it to node Y only if node Y has the higher delivery predictability than node X. PROPHET can increase redundancy with infinite replication, and control the frequency of forwarding with the apposite selection of relay nodes than Epidemic Routing.

Table I shows the feature of each DTN routing scheme. The suitability of each routing differs with the network's assumption. Therefore, we run experiments to compare the performance of each routing in disaster areas.

B. Fairness issue

Many-to-one communication in DTN causes a critical issue in terms of fairness. In disaster areas, the destination for each source node is supposed to be a base station connected to external networks. On the other hand, whether messages can be delivered or not responds to the mobility of nodes. Therefore, the delivery ratio varies according to the distance between a source node and a base station. In the next section, we also investigate the fairness of each DTN routing that we introduced above.

III. PERFORMANCE EVALUATION

To demonstrate the performance of DTN in a disaster scenario, we picked up six typical routing algorithms, i.e., Direct Delivery, First Contact, Epidemic Routing, SnW, BSW, and PROPHET, and executed extensive computer simulations by using Opportunistic Network Environment (ONE) [15], [16]. We suppose that five hundred mobile user terminals are distributed in the square field one kilometer on a side, and a base station is located at the center of the field. The transmission range of each mobile terminal is equal to 50m. Every node can transmit its own messages or other nodes' by following the employed routing algorithm. All nodes adopt the same routing scheme, and the destination of all messages is the base station. Random walk model [17] is utilized as the movement model of mobile users, and their moving speeds are set to within the range from 0.5m/s to 1.5m/s. We assume that each mobile user periodically generates a small message because it is supposed that the largest demand in disaster areas is to send out emergency signals and survival information. Actually, in our simulations, the message size and the message generation interval are randomly set to a value within the range [125B, 250B] and [10s, 20s], respectively. The upper bound of the number of message replicas, L, is set to fifty in SnW and BSW. Since the link rate is set to 2Mbps, one second is enough to complete a message transmission between nodes including mobile terminals and the base station. Messages are immediately discarded upon the expiration of Time To Live (TTL) equal to five hours. Simulation time is twelve hours, and the presented results in figures show the average value of more than ten trials.

A. Performance measures

We compare the performance of DTN routing schemes in terms of following aspects.

1) Message delivery ratio: The message delivery ratio is defined as the percentage between the number of messages successfully delivered to the base station and the number of messages sent out to the network. It is preferred that this value becomes closer to one hundred. The higher value implies the more reliable network.

2) Message delivery delay: The message delivery delay is calculated by averaging the time that successfully transmitted messages take to reach the base station. This value should be small as much as possible.

3) Transmission overhead: The transmission overhead can be quantified as the message transmission times between mobile terminals divided by that from a mobile terminal to the base station. A value being closer to zero indicates the more efficient message delivery.

B. Simulation results

We first discuss the fundamental performance of DTN routing algorithms. Simulations have been conducted changing the value of buffer size installed on each mobile terminal from 1kB to 10kB.

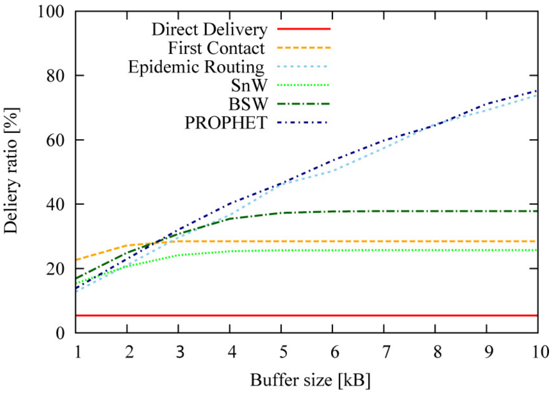

Fig. 3. Comparison in message delivery ratio

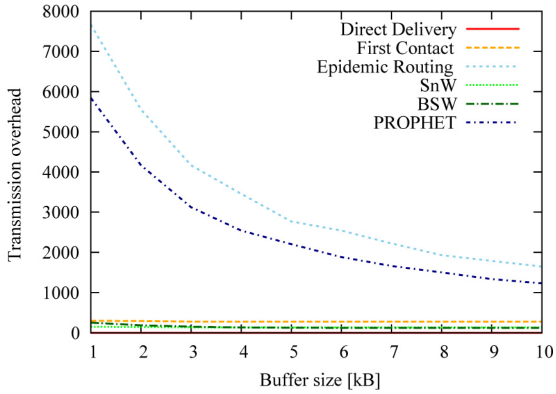

Fig. 5. Comparison in transmission overhead

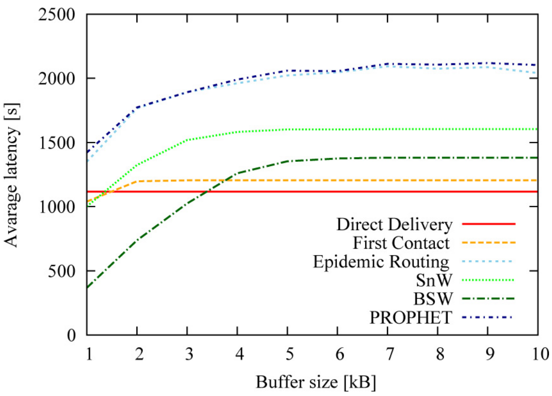

Fig. 4. Comparison in message delivery delay

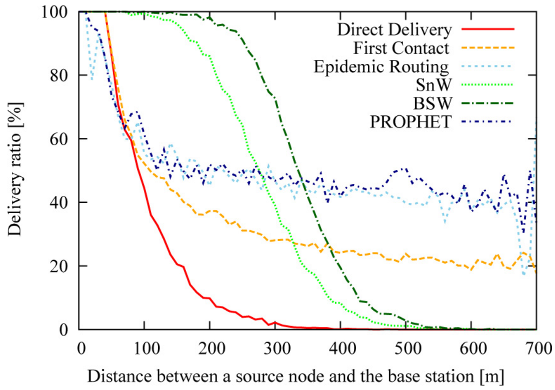

Fig. 6. Delivery ratios of message generated at different locations

Fig. 3 shows the message delivery ratio as a function of the buffer size. It is evident that the message delivery ratio of Direct Delivery is quite low and never affected by the buffer size. This is because Direct Delivery allows only direct message transmissions from a source node to the base station. In other words, its performance only depends on the mobility of mobile users. On the other hand, First Contact, SnW, and BSW can improve the message delivery ratio with increasing the buffer size but it is saturated as the buffer size becomes larger. In these routing algorithms which limit the number of replicas of each message, larger buffer has no effect on increasing the message delivery ratio, rather it is useless and wastes resources. In contrast to the above four routing algorithms, Epidemic Routing and PROPHET are able to increase the message delivery ratio in proportion to the size of buffer by having no limitation in the number of replicas. A higher message delivery ratio can be achieved by efficiently utilizing buffer capacities.

We can see from Fig. 4 that the message delivery delay represents the similar change for different buffer sizes as in the message delivery ratio in Direct Delivery, First Contact, SnW and BSW. By comparing First Contact, SnW, and BSW, it can be observed that SnW relatively presents the poor performance in both the message delivery ratio and the message delivery delay, i.e., the lowest delivery ratio and the largest delivery delay.

Fig. 5 shows the transmission overhead as a function of buffer size. We can find that Epidemic Routing and PROPHET have too higher transmission overhead because they create a lot of replicas without regulation. In other words, they can successfully deliver many messages with the price of this redundancy, and the larger buffer size contributes to improve the transmission efficiency. On the other hand, other routing algorithms except the above two schemes are not affected by the size of buffer because they limit the number of replicas. Since Direct Delivery, SnW, and BSW also limit the number of transmissions, their transmission overheads are lower than that of First Contact.

Next, we focus on the delivery ratio of messages generated at different locations. Fig. 6 shows the message delivery ratio as function of the distance between the source node of each message and the base station in the case of the buffer size equal to 5kB. The fairness issue is very important for users, and the message delivery ratio of each user is equal from any position around the base station in the fairness situation. We can find that the delivery ratio of Direct Delivery rapidly decreases as the distance becomes larger than the node's transmission range, i.e., 50m. SnW and BSW show curves similar to Direct Delivery, but they can keep almost the perfect delivery ratio when the distance is less than 200m. In these schemes, the replicas of each message are spread in the spray-

TABLE II
A COMPARISON OF DTN ROUTING SCHEMES

	Delivery ratio	Delivery delay	Transmission overhead	Fairness in delivery ratio
Direct Delivery	Low	Short	Zero	Low
First Contact	Moderate	Short	Low	Moderate
Epidemic Routing	High	Long	High	Moderate
SnW	Moderate	Moderate	Low	Low
BSW	Moderate	Short	Low	Low
PROPHET	High	Long	High	Moderate

phase but only the users' mobility can contribute to deliver the replicas after finishing the distribution of L replicas and entering the wait-phase. Therefore, the further improvement of their performance can be achieved by only increasing the value of . In contrast, the other three routing algorithms, First Contact, Epidemic Routing, and PROPHET which have other message transmission mechanisms, present that even messages generated at areas far from the base station can reach it with a certain probability. Epidemic Routing and PROPHET can relatively achieve the fair message delivery due to their multiple replicas compared with First Contact. However, in these routing algorithms relying on the message redundancy, the message delivery ratio of users around the base station is decreased by buffer overflows caused by the convergence of replicas coming from the entire network.

The performance comparison among six existing DTN routing algorithms is summarized in Table II. It is clear that none of existing routing schemes can achieve the fair message delivery. While SnW and BSW can improve the fairness by increasing the value L if a disaster area is small, its side effect on the transmission overhead and the message delivery ratio must be considered. In only terms of the fairness in the message delivery ratio, Epidemic Routing and PROPHET relatively present better performance. However, how to increase the absolute value of the successful message delivery ratio is still a remaining issue.

IV. CONCLUSION

In our research, we considered DTN with a base station connected to external networks as an emergency network, i.e., disaster areas. In such networks where many-to-one traffic flow from users to the base station is needed, the fairness of the message delivery ratio among users is an important performance metric but it has not been well studied so far. In this paper, we first pointed out the fairness issue in DTN, and then compared the performance of typical DTN routing schemes, Direct Delivery, First Contact, Epidemic Routing, SnW, BSW, and PROPHET, through computer simulations. From our results, it can be concluded that none of existing routing schemes can achieve the fair message delivery in disaster areas, which is still a remaining and challenging issue.

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