Replication Control for Ensuring Reliability of Convergecast Message Delivery in Infrastructure-aided DTNs

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***Abstract*—Hybrid networks constructed from cellular networks and Delay- and Disruption-Tolerant Networks (DTNs) are one of the solutions for providing reliable communications to mobile nodes in base-station-starved areas regardless of node mobility or density. However, no routing scheme in DTNs has considered the adaptation to other networks, i.e., cellular networks. Thus, the reliability of message delivery is dependent on the position relationship between source nodes and base stations. In this paper, we propose an advanced routing scheme that controls the maximum number of replicas according to the distance between the source node and the nearest base station. Furthermore, we show how to decide the maximum number of replica messages for the distance from the base stations by analyzing the message delivery reliability of an existing DTN routing scheme. Additionally, we execute extensive computer simulations to evaluate the performance of our proposed routing scheme. Our results show that our proposed routing scheme keeps the required reliability regardless of the source node location.**

***Keywords*—Delay- and Disruption-Tolerant Networks (DTNs), routing, replication control, base station**

I. Introduction

In recent years, cellular networks are more indispensable to provide various services or applications with the increase in mobile users and types of mobile devices. Thus, base stations need to be placed everywhere to construct complete cellular networks. However, developing countries and depopulated regions might not have a sufficient number of base stations because the profit does not match for communication common carriers. Furthermore, in remote areas such as mountains or isolated islands, it is difficult to place base stations because of geographical problems. Even in urban regions with a sufficient number of base stations, unexpected natural disasters can hinder the operation of these base stations due to their physical damage or loss of power. However, mobile nodes in these base-station-starved areas need communications to get information, confirm their safety, or request help.

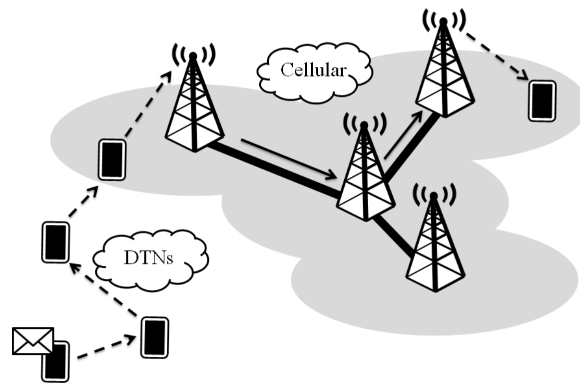

Fig. 1. Hybrid networks composed of cellular networks and DTNs.

Delay- and Disruption-Tolerant Networks (DTNs) [1], [2] have attracted much attention as a solution to achieve the message delivery even in these base-station-starved areas. This technique is used in various networks such as in sensor networks [3], Vehicular Ad-hoc Networks (VANETs) [4], [5], and so on. To the best of our knowledge, hybrid networks composed of cellular networks and DTNs have barely been studied. Furthermore, no routing scheme considers guaranteeing the reliability of message delivery in such networks.

In this paper, we propose an advanced routing scheme, which maintains the reliability in hybrid networks composed of cellular networks and DTNs. Our proposal is based on Spray and Wait (SnW) [6] routing, which limits the number of replicas per message, and controls the maximum number of replica messages according to the distance between the source node and its nearest base station intelligently. In addition, we analyze the optimal value for the maximum number of replicas to ensure the

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reliability of message delivery. Furthermore, we execute extensive simulations to evaluate the reliability of our proposed routing scheme, and the results show that our proposal outperforms the traditional SnW.

The remainder of this paper is organized as follows. In Section II, we first describe the basic concept of DTN and present relevant DTN routing schemes. Additionally, we also introduce several existing works about hybrid networks composed of DTNs and cellular networks. Section III proposes an advanced SnW that controls the maximum number of replicas according to the location relationship between the source node and the nearest base station. Furthermore, we give the optimal maximum number of replicas in the case that nodes behave the random walk by analyzing the message delivery ratio in Section IV. In Section V, we execute extensive computer simulations to evaluate the performance of our proposed routing scheme. Finally, we conclude this paper in Section VI.

II. Adopting DTNs to cellular networks

DTNs are one of the prevalent techniques for composing ad hoc networks, which aim at configuring mobile networks without the need for infrastructure. DTNs are tolerant to not only long delay but also frequent link disruptions, because they employ the store-and-forward method. In the store-and-forward method, nodes store messages in their buffer when they do not have other nodes in their transmission range, and forward their messages when they come into contact with other nodes. Moreover, DTNs improve the delivery reliability by distributing replicas of an original message to many relay nodes. As a result, out of coverage nodes can transmit their messages to base stations using the multi-hop transmissions even if the area has a low node density or a high node mobility. In this section, we survey the existing DTN routing schemes at first. Thereafter, we study the previous works about these hybrid networks composed of cellular networks and DTNs.

A. Traditional routing schemes in DTNs

Epidemic Routing (ER) [7] is the simplest routing scheme in DTNs. Every node replicates each message whenever it meets other nodes. This is the most reliable routing scheme in unconstrained networks, but general networks have some restrictions such as buffer size, battery capacity, and so on. So, ER is likely to cause a lot of message drops and decrease the reliability of message delivery. Therefore, many researchers have studied how to control the message drops for improving the message delivery reliability.

The next hop selection method is a solution that paid much research attention for adapting to the real networks in DTNs. Probabilistic Routing Protocol using History Encounter and Transitivity (PROPHET) [8] is the most famous routing scheme with the intelligent next hop selection. In PROPHET, each node determines the probabilities of successful delivery to each node in the network. This probability is referred as delivery predictability, and it is used to choose next hop nodes. When node A and another node B contact each other, node A increases the delivery predictability of node B, $DP_{(\mathrm{A,B})}$. Also, node B increases $DP_{(\mathrm{B,A})}$. On the other hand, node A decreases $DP_{(\mathrm{A,B})}$ if it has not been able to communicate with node B for a predetermined amount of time. When node A has a message destined to node C, and it comes into contact with node B, node A compares its delivery predictability to node C, $DP_{(\mathrm{A,C})}$, with that of node B to node C, $DP_{(\mathrm{B,C})}$. If $DP_{(\mathrm{A,C})}$ is less than $DP_{(\mathrm{B,C})}$, node A forwards a replica of the message to node B. Otherwise, node A does not forward a replica to node B when $DP_{(\mathrm{A,C})} > DP_{(\mathrm{B,C})}$,because the probability to come into contact with node C of node B is less than that of node A. By comparing the encounter probability to the destination for a message with the contacted node, PROPHET can reduce unuseful replications. In [9]–[11], nodes calculate the encounter probability by using other formulas, information, or other factors.

The replication control method which limits the number of replicas is another important solution. SnW is the most basic routing scheme with these methods. In SnW, every message is replicated a maximum number of times, L. L is determined by the network administrator so that each node can create up to L replicas per message. When node X creates a message M, node X has a right (replication right) that allows L times replication of the message M. If node X meets another node Y, and has more than one replication right for message M, node X forwards one replica of message M to node Y. With the repetition of this process, node X will end up with only one replication right for message M. At this point, node X will stop distributing replicas until it meets the destination of message M and directly forwards the message to it. Node Y or other relay nodes that have a message M only have a single replication right for the message. They wait until they encounter the destination, so that they transmit the message M to the destination directly, but never distribute it to other relay nodes. Furthermore, SnW has an additional distribution mode, called Binary Spray and Wait (BSW) [6]. Compared with giving a single distribution right to each relay node in SnW, BSW distributes half of the current replication rights to each relay node it encounters. For example, if node X has m replication rights for message M. When node X comes in contact with node Y, node X forwards $m/2$ replication rights and it keeps the remaining replication rights. In BSW, not only source nodes but also immediate nodes can distribute replicas by receiving half of the replication rights. Each node does not stop distributing until the number of the replication rights of message M equals to one. Thereafter, each node possesses the message till it meets the destination.

B. Hybrid networks composed of cellular networks and DTNs

In recent years, hybrid networks composed of cellular networks and DTNs gradually attracted attention [12], [13]. Fig. 2 shows the message delivery by the composed network of DTNs and cellular networks in base-station-starved areas. Mobile nodes in coverage areas transmit their own messages to the base station directly, but mobile nodes out of coverage areas cannot do the same. On the other hand, the mobile nodes, which are out of the coverage area of any base station, attempt to deliver their own messages through relay (i.e., via adjacent nodes). Indeed, for this to happen, one of the relaying nodes must be in the coverage area of a base station. Furthermore, these composed networks can allow every node to deliver messages. However, basic routing schemes for DTNs are not suitable for these networks because they do not consider the usage of available base stations. Thus, some researchers tried to develop new routing schemes for these networks. They often use various environmental parameters. For example, in [14], [15], nodes judge whether the contacted node is suitable to become a next hop or not based on the distances between it and the surrounding base stations, the load balance among these base stations, or node density. The work in [16] utilizes the radio signal strength instead of distance. Also, each node can change its replication policy, i.e., only forwarding or replication, by itself, if it can receive a signal from base stations. In [17], the authors assume that messages can be reliably transmitted to the base station if a node is within the coverage of a base station for a long time. Thus, a node transmits messages to nodes that have a comparatively long sojourn time in the base station's coverage area. The work in [18] changes the Time To Live (TTL) field of each message, which limits the time that a message can be transmitted in the network, according to the position of the node when it creates or receives a message. If a node is closer to a base station than a specific threshold, it will increase the TTL of the messages that are in its buffer. This is because a node sufficiently close to the base station has a high probability of successfully delivering a message to the base station.

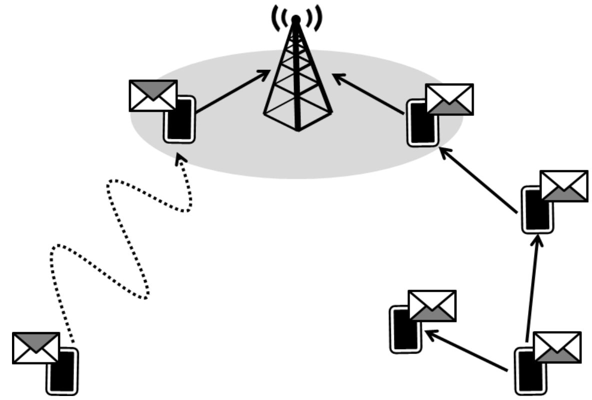


Fig. 2. Message delivery to infrastructures in hybrid networks of cellular networks and DTNs.

These routing schemes can improve the reliability of these hybrid networks by making efficient use of the available environmental parameters from base stations. However, the required time for forwarding cannot be ensured since these routing algorithms conduct calculations and comparisons every time nodes contact other nodes. In addition, these operations consume electrical power. These routing schemes may not be suitable for environments with low node density, high node mobility, and out of coverage areas, especially in disaster areas. Furthermore, the above mentioned routing schemes do not consider the issue that remote nodes are likely to achieve only low delivery reliability. Therefore, we propose an adaptive SnW which controls the maximum number of replicas according to the distance between a source node and the nearest base station to ensure the message delivery reliability regardless of the source node position.

III. A REPLICATION CONTROL METHOD BASED ON THE DISTANCE BETWEEN SOURCE NODES AND BASE STATIONS

To our knowledge, existing replication control routing schemes such as SnW always set the maximum number of replicas to one constant value. However, the optimal maximum number of replicas is different according to various relationships between a source node and the destination node. Therefore, in this section, we propose an adaptive SnW, which produces different values to be used as the number of replicas to each source node by using the distance between the source node and the nearest base station.

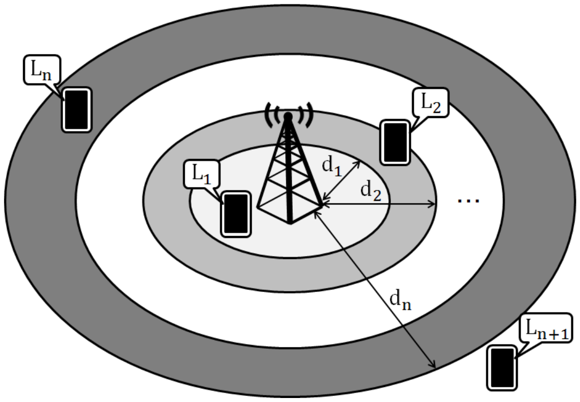


Fig. 3. The concept of the proposed routing scheme.

A. Supposed hybrid networks

Before presenting our proposed routing scheme, we summarize our assumed environment. We consider the communication in the base-station-starved areas. Mobile nodes cannot use the satellite networks because they usually do not have enough radio field strength to communicate with satellites directly. Furthermore, we focus on replication control routing schemes such as SnW. The flooding-based routing schemes such as ER cause a lot of message drops because they assume networks with unlimited resource. Also, during every node contact, the prediction-based routing schemes such as PROPHET consume a considerable amount of electric power because of repetitive (i.e., excessive) computation.

We use the distance between a source node and the nearest base station at a time when the source node creates a message to control the maximum number of replicas. This information is the simplest index to express the relationship between these two points. To calculate the distance between two points, we need the coordinates of the source node and the base station. Each node can determine its location from the Global Positioning System (GPS). However, they cannot obtain base stations' coordinates easily because GPS can only determine the receiver's coordinates. Therefore, in our proposed method, each base station gets its coordinates from the GPS and broadcasts them to all the nodes in the network. Nodes outside the coverage of base stations get their coordinates via multi-hop relaying among nodes in the coverage area of the base station. Since base stations are stationary, this broadcast is needed only once per base station. Therefore, we understand this operation rarely affects in terms of the buffer occupation or the energy consumption.

In the remainder of this section, we introduce our proposed replication control algorithm that decides the maximum number of replicas for a newly created message.

B. Deciding the maximum number of replicas

We describe the proposed replication control algorithm that decides the maximum number of replicas L for each created message according to the distance between the message source node and the nearest base station. At first, it is necessary to decide the set of distance thresholds, $D_{\mathrm{set}} = \{\mathrm{d_1}, \mathrm{d_2}, \cdots, \mathrm{d_n}\}$, and the set of the maximum number of replicas, $L_{\mathrm{set}} = \{\mathrm{L_1}, \mathrm{L_2}, \cdots, \mathrm{L_n}, \mathrm{L_{n+1}}\}$. Here, the distance threshold set is determined by using the following inequality,

$$\mathrm{d_1} < \mathrm{d_2} < \cdots < \mathrm{d_n}. \tag{1}$$

Fig. 3 shows the corresponding relationship between D_{set} and L_{set} in our proposed routing scheme. When a source node creates a new message at a distance d ($\mathrm{d}_{i-1} < d < \mathrm{d}_i$) away from its nearest base station, the source node sets the maximum number of replicas L for the message to L_i. If d is less than $\mathrm{d_1}$, L is set to $\mathrm{L_1}$. And if d is more than $\mathrm{d_n}$, the maximum number of replicas is set to $\mathrm{L_{n+1}}$. The following equation shows the relationship between D_{set} and L_{set} as mentioned above,

$$L = \begin{cases} \mathrm{L_1}, & (d \leq \mathrm{d_1}), \\ \mathrm{L}_i, & (\mathrm{d}_{i-1} < d \leq \mathrm{d}_i), \\ \mathrm{L_{n+1}}, & (d > \mathrm{d_n}). \end{cases} \tag{2}$$

As discussed previously, we can intuitively understand that close nodes need not create a lot of replicas for their messages to deliver these messages to the base station. Also, we know the number of replicas that are necessary for remote nodes to achieve successful deliveries to a base station is more than that required by close nodes. Thus, we determine the elements of L_{set} by using the following inequality,

$$\mathrm{L_1} < \mathrm{L_2} < \cdots < \mathrm{L_n} < \mathrm{L_{n+1}}. \tag{3}$$

By determining the maximum number of replicas as previously mentioned, it is reasonable to incur that our proposed routing scheme can improve the delivery reliability of remote source nodes with ensuring that of close source nodes. As a result, the reliability of the network can be improved.

Our proposed routing scheme is algorithmically presented in Algorithm 1. A source node starts to execute the algorithm when it creates a new message. First, the source node calculates the distance between itself and each base station, and recognizes the distance d_{min} to its nearest base station. After getting d_{min}, the node decides the most appropriate L from (2). Actually, our proposed routing scheme needs to know the optimal maximum

Algorithm 1 Replication control algorithm:

The source node calculates the distance from the nearest base station, $d_{\min}$.
$j \Leftarrow 1$
while $j \leq \mathrm{n}$ **do**
  if $d_{\min} < d_j$ **then**
    $L \Leftarrow \mathrm{L}_j$
    break;
  else if $j = \mathrm{n}$ **then**
    $L \Leftarrow \mathrm{L_n} + 1$
  end if
  $j \Leftarrow j + 1$
end while

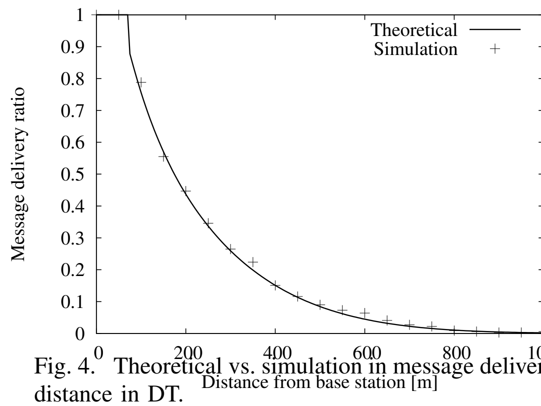


Fig. 4. Theoretical vs. simulation in message delivery ratio as against distance in DT.

number of replicas against the distance for each node mobility pattern. In Section IV, we analyze the optimal relationship between D_{set} and L_{set} by considering the random walk [19], which is one of the most famous mobility models, as the node mobility pattern.

IV. Analysis on the optimal number of replicas for random walk

In this section, we discuss the optimal maximum number of replicas, L_{opt}, for the random walk mobility. To decide L_{opt} given the distance from a base station d, we analyze the relationship between the message delivery ratio and d in Direct Transmission (DT) [20]. DT never replicates messages and forwards to nodes except for the destination node. DT can be regarded as SnW whose L is set to one. Moreover, if the node density is high, the source node finishes distributing L replicas promptly after creating the message because many nodes may exist in the transmission range of the source node. Even if the node density is low, SnW limits the hop counts of forwarding to one hop from the source node. So, we can regard the existence of L relay nodes as that L nodes accompany the source node to the relay points. Therefore, in this analysis, we ignore the phase that each source node distributes the replicated messages in SnW, and regard SnW that set the number of replicas to L can be regarded as DT that L source nodes having the same message exist. Generally speaking, the random walk mobility has the relationship with the normal distribution. The author in [21] analyze the moving probability, $p_{1\text{d}}$, from x_1 to x_2 in the one-dimensional random walk as follows,

$$p_{1\text{d}} = \frac{1}{\sqrt{2\pi N a^2}} \exp\left\{-\frac{x_2^2 - x_1^2}{2Na^2}\right\}, \tag{4}$$

where N and a denote the number of walks and the moving distance during a single walk. Equation (4) is isotropic and we treat the x and y axes equally, so we can develop it to the two-dimensional random walk simply. Let $P_{[S,D]}$ denote the probability that a node moves to the destination point D (with coordinates (x_d, y_d)) from the source point S (having coordinates (x_s, y_s)) after N times of random walk. The value of this probability is calculated as follows,

$$P_{[S,D]}(N) = \frac{1}{\pi N a^2} \exp\left(-\frac{(x_d - x_s)^2 + (y_d - y_s)^2}{Na^2}\right), \tag{5}$$

Now, we regard the message delivery that the source node comes into the coverage of a base station at least once. Thus, we must consider the probability that the source node arrives at the destination point D with never entering the coverage of the base station previously. This probability, $FP_{[S,D]}$, can be calculated as follows,

$$FP_{[S,D]}(N) = P_{[S,D]}(N) - \sum_{k=0}^{N-1} \iint_{CA} F(x,y,k)dxdy, \tag{6}$$

where CA means the coverage area of the base station and $F(x,y,k)$ is indicated by the following equation,

$$F(x,y,k) = FP_{[S,(x,y)]}(k) \cdot P_{[(x,y),D]}(N-k). \tag{7}$$

(7) calculates a probability that a node moves from the source point S to a point (x,y) at the k^{th} random walk and afterwards moves from the point (x,y) to the destination point D at the $(N-k)^{th}$ random walk. Therefore, the second part of (6) describes a probability that a node, who arrives at the destination point D at the N^{th} random walk, has entered the coverage area of the base station more than once before the N^{th} random walk.

Moreover, all points of the coverage area of the base station can become the destination point D. Let the

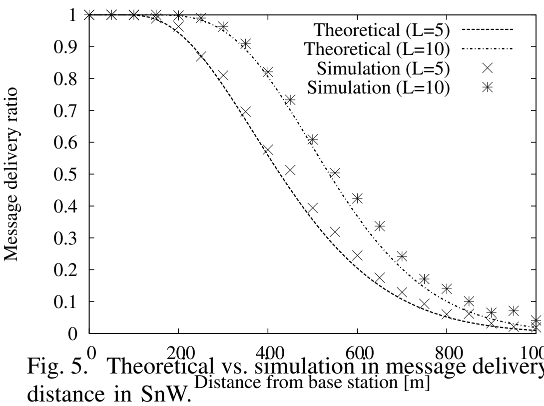


Fig. 5. Theoretical vs. simulation in message delivery ratio as against distance in SnW.

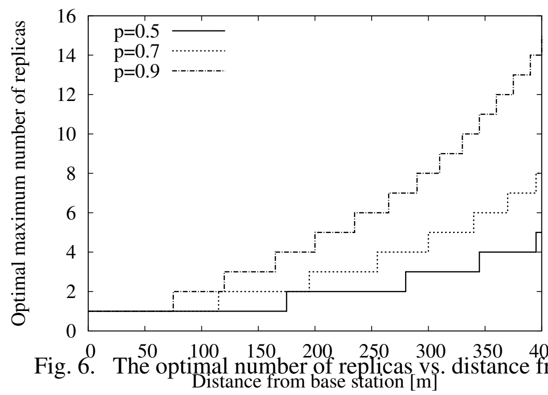


Fig. 6. The optimal number of replicas vs. distance from base station.

message delivery ratio of the source node located at the point S be denoted by $DR_{[S]}$, which is the probability that the source node has come into the coverage of the base station more than once until N times random walks. $DR_{[S]}$ can be expressed as:

$$DR_{[S]}(N) = \sum_{k=0}^{N} \iint_{CA} FP_{[S,(x,y)]}(k)dxdy. \qquad (8)$$

Usually, the TTL for the messages is set to a constant value. Also, when the duration time and wait time for once walk are denoted t_{walk} and t_{wait} respectively, we can calculate the maximum number of walks, $N_{\max}$, as follows,

$$N_{\max} = \frac{\text{TTL}}{t_{\text{walk}} + t_{\text{wait}}}. \qquad (9)$$

Here, since (5) is a symmetric function, the message delivery ratio in DT, DR^{dt}, can be eventually expressed by the following equation as a function of the distance, d, from the base station to the source node,

$$DR^{\text{dt}}(d) = \sum_{k=0}^{N_{\max}} \iint_{CA} FP_{[(d,0),(x,y)]}(k)dxdy. \qquad (10)$$

In order to compare with our theoretical result, we construct a simulation based on C language programing. This simulation measures the probability that a node being at distance d from the base station enters the coverage of the base station more than once in 600 random walks. The node can move 20m at a single walk and the coverage of the base station is a circle, the radius of which is 75m. The line and points in Fig. 4 show the theoretical and simulation results of DT, respectively. We can see that the theoretical result generally matches the simulation result.

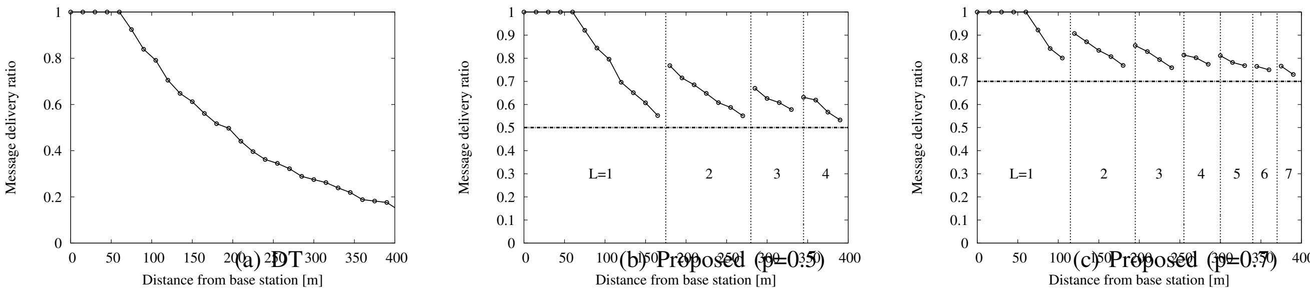
Next, we discuss the message delivery ratio of SnW. In SnW, only the source node is allowed to forward the message to other relay nodes. So, we may assume that the maximum number of replicas in SnW is set to L, that is equivalent to DT with L source nodes per one message. From this consideration, we can simply calculate the message delivery ratio of SnW to use the analysis result in the case of DT as follows,

$$DR^{\text{snw}}(d, L) = 1 - \{1 - DR^{\text{dt}}(d)\}^{L}. \qquad (11)$$

Fig. 5 shows the relationship between the theoretical and simulation results in SnW. We indicate that the cases of L equals 5 and 10. Both theoretical results are quite close to their respective simulation results. Therefore, we can discuss the optimal maximum number of replicas from these analyses. In the ideal environment, which has a sufficient number of users and infinite buffer size, the unlimited replication such as ER is the best routing scheme. However, in the real network environment, the number of nodes and the buffer size are limited. So we define the optimal maximum number of replicas as the minimum value that can achieve the required message delivery ratio, which should be insured regardless of the source node location. Therefore, the optimal maximum number of replicas, L_{opt}, is expressed by the following equation according to the distance d between the source node and the nearest base station:

$$L_{\text{opt}} = \left\lceil \frac{\log(1-p)}{\log\{1 - DR^{\text{dt}}(d)\}} \right\rceil, \qquad (12)$$

where p denotes the required message delivery ratio. Fig. 6 shows the optimal maximum number of replicas according to the distance from the base station in comparison with the required message delivery ratio. We can notice that the farther the source nodes are from the base station, the higher the values of the optimal maximum number of replicas to be set. Moreover, when the required message delivery ratio becomes higher, the change of the optimal maximum number of replicas becomes more exponential.



(a) DT (b) Proposed (p=0.5) (c) Proposed (p=0.7)

Fig. 7. The message delivery ratio vs. the distance from base station.

V. Simulations

We execute extensive computer simulations to evaluate the performance of our proposed routing scheme using the Opportunistic Network Environment (ONE) simulator [22], [23].

A. Simulation settings

Our goal is to ensure the reliability of message delivery in base-station-starved areas. It is worth noting that our simulation uses the default parameters of the ONE simulator that are widely used in the related works. We assume the existence of only one base station at the center of a 1000m $\times$ 1000m square area. In this simulation, we assume each node communicates with other nodes using Wi-Fi, so set transmission range and speed to 75m and 50Mbps, respectively. In fact, most of nodes cannot directly transmit their messages to the base station, and can only use multi-hop communications and their movement to deliver their messages to the base station, i.e., via DTN communications. All nodes move at 1 m/s according to the random walk mobility model, and continue to move for 20 seconds. During moving intervals, the nodes remain stationary for 10 seconds. A single node is selected as the message creator every 25 to 35sec, and it creates a single message with a size set to a value between 500kB to 1MB. Moreover, every node has 10MB as their buffer for messages. And, we employ the First-In-First-Out (FIFO) drop model and TTL is set for five hours. Finally, simulation time is set to 24 hours and we execute each simulation 100 times, and use the average values as results.

We use the message delivery ratio to evaluate the performance of our proposed routing scheme. The message delivery ratio, DR, describes the rate of successful deliveries, i.e., the reliability, and is expressed as:

$$DR = \frac{DM}{CM}, \tag{13}$$

where DM denotes the number of successfully delivered messages and CM denotes the number of created messages. A high message delivery ratio indicates better performance, and its maximum value is one.

B. Simulation results

At first, we execute a simulation to confirm that our proposed routing scheme can achieve the required message delivery ratio with no relation to the distance from the base station. In this simulation, we use 0.5 and 0.7 as the value of required message delivery ratio. We set D_{set} and L_{set} to the appropriate value for each required message delivery ratio from (12) and Fig. 6. Also, the number of nodes is set to one thousand. Fig. 7(a) shows the relationship between the message delivery ratio and the distance from the base station when the source node creates a new message in DT. When the maximum number of replicas is limited, the message delivery ratio decreases with increasing the distance between the source nodes and the base station like Fig. 7(a). Fig. 7(b) and 7(c) shows the one in the case of our proposals that set p to 0.5 and 0.7, respectively. The parallel lines are their required message delivery ratio, and the vertical lines are the distance that our proposed routing scheme changes the value of L based on (12) in these figures. Along with DT, our proposed routing scheme also limits the maximum number of replicas based on the distance from the infrastructure. So, in each blocks divided by L, our proposal monotonically decreases the message delivery ratio according to the distance from the infrastructure. However, unlike DT, the message delivery ratio in our proposal never fall below the value of p in every blocks divided by the value of L. So, it is found that our proposed routing scheme ensures the reliability on demand with no relationship to the source location.

Next, we study the effect of the number of nodes in the network, while keeping the area size fixed to observe the relationship between our performance indexes and the node density. This is essential because a routing scheme

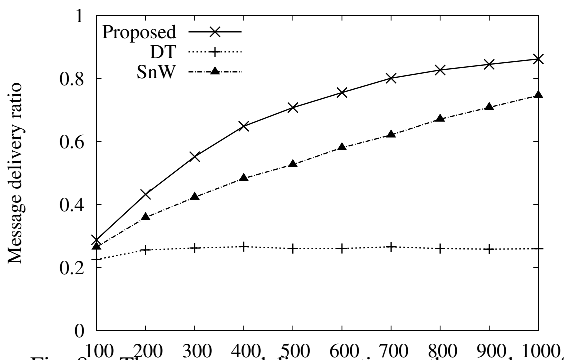


Fig. 8. The message delivery ratio vs. the number of nodes.

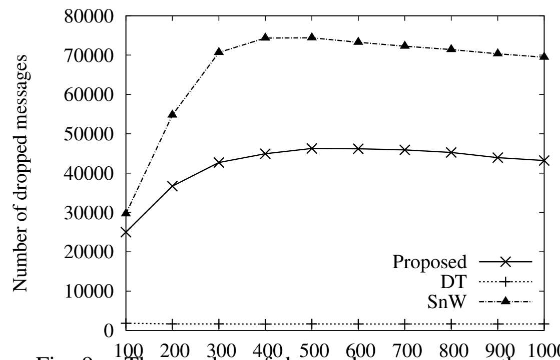


Fig. 9. The number of dropped messages vs. the number of nodes.

should provide high performance in any environment, especially node density. We set D_{set} and L_{set} of our proposed routing scheme to the appropriate values for the case that the required message delivery ratio is set to 0.9. Also we use DT and SnW for comparison. In addition, we set L on SnW to 30, which is the maximum value of our proposed routing scheme in these simulations. Fig. 8 plots the message delivery ratio vs. the number of nodes in the network. From Fig. 8 shows that our proposed routing scheme achieves the higher message delivery ratio than DT and SnW. As discussed previously, we can regard DT as SnW that limits L to one. In our proposed routing scheme, only node close to the base station set one as L. And as can observe from Fig. 7(a), the nodes remote from the base station cannot achieve the high message delivery ratio. Therefore, the message delivery ratio in DT is very low in comparison with SnW and our proposal. In addition, in SnW, we set L to the maximum value that our proposal sets as L. So, the redundancy of messages is higher than our proposed scheme. However, the message delivery in SnW is lower than our proposed routing scheme. This result occurs by the message drops from buffer of mobile nodes. Fig. 9 shows the number of message drops. In SnW, nodes close to the base station replicate their messages more than necessary because it sets L to the enough value to deliver the messages for nodes remote from the base station. As a result, SnW cannot provide the higher message delivery ratio than our proposed routing scheme since it incurs the frequent message drops. On the other hand, our proposal improves the reliability with reduction of message drops to let each source node limit L to bare essential value based on the distance from the base station.

From these simulations, we understand that our proposed routing scheme can maintain the required message delivery ratio, and provide a better message delivery ratio than conventional DTN routing schemes in real base-station-starved areas and hybrid networks.

VI. Conclusion

Hybrid networks composed of cellular networks and DTNs provide reliable communications for nodes in base-station-starved areas which only cellular networks cannot cover completely and mobile nodes have a low density and/or high mobility. Contemporary DTN routing schemes have not considered to ensure a message delivery ratio regardless of each source node location. Therefore, in this paper, we propose an adaptive SnW that controls the maximum number of replicas according to the distance between a source node and its nearest base station. Compared with the existing routing schemes, our proposed routing scheme can improve the message delivery reliability of remote nodes (i.e., avoids the message drops) and also reduce unnecessary replications of nearby nodes without complex calculations and operations. Additionally, it can be adapted to any network according to the network environment parameters. Furthermore, we analyze the message delivery ratio in the random walk for deciding the optimal maximum number of replicas. We evaluate the performance of our proposed adaptive SnW by extensive computer simulations and show that it ensures the required reliability with no relationship with the source node location. In addition, our adaptive SnW improves more than 10% message delivery reliability in comparison with classical SnW. In conclusion, we expect that our proposed routing scheme with replication control can achieve better performance in environments that have a limited coverage area, low node density, and high node mobility.

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