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An Epidemic Broadcasting Mechanism in Delay/Disruption-Tolerant Networks Utilizing Contact Duration Distribution

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***Abstract*—Epidemic broadcasting, in which an infected node repeatedly forwards a copy of a message to other nodes, realizes one-to-many communication in delay/disruption-tolerant networks. In epidemic broadcasting, the key is to control the number of message forwardings among nodes while maintaining a short message delivery time in the network. In this paper, we present a novel idea for improving the performance of epidemic broadcasting: when an infected node encounters a (possibly) susceptible node, the infected node intentionally delays its message forwarding since this may increase the chance of simultaneous transmission to multiple susceptible nodes. On the basis of this idea, we propose HCD-BCAST (History-based Contact Duration aware BroadCAST), which significantly reduces the number of message forwardings. In HCD-BCAST, each node autonomously determines the message forwarding delay based on the contact duration distribution measured by that node. Through simulations, we show that HCD-BCAST achieves a reduction of approximately 10-40% in the number of message forwardings compared with history-based self-adaptive broadcast and k-neighbor broadcast.**

I. Introduction

In recent years, DTNs (Delay/disruption-Tolerant Networks) [1], [2] which realize communication under conditions where continuous end-to-end connection is not guaranteed, have attracted considerable attention. For instance, in MANET (Mobile Ad-hoc NETwork) [3], which is a type of DTN, network links between nodes change frequently due to node movement. Therefore, conventional communication methods for realizing end-to-end network connections cannot be applied to DTNs without being modified [4], [5]. In many DTNs, a message is transmitted by store-and-carry forwarding [6] for one-to-many communication that utilizes the mobility of nodes. Examples of applications of DTNs [7] include conceptual interplanetary communication networks [8], temporary communication networks in disaster-affected areas [9] and sensor network used for observing animals in their natural habitats [10] .

DTNs utilize epidemic broadcasting, where an infected node forwards a copy of a message to other nodes for realizing one-to-many communication. In simple epidemic broadcasting, the number of duplicate messages increases exponentially with time. Therefore, in DTNs, it is critical to suppress duplicate message forwarding while maintaining the necessary time of message delivery.

A conventional approach for reducing the number of message forwardings in epidemic broadcasting is to avoid duplicate message forwarding from a node to other infected nodes. For instance, SA-BCAST (Self-Adaptive BroadCAST) [11] suppresses duplicate message forwarding by exponentially reducing the message forwarding probability according to the number of received duplicate messages. In HP-BCAST (History-based P-BCAST) [12], [13], each node manages its own history of message transmission and suppresses duplicate message forwarding by skipping message forwarding to infected nodes. There is also HSA-BCAST (History-based Self-Adaptive BroadCAST), which uses both adaptive control of transmission probability as found in SA-BCAST and management of message transmission history as found in HP-BCAST. HSA-BCAST can efficiently broadcast messages to the whole network while keeping the number of message forwardings small.

On the other hand, there is a approach to reduce the number of message forwardings by utilizing the characteristics of radio communication and delivering a message to multiple nodes simultaneously. In epidemic broadcasting using radio communication, a certain node broadcasts a message to other nodes within its radio communication range. Radio communication allows for a message to be delivered to multiple nodes simultaneously. Against this background, epidemic broadcasting methods for raising the efficiency of DTNs have been proposed [14], [15]. For instance, in k-neighbor-BCAST [14], a node broadcasts a message only when more than k nodes are within its communication range. A node broadcasts a message only when it detects at least one susceptible node and more than k (susceptible or infected) nodes within its communication range. Therefore, nodes can deliver a message to multiple nodes simultaneously by means of a single message forwarding utilizing the characteristics of radio communication.

An infected node has to wait to forward a message until it is ready to communicate with multiple susceptible nodes simultaneously in order to increase the number of simultaneous transmissions to multiple nodes, but the waiting (delay) lengthens the necessary time of message delivery. Though k-neighbor-BCAST increases the number of simultaneous transmissions, the necessary time of message delivery is sensitive to its control parameter k

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and it is difficult to decide appropriate k. If k is too large value, an infected node continues waiting until it is ready to communicate with k nodes simultaneously, and misses the chance of message forwarding.

In order to increase the number of simultaneous transmissions while maintaining the necessary time of message delivery, an infected node is necessary to assign a suitable message forwarding delay when it encounters a susceptible node. When an infected node encounters a susceptible node, the infected node should not forward its message immediately, but instead should intentionally delay its message forwarding until other susceptible nodes enter its radio communication range since this may increase the chance of simultaneous transmission to multiple susceptible nodes. If the message forwarding delay is too short, the possibility that other susceptible nodes might enter the radio communication range of the infected node becomes low, and we cannot fully utilize the broadcasting characteristics. If the message forwarding delay is too long, however, susceptible nodes that were ready to communicate with the infected node may leave its radio communication range, leading to failed message transmission and consequently lengthening the necessary time of message delivery in epidemic broadcasting. Therefore, it is essential to select an appropriate message forwarding delay that utilizes the characteristics of broadcasting by radio communication while maintaining the necessary time of message delivery.

In this paper, we propose a History-based Contact Duration BroadCAST (HCD-BCAST) mechanism that can significantly reduce the number of message forwardings while maintaining the necessary time of message delivery by intentionally delaying message forwarding on the basis of the contact duration distribution measured by each node. Through simulations, we show that HCD-BCAST achieves a reduction of approximately 10-40% in the number of message forwardings compared with history-based self-adaptive broadcast and k-neighbor broadcast.

The remainder of this paper is organized as follows. Section II explains the idea behind the proposed HCD-BCAST mechanism and the operation of each node. Section III investigates the characteristics of HCD-BCAST and evaluates the effectiveness of the proposed mechanism through simulations.

II. HCD-BCAST (History-based Contact Duration-aware Broadcasting)

A. Idea

We expect that when an infected node encounters a susceptible node, the infected node can forward a message to multiple nodes by means of a single message forwarding if the message is not forwarded immediately but with a certain delay which allows other susceptible nodes to enter the radio communication range.

We show an example in Figure 1. At time $t = 2$, an infected node encounters a susceptible node. When all nodes move, the infected node encounters an additional susceptible node at time $t = 3$. If the infected node forwards a message not at time $t = 2$ but at time $t = 3$, the infected node can transmit a message to two susceptible nodes simultaneously.

When the message forwarding delay is too short, the likelihood that other susceptible nodes will enter the radio communication range of the infected node is low, and infected nodes cannot fully utilize the characteristics of broadcasting by radio communication. If the message forwarding delay is too long, however, susceptible nodes that were originally ready to communicate with the infected node may leave its radio communication range, and message forwarding may become impossible. Therefore, an efficient epidemic broadcasting mechanism must be able to choose an appropriate message forwarding delay that utilizes the characteristics of broadcasting by radio communication while maintaining the necessary time of message delivery.

We consider that the message forwarding delay should be determined by two factors, namely (a) the contact duration distribution of infected and susceptible nodes, and (b) the number of infected nodes around a susceptible node.

By using (a), an infected node can determine the probability that a susceptible node might leave its radio communication range if the infected node delays message forwarding. If we assume that the contact duration distribution is stationary, each node can derive the contact duration distribution by recording the duration of contact with other nodes encountered in the past. Note that the derivation is achieved without an extra communication since nodes are habitually watching nodes within their communication range.

By using (b), an infected node can set a message forwarding delay according to the situation at hand while maintaining high transmission probability to susceptible nodes. When the message forwarding delay is long, an infected node may be unable to forward messages to susceptible nodes because they may leave its radio communication range. However, when there are other infected nodes, the susceptible node may be able to receive a message from these nodes. Hence, we consider that the message forwarding delay should be controlled according to the number of susceptible nodes.

B. Operation

In the proposed HCD-BCAST mechanism, each node measures the distribution of the duration of contact with other nodes, and HCD-BCAST can significantly decrease the number of message forwardings while maintaining a short message delivery time by intentionally delaying message forwarding based on the measured contact duration distribution.

In HCD-BCAST, each node measures its own contact duration distribution, which the node uses to set its message forwarding delay such that the forwarding probability in the cluster becomes a constant. HCD-BCAST manages the history of message transmission by the same method as HP-BCAST. Infected nodes determine their respective message forwarding delays based on their own contact duration distributions and the number of infected nodes around the encountered susceptible node.

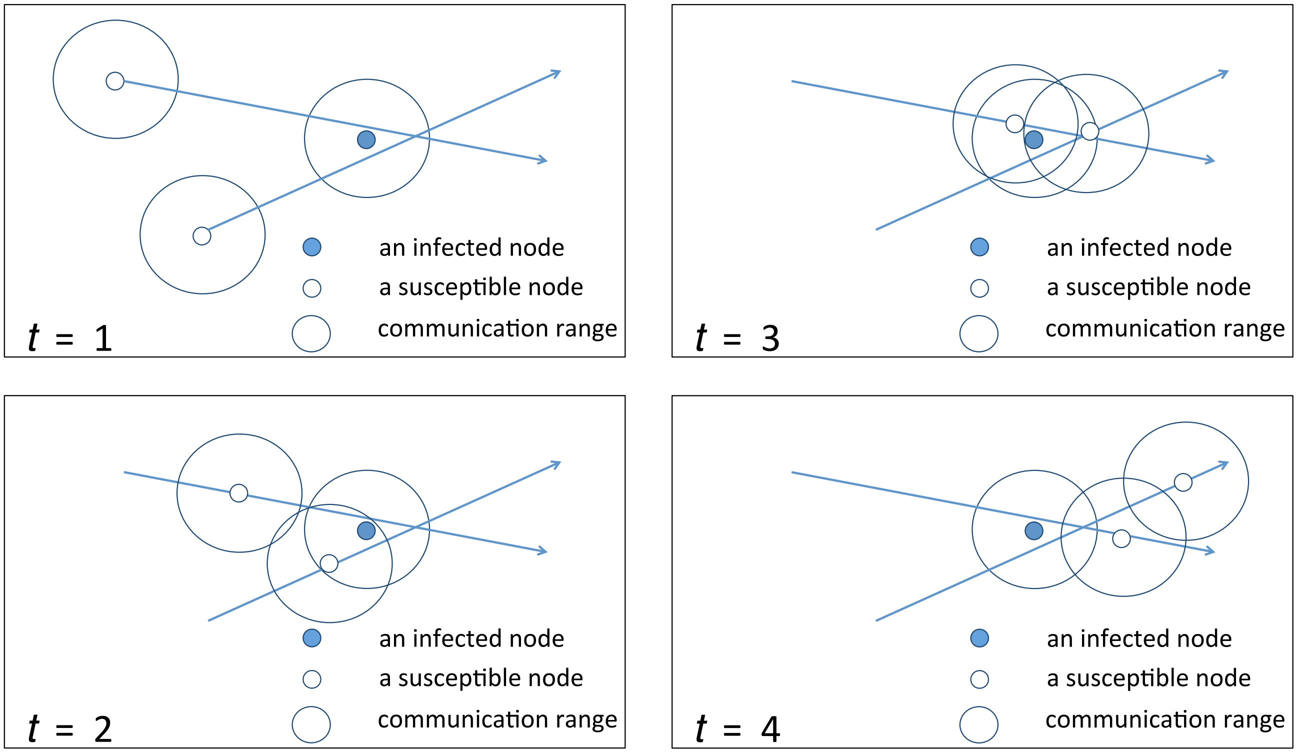

Fig. 1. An example where the characteristics of broadcasting by radio communication are utilized by introducing a message forwarding delay

Below, we explain how HCD-BCAST sets the message forwarding delay.

Here, we assume that there are N infected nodes $I_1 \ldots I_N$ around a new neighbor node S, and that these nodes forward a message with the same probability p. In such a situation, the probability p_{success} that node S receives a message at least once is given by

$$p_{\text{success}} = 1 - (1-p)^N. \tag{1}$$

Therefore, in order to control the probability p_{success} , infected nodes $I_1, \ldots, I_N$ should set their forwarding probability p as follows:

$$p = 1 - (1 - p_{\text{success}})^{1/N}. \tag{2}$$

In this way, infected nodes adjust the message forwarding delay so that the forwarding probability satisfies Eq. (2) with their own contact duration distribution. We let $P(x)$ denote the cumulative distribution function of the measured contact duration distribution, and all nodes $I_1 \ldots I_N$ delay message forwarding for T_S, satisfying the following equation:

$$1 - P(T_S) = p. \tag{3}$$

Namely,

$$\begin{aligned} T_S &= P^{-1}(1-p) \\ &= P^{-1}((1-p_{\text{success}})^{1/N}), \end{aligned} \tag{4}$$

where $P^{-1}(T_S)$ is the inverse function of $P(x)$. The infected nodes delay message forwarding for T_S upon encountering susceptible node S. The infected node forwards a message if node S resides within its radio communication range after T_S has elapsed.

However, the number N of infected nodes around node S is needed in order to determine T_S from Eq. (4). We use $\hat{N}$ to denote the derived number of infected nodes within the radio communication range when an infected node encounters node S.

By following this operation, HCD-BCAST can substantially reduce the number of message forwardings by deliberately delaying message forwarding while maintaining a high success rate of message forwarding to node S from nodes $I_1 \ldots I_N$ with a probability of p_{success}.

p_{success} is a control parameter that adjusts the rapidity of message delivery. A larger value of p_{success} leads to a shorter message forwarding delay, and infected nodes forward messages more often. Note that in the case of $p_{\text{success}} = 1$, HCD-BCAST is equivalent to the HP-BCAST algorithm.

The algorithm of the HCD-BCAST is shown in the pseudocode in Algorithm 1. When a new node S enters into the communication range of an infected node, the infected node sets the message delay T_S if it does not have a record of the transmission history of the new node. $\mathcal{F}_1$ denotes p satisfies Eq. (2), and $\mathcal{F}_2$ denotes T_S satisfies Eq. (4) (lines 2-7). Then, the infected node broadcasts a message to its

Algorithm 1 Pseudocode for the HCD-BCAST algorithm

```
1: while True do
2:   if new neighbor node S then
3:     if there is no history of communication with the
       new neighbor node S then
4:       p ← F_1(p_success, N);
5:       T_S ← F_2(p, P(x));
6:     end if
7:   end if
8:   for all T_S do
9:     if timer T_S expires then
10:      if the node S is still within the range then
11:        Broadcast message to neighbors;
12:        for all T_S do
13:          disable timer T_S
14:        end for
15:      end if
16:    end if
17:  end for
18: end while
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neighbors and disables timer T_S if any T_S expires and the new node S is still within the communication range. (lines 8-17).

III. Simulation

A. Characteristics of HCD-BCAST

We investigated the following characteristics of HCD-BCAST through simple simulations.

1) Accuracy of estimating N, which denotes the number of infected nodes around a susceptible node S
2) Success rate of message transmission from infected node $I_1 \dots I_N$ to susceptible node S
3) The reduction in the number of message forwardings by intentionally delaying message forwarding

First, we investigated the accuracy of estimating N, which denotes the number of infected nodes around a susceptible node S. HCD-BCAST derives $\hat{N}$, which denotes the number of infected nodes at the moment when an infected node encounters susceptible node S. Below, we define N as the number of infected nodes that susceptible node S encounters for an average contact duration T after the encounter between the susceptible node S and an infected node.

In our simulation, 100 nodes moved according to a random waypoint mobility model [16] in a 1000×1000 [m] simulation field. At the initial state, only a single node broadcast a message to all other nodes with HCD-BCAST. The velocity of nodes was uniformly distributed in $[1, 2]$ [m/s]. The radio communication range of nodes was 25, 50 or 75 [m], with an average contact duration T of 20, 38 or 56 [s] respectively.

In our simulation, we measured N and $\hat{N}$ and calculated MAE (Mean Absolute Error) of $\hat{N}$ with respect to N. When the radio communication range was 25, 50 or 75 [m],

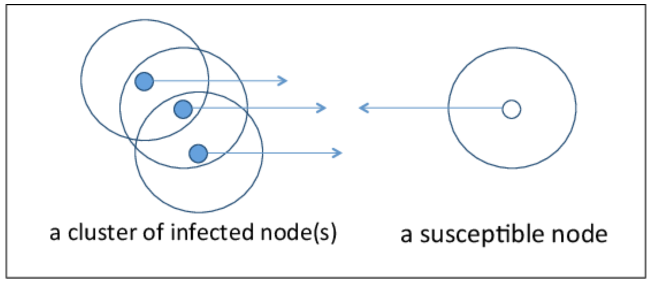

Fig. 2: Simulation model for investigating the success rate of message transmission from infected nodes $I_1 \dots I_N$ to susceptible node S

MAE of N was 0.27, 0.92 and 1.60, and the average of N was 1.35, 2.59 and 4.22. Therefore, we consider that HCD-BCAST achieves a certain level of accuracy in estimating N with increasing communication range.

Next, we investigated the success rate of message transmission from infected nodes $I_1, I_{,2}, \dots, I_N$ to susceptible node S. If HCD-BCAST operates completely as expected, the success rate of message transmission should perfectly correspond to the value of the control parameter p_{success}.

To measure the success rate of message transmission, we carried out the simulation shown in Figure 2. We changed the number of infected nodes in node clusters between 1 and 4, and varied the value of the control parameter p_{success}. We repeated the simulation 30 times with the same conditions and measured the rate at which a susceptible node was able to receive a message upon approaching a cluster of infected nodes. In our simulation, the initial positions of infected nodes were uniformly distributed inside of a circle 50 [m] in diameter, and the radio communication range of all nodes was 50 [m]. we gave these nodes contact duration distribution in advance.

Figure 3 shows the success rate of message transmission when we varied the number of infected nodes between 1 and 4. This result shows that the success rate of message transmission approximately corresponds to the value of control parameter p_{success}. It appears that there is a particularly close correspondence between the success rate of message transmission and p_{success} when the number of infected nodes is small and the value of p_{success} is relatively small .

In contrast, when the number of infected nodes is small and the value of p_{success} is large, the success rate of message transmission is slightly lower than p_{success}. Theoretically, the success rate of message transmission is equal to p_{success} if the durations of contact between each infected node and a susceptible node are independent of each other. However, the contact durations are not independent due to the speed of susceptible nodes. If the speed of susceptible nodes is high, the respective contact durations for all infected nodes are short. Hence, the contact durations are interrelated.

Finally, we investigated the reduction in the number of message forwardings resulting from intentionally delaying

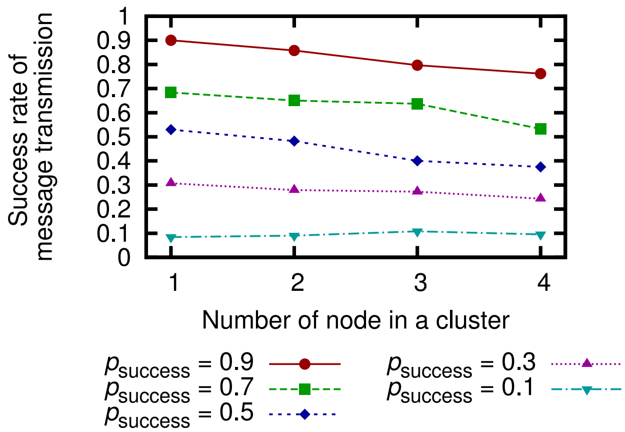

Fig. 3: Relation between the number of infected nodes in a cluster and the success rate of message transmission

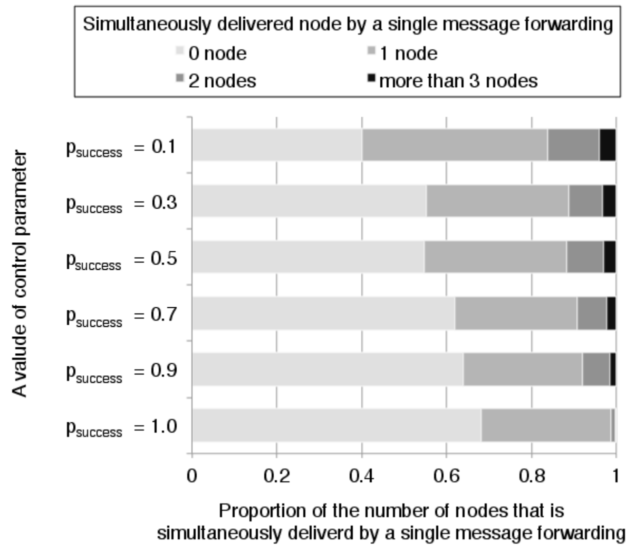

Fig. 4: Ratio of the number of nodes that simultaneously receive a message by means of a single message forwarding when control parameter p_{success} is varied between 0.1 and 1.0

message forwarding. Again, we used the abovementioned simulation setup with 100 nodes moving according to a random waypoint mobility model. We measured how many susceptible nodes were able to receive the message simultaneously by means of a single message forwarding until 90% of all nodes received the message. We repeated the simulation 30 times and calculated the number of nodes that simultaneously received the message.

Figure 4 shows the ratio of the number of nodes that simultaneously received a message by a single message forwarding when p_{success} was varied between 0.1 and 1.0. Note that the legend 0 node represent a message forwarding to an infected node that has already had the message. This result shows that a smaller value of p_{success} increases the chance of infected nodes delivering a message simultaneously to multiple nodes by a single forwarding. Namely, HCD-BCAST can utilize the characteristics of broadcasting when p_{success} is small (i.e., when message forwarding is intentionally delayed).

B. Performance comparison with HSA-BCAST and k-neighbor-BCAST

To verify the effectiveness of the proposed HCD-BCAST mechanism under various conditions, we compared the performance of HCD-BCAST with those of the conventional mechanisms, HSA-BCAST and k-neighbor-BCAST.

We ran the simulation described in Section III-A and measured the total number of message forwardings and the time until 90% of all nodes received the message (90% delivery time). To focus on the characteristics, we assumed that there was no delay in radio communication and all nodes had enough storage to record their respective message transmission histories.

HSA-BCAST and HCD-BCAST judge whether an encounter node is susceptible or infected with message transmission histories. On the other hand, k-neighbor-BCAST judges whether an encounter node is susceptible or infected by querying the node without message transmission histories [14]. In this simulation, to focus on the timing and frequency of message forwardings, we use k-neighbor-BCAST that is incorporated in message transmission histories [12], [13].

In general, the performance of an epidemic broadcasting mechanism is heavily depndent on the choice of control parameters. Therefore, in our simulation, we compare the performances of HCD-BCAST, HSA-BCAST, and k-neighbor-BCAST, under a diverse range of control parameters.

In the simulation, we changed the control parameters N_{th} and c of HSA-BCAST [11], where N_{th} denotes the threshold of the change rate in the number of nodes within the communication range of an infected node used for determining whether the infected node should forward a message. Here, c is a parameter which determines an exponential decay in the forwarding probability according to the number of duplicate messages received by other nodes.

Similarly, we changed the control parameter k of k-neighbor-BCAST [14], where k denotes the threshold of the number of nodes within the communication range used for determining whether to broadcast a message. An infected node broadcasts a message only when it detects more than k nodes within its communication range. An infected node broadcasts a message only when it detects at least one susceptible node and more than k (susceptible or infected) nodes within its communication range.

We show the 90% delivery time and the total number of message forwardings for a field size of 1000×1000 [m] and a communication range of 50 [m] in Figure 5. In epidemic broadcasting, there is a trade-off between rapidity

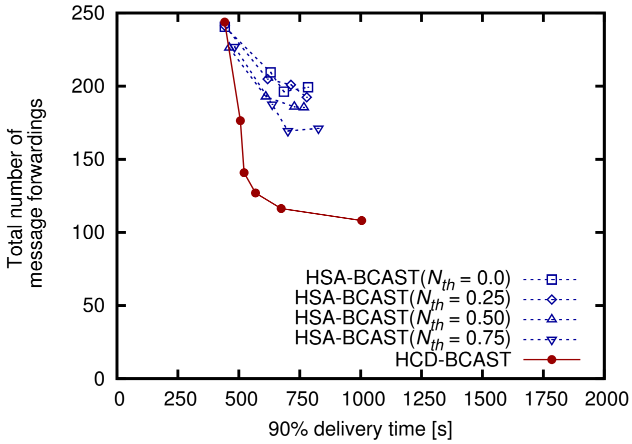

Fig. 5: Relation between 90% delivery time and total number of message forwardings for a field size of 1000×1000 [m] and a radio communication range of 50 [m] (HSA-BCAST vs. HCD-BCAST)

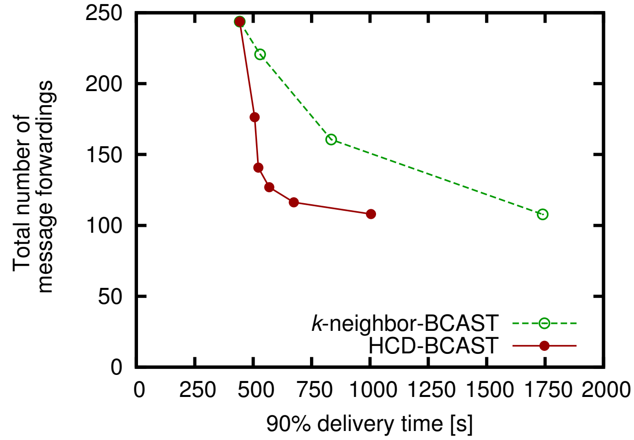

Fig. 6: Relation between 90% delivery time and total number of message forwardings for a field size of 1000×1000 [m] and a radio communication range of 50 [m] (k-neighbor-BCAST vs. HCD-BCAST)

and efficiency of message delivery. Therefore, in the figure, when the curve describing the changes in the control parameters is closer to the lower left corner of the graph, it indicates better performance of the corresponding epidemic broadcasting mechanism.

Figures 5 and 6 show that HCD-BCAST realizes a rate of message delivery equivalent to that of HSA-BCAST and k-neighbor-BCAST by means of a small number of message forwardings. HCD-BCAST achieves a reduction of approximately 10-40% in the number of message forwardings compared to HSA-BCAST and k-neighbor-BCAST. The points for HCD-BCAST in the figure correspond to the results for $p_{\text{success}} = 1, 0.9, 0.7, 0.5, 0.3$ and 0.1. Similarly, the points for HSA-BCAST in the figure correspond to the results for $c = 1$, 2, 4 and 8. The points for k-neighbor-BCAST in the figure correspond to the results for $k = 1$, 2 and 3. On the left of the graph, the points for HCD-BCAST, HSA-BCAST and k-neighbor-BCAST overlap because these points respectively represent the results for $p_{\text{success}} = 1$, $c = 1$ and $k = 1$; in other words, these parameters do not control the message forwarding as they do in HP-BCAST.

We compared the performance of HCD-BCAST with that of HSA-BCAST in detail. To verify the effectiveness of HCD-BCAST under various conditions, we simulated HCD-BCAST and HSA-BCAST for different radio communication ranges and node densities in the field.

We investigated the impact of the communication range through simulations for various numbers of nodes. Figure 7 shows the relation between 90% delivery time and the total number of message forwardings for a field size of 1000×1000 [m] and a radio communication range of 25, 50 and 75 [m]. We set the parameter N_{th} of HSA-BCAST to 0.75 because at this value HSA-BCAST showed the most favorable characteristics .

In Figure 7, all curves for HCD-BCAST are located below and to the left of those for HSA-BCAST. This indicates that the performance of HCD-BCAST is higher than that of HSA-BCAST regardless of the radio communication range (see Fig. 7).

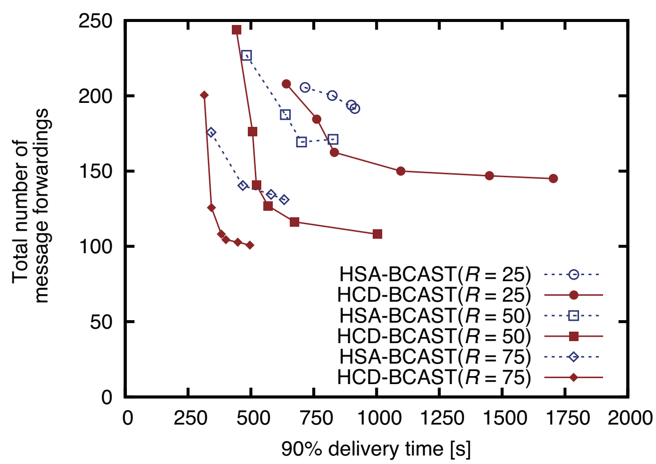

Fig. 7: Relation between 90% delivery time and total number of message forwardings for a field size of 1000×1000 [m] and a radio communication range of 25, 50 and 75 [m] (HSA-BCAST vs. HCD-BCAST)

We also investigated the impact of node density through simulations with various numbers of nodes. Figure 8 shows the relation between 90% delivery time and the total number of message forwardings for a radio communication range of 50 [m] and a number of nodes of $50, 100$ and 150. We set the control parameter N_{th} of HSA-BCAST to 0.75. The simulation results indicate that the performance of HCD-BCAST is higher compared with that of HSA-BCAST because all curves for HCD-BCAST are located

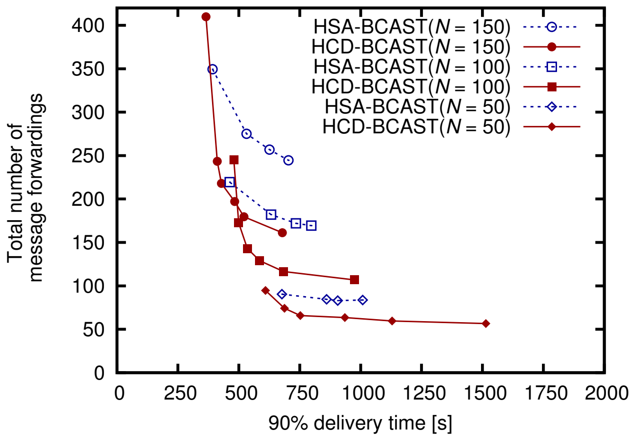

Fig. 8: Relation between 90% delivery time and total number of message forwardings for a radio communication range of 50 [m] and a number of nodes of 50, 100 and 150 (HSA-BCAST vs. HCD-BCAST)

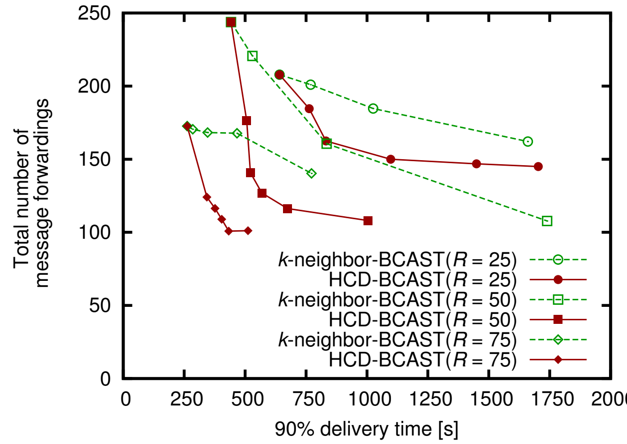

Fig. 9: Relation between 90% delivery time and total number of message forwardings for a field size of 1000×1000 [m] and a radio communication range of 25, 50 and 75 [m] (k-neighbor-BCAST vs. HCD-BCAST)

below and to the left of those for HSA-BCAST. This indicates that the performance of HCD-BCAST is higher than that of HSA-BCAST regardless of the node density.

HCD-BCAST shows higher performance than HSA-BCAST regardless of the communication range and the node density. The main reasons for this are that while HSA-BCAST reduces the number of duplicate message forwardings by reducing the forwarding probability according to the number of duplicate message receptions, it does not have any mechanism for increasing the number of transmissions to multiple nodes by a single message forwarding. On the other hand, HCD-BCAST increases the number of successful transmissions to multiple nodes by a single message forwarding by intentionally delaying message forwarding.

Next, we compared the performance of HCD-BCAST with that of k-neighbor-BCAST. Similarly, we simulated HCD-BCAST and k-neighbor-BCAST with different radio communication ranges and node densities in the field. In the original version of k-neighbor-BCAST, the control parameter k is restricted to integer values. To relax this restriction, we added a trivial extension to the k-neighbor-BCAST algorithm allowing the control parameter k $(i < k < i+1)$ to take non-integer values, whereby infected nodes chose i as the threshold with probability $i + 1 - k$ and $i + 1$ with probability $k - 1$.

Figure 9 shows the relation between 90% delivery time and the total number of message forwardings for a field size of 1000×1000 [m] and a radio communication range R of 25, 50 and 75 [m]. We varied the parameter k of k-neighbor-BCAST between 1, 1.25, 1.5 and 1.75 when R was 25 and between 1, 2 and 3 when R was 50 or 75. The simulation results indicate that HCD-BCAST provides performance superior to that of k-neighbor-BCAST because all curves for HCD-BCAST are located below and to the left of those for k-neighbor-BCAST. Therefore, the results indicate that HCD-BCAST shows better characteristics than HSA-BCAST regardless of the radio communication range and the node density.

Next, we investigated the impact of node density through simulations with various numbers of nodes. Figure 10 shows the relation between 90% delivery time and the total number of message forwardings for a radio communication range of 50 [m] and a number of nodes of $50, 100$ and 150. We changed the control parameter k for k-neighbor-BCAST between 1, 2 and 3. The simulation results indicate that HCD-BCAST provides performance superior to that of k-neighbor-BCAST, except in the case of the lowest node density. In Figure 10, although the curves at $N = 50$ almost overlap, the curves for HCD-BCAST at $N = 100$ and 150 are located below and to the left of those for k-neighbor-BCAST, indicating that the performance of HCD-BCAST is higher than that of HSA-BCAST regardless of the number of nodes.

Compared with k-neighbor-BCAST, HCD-BCAST shows higher performance regardless of the communication range and the node density. The main reasons for this are as follows. Unlike HSA-BCAST, k-neighbor-BCAST has a mechanism that increases the number of transmissions to multiple nodes by means of a single message forwarding because in k-neighbor-BCAST an infected node broadcasts a message only when there are more than k nodes (including at least one susceptible node) within the communication range of the broadcasting node. However, k-neighbor-BCAST does not fully utilize the characteristics of broadcasting, even though infected nodes transmit to multiple nodes by means of a single message forwarding. For instance, if an infected node I broadcasts a message to k nodes within its communication range and a susceptible node enters the communication range of node I, node I broadcasts the message again to $k + 1$ nodes. Moreover, every time the infected node I detects a susceptible node,

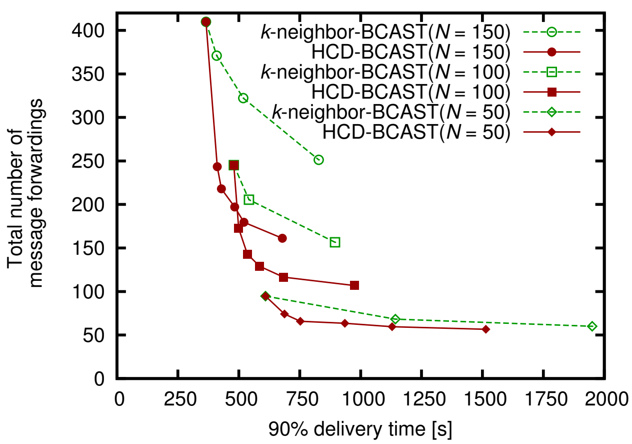

Fig. 10: Relation between 90% delivery time and total number of message forwardings for a radio communication range of 50 [m] and a number of nodes of 50, 100 and 150 (k-neighbor-BCAST vs. HCD-BCAST)

the former broadcasts repeatedly unless the number of nodes within the communication range of infected node I becomes less than k. In other words, the infected node forwards the message to only a single susceptible node. This problem is especially likely to occur when the contact duration is long and the frequency of contact among nodes is high. As Figures 9 and 10 suggest, when the communication range is wide (i.e., the contact duration is long) and the density of nodes is high (i.e., the frequency of contact is high), there is a notable difference in performance between HCD-BCAST and k-neighbor-BCAST.

IV. Conclusion and Future Work

In this paper, we have proposed HCD-BCAST, which significantly reduces the number of message forwardings while maintaining the rapidity of message delivery. In HCD-BCAST, each node independently determines the message forwarding delay based on the contact duration distribution measured by that node. Through simulations, we have shown that HCD-BCAST achieves a reduction of approximately 10-40% in the number of message forwardings compared with HSA-BCAST and k-neighbor-BCAST.

In future work, we plan to evaluate the performance of HCD-BCAST with realistic mobility models, radio communication models and traffic patterns. Furthermore, the evaluation of the rapidity and efficiency of message delivery of HCD-BCAST by mathematical analysis is also important. We plan to extend HCD-BCAST in order to make it applicable to environments where the contact duration distribution is not stationary, by renewing the distribution. In addition, it would also be useful to devise a mechanism for adaptive tuning of the control parameter p_{success} of HCD-BCAST, which controls the success rate of message transmission. We expect the performance of HCD-BCAST to improve if the control parameter p_{success} is tuned adaptively according to the communication range.

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