PAPER

# Contact Duration-Aware Epidemic Broadcasting in Delay/Disruption-Tolerant Networks**

**Kohei WATABE**[†*a)] *and* **Hiroyuki OHSAKI**[††b)], *Members*

**SUMMARY** DTNs (Delay/Disruption-Tolerant Networks) composed of mobile nodes in low node-density environments have attracted considerable attention in recent years. In this paper, we propose a CD-BCAST (Contact Duration BroadCAST) mechanism that can reduce the number of message forwardings while maintaining short message delivery delays in DTNs composed of mobile nodes. The key idea behind CD-BCAST is to increase the probability of simultaneous forwarding by intentionally delaying message forwarding based on the contact duration distribution measured by each node. Through simulations, we show that CD-BCAST needs substantially less message forwardings than conventional mechanisms and it does not require parameter tuning under varieties of communication ranges and node densities.

***key words:*** *delay/disruption-tolerant networks, opportunistic networks, epidemic broadcasting, contact duration distribution, mobile ad-hoc network*

## 1. Introduction

In recent years, DTNs (Delay/Disruption-Tolerant Networks) [1]–[3] that realize communication under conditions in which continuous end-to-end connectivity is not guaranteed have attracted considerable attention. In MANETs (Mobile Ad-hoc NETworks) [4], a class of DTNs, network links between nodes frequently change because of node mobility. Therefore, conventional communication methods for realizing end-to-end network connections [5], [6] cannot be applied to DTNs without modification. In several DTNs, a message is delivered by store-and-carry forwarding [7] for communication, which utilizes the mobility of nodes. For example, applications of DTNs include conceptual interplanetary communication networks [8], temporary communication networks in disaster-affected areas [9], and sensor networks used for observing animals in their natural habitats [10]. To increase the probability of successfully message delivery, DTN nodes can utilize epidemic broadcasting [11]–[15], where an infected node — i.e., a node that holds a message — forwards a copy of the message to other nodes to realize one-to-many communication. In a simple epidemic broadcasting, an infected node forwards the copy of a message every time another node enters the radio communication range. As a result, the number of duplicate messages increases exponentially with time.

In epidemic broadcasting in DTNs, reducing the number of message forwardings is essential for improving efficiency, thereby reducing both energy and bandwidth consumption. Fewer message forwardings leads to lower energy consumption for message delivery, thereby prolonging the lifetime of DTNs on energy-hungry environments. In particular, in sensor networks composed of energy-strapped nodes for environmental monitoring, it is important to continue monitoring without an energy supply for long periods of time [16], [17]. Furthermore, in DTNs composed of nodes with large-capacity batteries (e.g., vehicular ad-hoc networks), fewer message forwardings leads to lower bandwidth consumption, thereby increasing the transport capacity of the DTNs.

Conventional approaches for reducing the number of message forwardings in epidemic broadcasting are classified into the following two types: (1) approaches that reduce duplicate message forwardings and (2) approaches that increase simultaneous forwardings.

SA-BCAST (Self-Adaptive BroadCAST) [18], [19] suppresses duplicate message forwarding by exponentially reducing the message forwarding probability according to the number of duplicate messages received. In HP-BCAST (History- and Push-based BCAST) [11], each node manages its own history of message forwarding and suppresses duplicate message forwarding by not forwarding messages to infected nodes. HSA-BCAST (History-based Self-Adaptive BroadCAST) [18] uses the adaptive control of the forwarding probability, as found in SA-BCAST, along with the management of message forwarding history, as found in HP-BCAST.

In constant, there is an approach to reduce the number of message forwardings by utilizing the characteristics of radio communication and forwarding a message to multiple nodes simultaneously. In epidemic broadcasting using radio communication, a node forwards a message to all the other nodes within its radio communication range. Radio communication allows for a message to be delivered to multiple nodes simultaneously. Epidemic broadcasting mechanisms for improving the efficiency of DTNs have been proposed using this approach [12], [13]. In $k$-neighbor-BCAST ($k$-

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neighbor-BroadCAST) [13], which is a representative of the mechanisms that increase the number of simultaneous forwardings, an infected node forwards a message only when the following two conditions hold: (1) $k$ nodes exist in the communication range and (2) at least one of these nodes is a susceptible node (i.e., a node that does not hold a message). Therefore, nodes can simultaneously deliver a message to multiple nodes by means of a single message forwarding by utilizing the characteristics of radio communication.

Several mechanisms for epidemic broadcasting have been proposed, but each has drawbacks. The mechanisms, including HSA-BCAST, that reduce duplicate forwardings do not increase the number of simultaneous forwardings, though we can increase the number of simultaneous forwardings while reducing duplicate forwardings. In contrast, when using mechanisms such as $k$-neighbor-BCAST, which increases the number of simultaneous forwardings, parameter tuning is difficult because the number of nodes within a communication range varies depending on the range, node density, and other factors.

In this paper, we propose CD-BCAST, which can substantially reduce the number of message forwardings while maintaining short message delivery delay by intentionally delaying message forwarding on the basis of contact duration distribution measured by each node. We define contact duration as the duration in which two nodes are in contact with each other (i.e., reside within each of their communication ranges). In CD-BCAST, each infected node measures the contact duration distribution by recording contact durations with other nodes. To increase the number of simultaneous forwardings, an infected node intentionally delays its message forwarding until it can forward the message to multiple susceptible nodes; however, when the delay exceeds the contact duration, the infected node fails to forward the message to the susceptible node, thereby increasing message delivery delay. CD-BCAST overcomes the weaknesses of conventional mechanisms by utilizing a contact duration distribution, and that does not require parameter tuning under varieties of communication ranges and node densities. Through simulations, we show that CD-BCAST reduced 10–40% of the total number of message forwardings as compared with that of HSA-BCAST. We also show that the performance of CD-BCAST is not sensitive to its control parameters.

The remainder of this paper is organized as follows. Section 2 explains the idea behind our proposed CD-BCAST approach and describes the operation of each node. Section 3 provides investigation of the fundamental properties of CD-BCAST through simulation under simple scenarios. Section 4 provides performance comparison between conventional mechanisms and CD-BCAST, which shows that CD-BCAST reduces the total number of forwardings and is not sensitive to its control parameters. Finally, we conclude this paper in Sect. 5 and provide directions for future works.

## 2. Contact Duration-Aware Mechanism for Epidemic Broadcasting

We propose an efficient epidemic broadcast mechanism called CD-BCAST, which substantially reduces the total number of forwardings. CD-BCAST intentionally delays message forwarding hoping that delaying message forwarding will contribute to a high probability of simultaneous message forwarding to multiple nodes. The problem we face is to select an appropriate time delay to achieve better performance because the infected node will not forward the message to a susceptible node when the delay time exceeds the contact duration. To address this challenge, CD-BCAST measures contact duration distribution by recording contact durations and calculating delay times based on the measured contact duration distribution. In this section, we describe the idea behind our proposed CD-BCAST approach and describe the operation of each node.

### 2.1 Key Concepts

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 delay that allows other susceptible nodes to enter the radio communication range. Illustrated in Fig. 1, an infected node can forward a message to multiple nodes if the forwarding is appropriately delayed. In the figure, at time $t = 2$, an infected node encounters a susceptible node. As all nodes continue to move, the infected node encounters an additional susceptible node at time $t = 3$. If the infected node forwards a message at time $t = 3$ instead of time $t = 2$, the infected node can simultaneously forward a message to the two susceptible nodes.

If the message forwarding delay is too long or too short, the infected node is unable to increase the number of simultaneous forwarding. When the message forwarding delay is too short, the infected node is unlikely to encounter an additional susceptible node before it forwards its message, leading to an inefficient use of the characteristics of radio communication. In contrast, if the message forwarding delay is

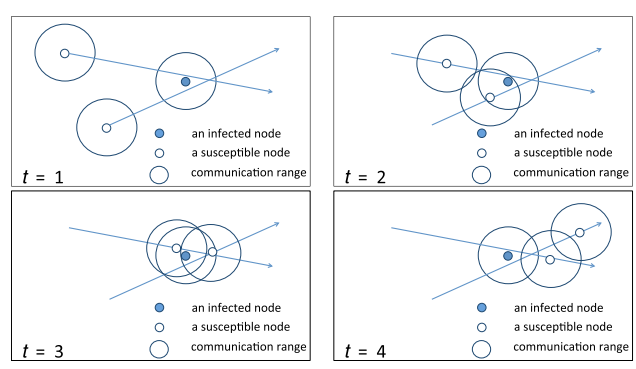


**Fig. 1** Example in which the characteristics of radio communication are utilized by introducing a forwarding delay.

too long, the infected node will likely fail to forward its message to the susceptible node it initially encountered (i.e., the infected node cannot simultaneously forward its message to all nodes at $t = 4$ in Fig. 1). Therefore, an efficient epidemic broadcasting mechanism should be able to calculate an appropriate message forwarding delay time that utilizes the characteristics of radio communication while maintaining acceptable message delivery delay.

The key idea behind CD-BCAST is to use the information regarding the situation around an infected node. We consider that the message forwarding delay should be determined by the following two factors: (1) the number of infected nodes around a susceptible node; and (2) the contact duration distribution of infected and susceptible nodes. By using (1), an infected node can suppress message forwarding according to the situation around a susceptible node. A smaller forwarding probability is desirable when other infected nodes are located around a susceptible node because it is expected that they will forward the message to the susceptible node. If multiple infected nodes forward the message to the susceptible node, then we face the problem of duplicate forwardings. A long message forwarding delay corresponds to small forwarding probability because the probability that an infected node fails to forward its message to a susceptible node increases. Therefore, we should increase the message forwarding delay when there are many infected nodes around a susceptible node. By using (2), 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 extra communication because nodes are already monitoring nodes within their communication range.

### 2.2 Operation

CD-BCAST can substantially reduce the number of message forwardings while maintaining short message delivery delay by intentionally delaying message forwarding on the basis of contact duration distribution. In CD-BCAST, each node measures its own contact duration distribution, which each node then uses to set its message forwarding delay such that the probability that a susceptible node receives a message from multiple infected nodes is constant. Infected nodes determine their respective message forwarding delays on the basis of their own contact duration distributions and the number of infected nodes around the encountered susceptible node.

Infected nodes should tune their message forwarding probabilities as follows. We first assume that there are $N$ infected nodes $\{I_1, \ldots, I_N\}$ around susceptible node $S$; furthermore, we assume that these nodes forward a message independently with the same probability $p$. In such a situation, probability $p_{\text{receive}}$ that node $S$ receives a message at least once is given by

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

Therefore, to control probability $p_{\text{receive}}$, infected nodes $\{I_1, \ldots, I_N\}$ should set their forwarding probability $p$ as

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

By keeping forwarding probabilities that are larger than $p$, CD-BCAST maintains short delivery delay. The number $N$ of infected nodes around node $S$ is needed to determine $p$ from Eq. (1). $\hat{N}$ denotes the derived number of infected nodes within the radio communication range when an infected node encounters node $S$. There are two options for tracking the infection status of other nodes and deriving the number $\hat{N}$ of infected nodes within the radio communication range. The first option is to maintain a history of message forwardings, an approach used in [11]. In this case, each node manages its own history of message forwardings and exchanges it by piggybacking it on transmitted message. The second option is to manage a holding message list, an approach used in [12], [13]. In this case, each node exchanges a list of messages it is holding on every contact. Both the approaches generate a communication overhead; the optimal approach should be determined by considering the environment of the DTN because the amount of the overhead depends on the environment. Whereas a more comprehensive study of how the optimal approach should be determined is outside the scope of this paper, CD-BCAST works regardless of which option we take (we will show that CD-BCAST provides better performance regardless in Sect. 4).

Infected nodes adjust message forwarding delay times such that forwarding probability $p$ satisfies Eq. (1) with their own contact duration distribution. We let $P(x)$ denote the measured CDF (Cumulative Distribution Function) of the contact duration distribution and $T_S$ denote $x$ satisfying the following equation:

$$1 - P(x) \geq p. \tag{2}$$

More specifically, $T_S$ is

$$T_S = P^{-1}(1 - p).$$

Infected nodes $\{I_1, \ldots, I_N\}$ delay message forwarding for $T_S$ after encountering susceptible node $S$. The infected node forwards a message if node $S$ resides within its radio communication range after $T_S$ has elapsed.

By using this approach, CD-BCAST substantially reduces the number of message forwardings by deliberately delaying message forwarding while maintaining a high message receive probability of node $S$ from nodes $\{I_1, \ldots, I_N\}$ with probability $p_{\text{receive}}$. Note that $p_{\text{receive}}$ is a control parameter that adjusts the frequency of message delivery. Larger values of $p_{\text{receive}}$ lead to shorter message forwarding delays, and infected nodes forward messages more often.

In Algorithm 1, the CD-BCAST algorithm is shown using pseudocode. When susceptible node $S$ enters the communication range of an infected node, the infected node sets

**Algorithm 1** Pseudocode for the CD-BCAST algorithm

```
1:  while true do
2:      if susceptible node S enters the communication range then
3:          p ← F1(p_receive, N);
4:          T_S ← F2(p, P(x));
5:      end if
6:      for all S do
7:          if timer T_S expires then
8:              if node S resides within range then
9:                  forward message to all nodes within range;
10:                 for all T_S do
11:                     disable timer T_S;
12:                 end for
13:             end if
14:         end if
15:     end for
16: end while
```

message forwarding delay $T_S$. $\mathcal{F}_1$ denotes $p$ satisfies Eq. (1), and $\mathcal{F}_2$ denotes $T_S$ satisfies Eq. (2) (i.e., lines 2-7 of Algorithm 1). Next, the infected node forwards a message to all the nodes within the communication range and disables timer $T_S$ if $T_S$ expires and node $S$ is still within the communication range. (i.e., lines 8-17 of Algorithm 1).

Like the conventional mechanisms [13], [18], [19], in CD-BCAST, each node manages a neighbor node list by listening (broadcasted) beacon frames from other nodes. Each node broadcasts a beacon frame periodically. A beacon frame contains an ID of a node that broadcasts it, and the other nodes are able to know the presence of the neighbor node by receiving the beacon frame. When a node receives a beacon frame from node $X$ that is not contained in its neighbor node list, the node adds the node $X$ to the neighbor node list. If a node cannot receive a beacon frame from node $X$ during a period $\delta$, the node $X$ is removed from the neighbor node list. In this paper, we consider the simplest mechanism as in conventional mechanisms [13], [18], [19]. We can embed the position information, migration information, and so on into the beacon. The design of such advanced mechanisms, however, is beyond the scope of this paper.

A contact duration distribution used to determine the message forwarding delay is measured on the basis of the records of contact duration by each node. Since each node manages its neighbor node list by utilizing beacon frames, each node can record a contact duration that is defined as the time elapsed from the initial reception of the beacon frame to the disappearance of the node due to timeout. Contact duration can be measured without any communication overhead (though there is a slight computational and memory overhead) because nodes that compose a DTN are always sending beacons to communicate. Contact duration distribution is analytically derived via the simple mobility model by Samar et al. [20], [21]. Because the mobility of nodes is unknown and more complicated in the real world, we use measured contact duration distribution based on contact durations that are recorded by each node. In CD-BCAST, each node records contact durations with the oldest record being deleted if the number of records exceeds $n_{\max}$; this prevents an increase in memory overhead. Here, we assume that node $X$ encountered other nodes $n$ times ($0 < n \leq n_{\max}$) in the past and that their records of contact duration are $\{D_1, D_2, \ldots, D_n\}$. The measured CDF $P(x)$ of contact duration of node $X$ is

$$P(x) = \frac{1}{n}\sum_{i=1}^{n} \mathbf{1}_{\{D_i < x\}},$$

where $\mathbf{1}_{\{\cdot\}}$ denotes an indicator function. We define $P(x) = \mathbf{1}_{\{0<x\}}$ when $n = 0$. Note that contact duration does not depend on node density.

## 3. Fundamental Properties of CD-BCAST

Through simulations, we investigated the following four fundamental properties of CD-BCAST: (1) the accuracy of estimating $N$, which denotes the number of infected nodes around a susceptible node $S$; (2) the message receive probability of a susceptible node from multiple infected nodes in simple scenario; (3) the effect of reducing the number of message forwardings by intentionally delaying message forwarding; (4) the relationship between the accuracy of contact duration distribution and characteristic (3); (5) the impact of the distribution of nodes on a field.

### 3.1 Estimation of the Number $N$ of Infected Nodes around a Susceptible Node

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

In our simulation, 100 nodes moved according to the RWP (Random WayPoint) mobility model [22] in a $1000 \times 1000$ [m] simulation field. At the initial state, only a single node holds a message and nodes deliver the message to all the nodes via CD-BCAST. The velocity of nodes was uniformly distributed in the range $[1.0, 2.0]$ [m/s]. Radio communication range $R$ of nodes was 25, 50, and 75 [m], with average contact duration $T$ of 19.35, 38.85 or 58.33 [s], respectively. Parameter $p_{\text{receive}}$ of CD-BCAST was set to 0.7. To track the infection status of other nodes, we maintained a history of message forwardings. Each node broadcasted a beacon every 1 [s], and the timeout $\delta$ used for detecting node disappearance was set to 1 [s]. We assumed that there was no propagation delay in the radio communication and that all nodes had enough storage to record their respective message forwarding histories, as well as their records of contact duration (with $n_{\max}$ being infinite).

We measured $N$ and $\hat{N}$, and calculated the MAE (Mean Absolute Error) of $\hat{N}$ with respect to $N$ by repeating the simulation 30 times with different random seeds. When radio

communication range $R$ was 25, 50, and 75 [m], the MAE of $N$ was 0.29, 0.61, and 1.02, respectively; furthermore, the average of $N$ was 1.56, 2.27, and 3.19, respectively. Therefore, we observe that CD-BCAST achieved a certain level of accuracy in estimating $N$ though it is difficult to predict future contacts of randomly moving nodes.

### 3.2 Message Receive Probability from Multiple Nodes

Next, we investigated the message receive probability of susceptible node $S$ from multiple infected nodes $\{I_1, \ldots, I_N\}$. Through our simulation, we confirmed that CD-BCAST could appropriately suppress message forwarding according to the situation around a susceptible node. If CD-BCAST operates as expected, the message receive probability of a susceptible node should correspond to control parameter $p_{\text{receive}}$.

To derive the message receive probability of a susceptible node, we performed the simulation shown in Fig. 2. In our simulation, the initial positions of infected nodes were uniformly distributed inside a circle with a diameter of 50 [m], and radio communication range $R$ of all nodes was 50 [m]. A cluster of infected nodes and one susceptible node moved at a velocity of 1.5 [m/s] and pass one another, thereby trying to deliver a message from the infected nodes to the susceptible node. We set the number of infected nodes in the cluster to values 1-4, and varied control parameter $p_{\text{receive}}$. The contact duration distribution was given in advance. We repeated the simulation 30 times for each condition and derived the probability at which the susceptible node was able to receive a message upon approaching a cluster of infected nodes.

Figure 3 shows the message receive probabilities of the susceptible node when we varied the number of infected nodes. Results show that the message receive probability of a susceptible node approximately corresponds to control parameter $p_{\text{receive}}$. It appears that there was a particularly close correspondence between the message receive probability of the susceptible node and $p_{\text{receive}}$ when the number of nodes in the cluster of infected nodes was small. In contrast, when the number of nodes in the cluster of infected nodes was large, the message receive probabilities of the susceptible node was slightly lower than $p_{\text{receive}}$. Theoretically, the message receive probability of the susceptible node corresponds to $p_{\text{receive}}$ if the duration of contact between each infected node and the susceptible node are independent of one another; however, contact durations are not independent because of the velocity of the susceptible node. If the velocity of the susceptible node was high, the respective contact durations for all the infected nodes were short. Hence, the contact durations were correlated.

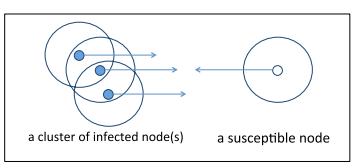


**Fig. 2** Simulation model for investigating message receive probabilities of susceptible node $S$ from infected nodes $\{I_1, \ldots, I_N\}$.

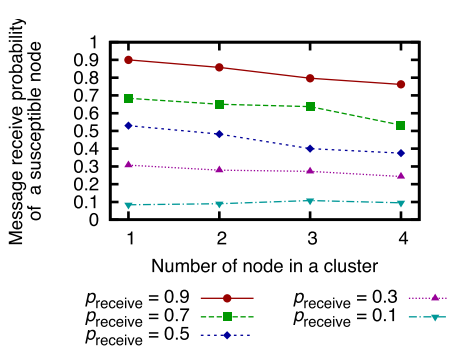


**Fig. 3** Relation between the number of infected nodes in a cluster and message receive probabilities of the susceptible node.

### 3.3 Effect of Reducing the Number of Message Forwardings

We investigated the reduction in the number of message forwardings resulting from intentionally delaying message forwarding. We used the aforementioned simulation setup (see Sect. 3.1) except for $p_{\text{receive}}$. We repeated the simulation 30 times and calculated the number of nodes that simultaneously received the message.

We derived how many susceptible nodes were able to simultaneously receive the message by means of a single message forwarding until 90% of all the nodes received the message. Figure 4 shows the ratio of the number of nodes that simultaneously received a message from a single message forwarding when $p_{\text{receive}}$ was varied between 0.1 and 1.0. Note that in the legend, 0 nodes represents a message forwarding to an infected node that has already held the message. These results show that a smaller value of $p_{\text{receive}}$ increased the opportunity of infected nodes delivering a message simultaneously to multiple nodes via a single message forwarding. More specifically, CD-BCAST was able to utilize the characteristics of radio communication

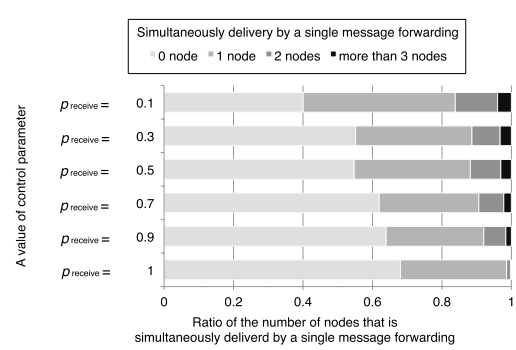


**Fig. 4** Ratio of the number of nodes that simultaneously received a message by means of a single message forwarding when control parameter $p_{\text{receive}}$ was varied between 0.1 and 1.0.

when $p_{\text{receive}}$ was small.

### 3.4 Impact of Accuracy of a Contact Duration Distribution on Performance

We investigated the impact of the accuracy of contact duration distribution on the performance of CD-BCAST. In CD-BCAST, infected nodes measure the distribution by storing records of contact durations and determining forwarding delays with such distributions. Therefore, the performance of CD-BCAST may suffer from the measured contact duration distribution if an infected node does not have enough information about the distribution (i.e., the number $n$ of records of contact duration is small).

To investigate the impact of the accuracy of contact duration distribution on performance, we performed two simulations under the following two conditions: (1) each node was given the contact duration distribution in advance; and (2) each node had no information regarding contact duration distribution at $t = 0$. Under the condition (2), each node has no record of contact duration at time 0 (i.e., $P(x) = \mathbf{1}_{\{0<x\}}$) and measures the contact duration distribution. Except for the initial contact duration distribution, the simulation setup is the same as the the aforementioned simulation setup (see Sect. 3.3). In the simulation, we derived the periods until 90% of all the nodes received the message (i.e., 90% delivery time), with results shown in Figure 5. Figure 6 shows the total number of message forwardings at the 90% delivery time mark. Furthermore, Fig. 7 shows the measured CDF $P(x)$ of contact duration at time 300, 1000, and 1000000 [s]. According to Figus. 5 and 7, we confirm that it was difficult to measure contact duration distribution accurately before 90% delivery time; however, performance did not suffer according to Figs. 5 and 6. Results show that CD-BCAST appropriately worked even if measured CDF $P(x)$ was derived by a small number of records of contact durations.

It is more difficult to accurately estimate the contact duration distribution when the distribution has larger variance. We therefore performed simulations in which the node velocity was fixed at 1.5 [m/s]. We used the aforementioned simulation setup in this section except for node velocity. In this simulation, a node occasionally moved in parallel with another node at the same velocity though nodes mostly passed each other. Hence, a node is likely to keep another node within the communication range for a long time. Therefore, the contact distribution of the node in this simulation had a larger variance than the aforementioned simulation. The standard deviations of the distributions in the simulation and the aforementioned simulation were 374.4 [m/s] and 26.4 [m/s], respectively. The simulation results with/without contact duration distribution given in advance are shown in Figs. 8 and 9. We obtained similar results to the aforementioned simulation with small variance of contact duration distribution, and cannot found significant impact of estimation difficulty due to the large variance on the performance.

Additionally, we investigate the impact of the estimation error due to beacon frame loss on the performance of CD-BCAST. In DTNs, even if two nodes reside within each of their communication ranges, a beacon frame cannot often be received due to several reasons including radio interference and collision. We performed simulations with beacon frame loss. In our simulation, a beacon frame was randomly discarded with probability $q$. We changed the beacon error rate $q$ variously, and investigated the dependency of the performance on the beacon error rate in the cases where $p_{\text{success}}$ are 0.7 and 1.0 (i.e. CD-BCAST and P-BCAST). We used the aforementioned simulation setup in Sect. 3.3 except for a beacon error rate and the setting of $p_{\text{success}}$. The results are shown in Figs. 10 and 11. We can find from these figures that the results of CD-BCAST gradually converge to that of P-BCAST as beacon error rate increases. In a network that is frequently disconnected, it is desired to forward a message immediately (like P-BCAST). When the beacon error rate is high, the behavior of CD-BCAST achieves that of P-BCAST since the contact duration becomes shorter.

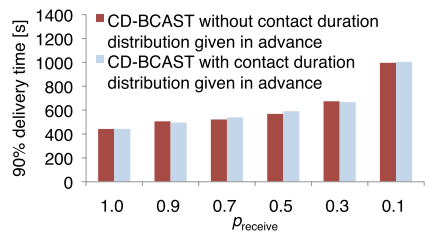


**Fig. 5** The impact of given contact duration distribution on 90% delivery time.

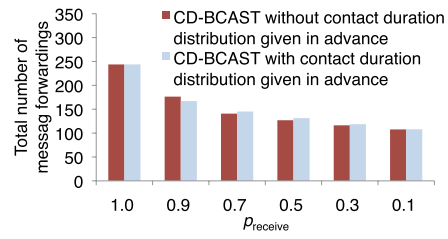


**Fig. 6** The impact of given contact duration distribution on total number of forwardings.

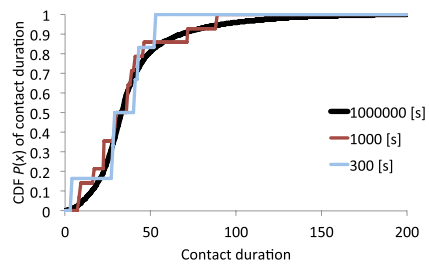


**Fig. 7** Measured CDF $P(x)$ of contact duration at each time.

### 3.5 Impact of Node Distribution on a Field

In DTNs, a node distribution on a field should affect the performance of epidemic broadcasting. In real DTNs, node

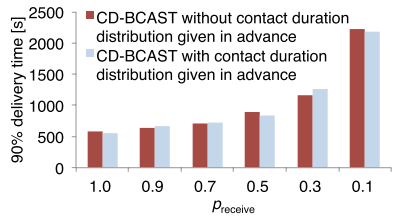


**Fig. 8** The impact of variance of a contact duration distribution on 90% delivery time.

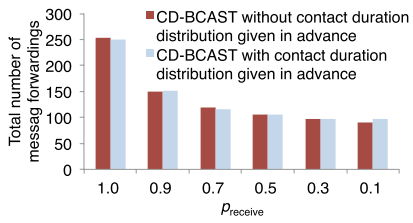


**Fig. 9** The impact of variance of a contact duration distribution on the total number of forwardings.

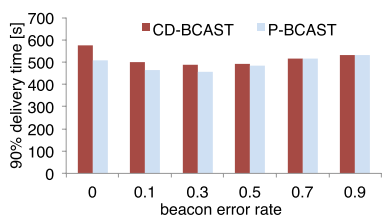


**Fig. 10** The impact of beacon error rate on 90% delivery time.

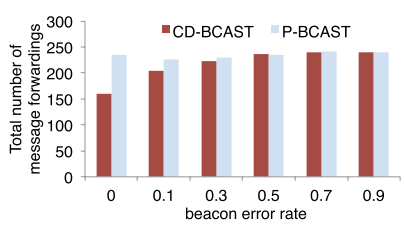


**Fig. 11** The impact of beacon error rate on the total number of forwardings.

density on a field may be sometimes non-uniform. However, node density on a field in the RWP mobility model and most of the other mobility models is nearly uniform. To investigate the effect of non-uniformity of node density on performance of CD-BCAST, we performed a simulation in which the node density is not uniform. In our simulation, we consider two types of node: sparse and dense nodes. Sparse nodes were distributed in $1000 \times 1000$ [m] field, and dense nodes are distributed in $500 \times 500$ [m] field. Bottom-left corners of the two fields were located at the same point. Each node moved according to the RWP mobility model on its field. By changing the ratio of number of the dense nodes to the number of all nodes, we can change the non-uniformity of node density. We performed simulations, changing the ratio from 0.25 to 0.75. The control parameter $p_{\text{receive}}$ of CD-BCAST was set to 0.7. We performed the simulation

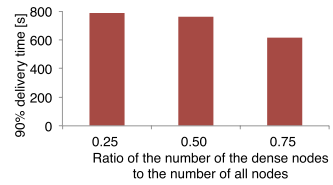


**Fig. 12** The impact of node distribution on a field on 90% delivery time.

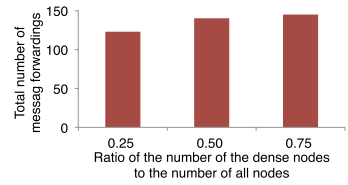


**Fig. 13** The impact of node distribution on a field on the total number of forwardings.

with the same setup as in Sect. 3.3 except for mobility model and $p_{\text{receive}}$. Figures 12 and 13 show that 90% delivery time and the total number of message forwardings in the simulation. Figure 12 shows that the 90% delivery time decreases when the ratio of nodes within a dense field is high. The main reason for this is that a high density field accelerates spread of message. On the other hand, the total number of message forwardings increases as the ratio of nodes within a dense field increases. The fall of the node density of sparse field increases the number of forwardings since it is difficult to forward a message to multiple nodes.

## 4. Comparing the Performance of CD-BCAST with Conventional Mechanisms

In this section, we compare the performance of CD-BCAST with that of conventional mechanisms, thereby showing that CD-BCAST overcomes the weaknesses of existing mechanisms.

### 4.1 Performance Comparison with HSA-BCAST

To verify the effectiveness of our proposed CD-BCAST approach under various conditions, we compared the performance of CD-BCAST with that of HSA-BCAST. We performed the simulation with the same setup as in Sect. 3.3 except for an epidemic broadcast mechanism. We derived the total number of message forwardings and 90% delivery time by repeating the simulation 30 times. In HSA-BCAST, each infected node managed a history of message forwardings to know whether an encountered node is infected or susceptible. For this simulation, CD-BCAST also used the same approach. In general, the performance of an epidemic broadcasting mechanism is heavily dependent on the choice of control parameters. Therefore, in the simulation, we changed control parameters $N_{\text{th}}$ and $c$ of HSA-BCAST. $N_{\text{th}}$ denotes the threshold of the change rate in the number of nodes within a communication range of an infected node used for determining whether the infected node should for-

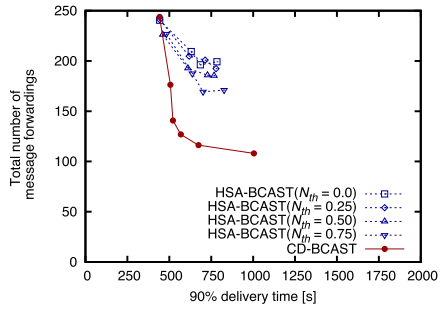


**Fig. 14** Relation between 90% delivery time and the total number of message forwardings for HSA-BCAST and CD-BCAST.

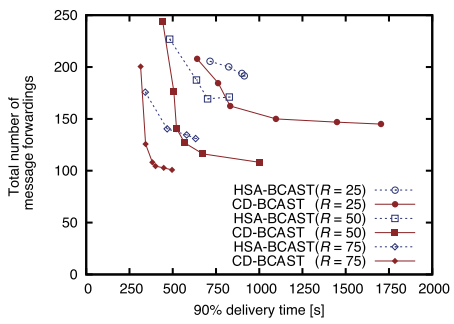


**Fig. 15** Relation between 90% delivery time and the total number of message forwardings for a radio communication range $R$ of 25, 50, and 75 [m] for HSA-BCAST and CD-BCAST.

ward a message; $c$ is a parameter that controles exponential decay in the forwarding probability according to the number of duplicate messages received by other nodes.

In Fig. 14, we show the 90% delivery time and total number of message forwardings. Respective points for CD-BCAST in the figure are related to the results for $p_{\text{receive}}$ = 1.0, 0.9, 0.7, 0.5, 0.3, and 0.1 in order from left to right. Similarly, respective points for HSA-BCAST in the figure are related to the results for $c$ = 1.0, 2.0, 4.0, and 8.0 in order from left to right. In epidemic broadcasting, there is a tradeoff between message delivery delay and the 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. On the left of the figure, the points for CD-BCAST and HSA-BCAST ($N_{\text{th}}$ = 0.0) overlap because these points represent the results for $p_{\text{receive}}$ = 1.0 and $c$ = 1.0, respectively; in other words, these parameters do not control message forwarding as they do in HP-BCAST. The figure shows that CD-BCAST achieved a rate of message delivery equivalent to that of HSA-BCAST by means of a small number of message forwardings. More specifically, CD-BCAST achieved a reduction of approximately 10-40% in the number of message forwardings compared to HSA-BCAST.

We also investigated the impact of communication range through simulations for various numbers of nodes. Figure 15 shows the relation between 90% delivery time and

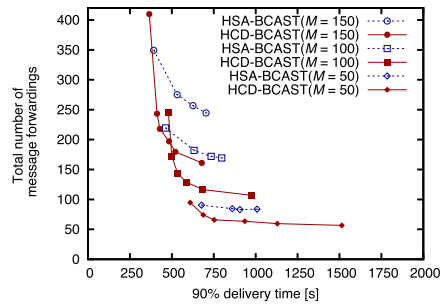


**Fig. 16** Relation between 90% delivery time and the total number of message forwardings for radio communication range $R$ of 50 [m] and a number $M$ of nodes of 50, 100, and 150 for HSA-BCAST and CD-BCAST.

the total number of message forwardings for a radio communication range $R$ of 25, 50, and 75 [m]. The simulation setup we used in this simulation matches the aforementioned setup except for radio communication range $R$ and the HSA-BCAST parameter $N_{\text{th}}$, which we set to 0.75 because at this value HSA-BCAST showed the most favorable characteristics. In Fig. 15, all curves for CD-BCAST are located below and to the left of those for HSA-BCAST, which indicates that the performance of CD-BCAST was higher than that of HSA-BCAST regardless of radio communication range $R$.

Finally, we investigated the impact of node density through simulations with various numbers $M$ of nodes. Figure 16 shows the relation between 90% delivery time and the total number of message forwardings for a radio communication range $R$ of 50 [m] and a number $M$ of nodes of 50, 100, and 150. We set control parameter $N_{th}$ of HSA-BCAST to 0.75. The simulation results indicate that the performance of CD-BCAST was higher as compared with that of HSA-BCAST because all curves for CD-BCAST are located below and to the left of those for HSA-BCAST. This indicates that the performance of CD-BCAST was higher than that of HSA-BCAST regardless of node density.

### 4.2 Performance Comparison with $k$-Neighbor-BCAST

To further verify the effectiveness of our proposed CD-BCAST approach, we compared the performance of CD-BCAST with that of $k$-neighbor-BCAST, which increases simultaneous forwardings. $k$-neighbor-BCAST has an inherent weakness in which parameter tuning is difficult because the number of nodes within communication range varies depending on range, node density, and other factors.

To show that CD-BCAST does not require parameter tuning for changes in communication range and node density, we performed the simulation and derived the total number of message forwardings and the 90% delivery time when a message is delivered via CD-BCAST and $k$-neighbor-BCAST. The simulation setup was the same as that described in Sect. 3.3, except for the epidemic broadcasting mechanisms and the change communication range and the number $N$ of nodes. In $k$-neighbor-BCAST, each infected node manages a holding message list and exchanges it with other nodes to track whether an encountered node is infected

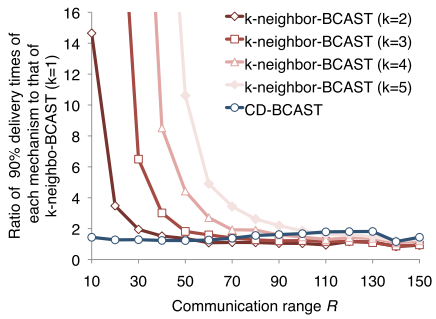


**Fig. 17** Ratio of 90% delivery times of each epidemic broadcasting mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$ with changing communication range $R$ for $k$-neighbor-BCAST and CD-BCAST.

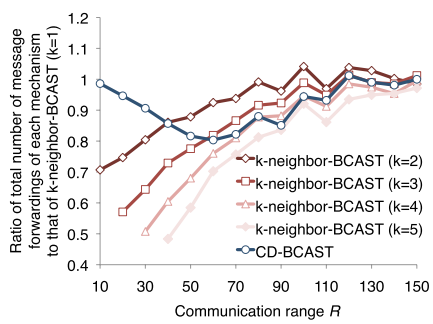


**Fig. 18** Ratio of the numbers of message forwardings of each epidemic broadcasting mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$ with changing communication range $R$ for $k$-neighbor-BCAST and CD-BCAST.

or susceptible. In this simulation, CD-BCAST also used the same approach. Note that these results cannot be directly compared with the results of previous section because the exchange of holding message lists generates communication overhead. In $k$-neighbor-BCAST, parameter $k$ denotes the threshold of the number of nodes within a communication range of an infected node used for determining whether the infected node should forward a message; we changed parameter $k = 1, 2, 3, 4$, and 5 for our simulation. Parameter $p_{\text{receive}}$ was set at a fixed value 0.7.

Figure 17 shows the ratio of 90% delivery time of each epidemic broadcast mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$, and Fig. 18 shows the ratio of the total number of forwardings of each epidemic broadcast mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$ with the communication range $R$ varied from 10 to 150 [m] with step size of 10 [m]. Note that each infected node forwards a message immediately and minimizes the message delivery delay when the parameter $k$ of $k$-neighbor-BCAST is 1. 90% delivery time and the total number of forwardings of $k$-neighbor-BCAST with the parameter $k = 1$ for various $R$ are shown in Table 1. We set the number $M$ of nodes to 100 in our simulation. According to Fig. 17, we found that 90% delivery times of $k$-neighbor-BCAST were much larger than compared with minimized message delivery delay when the communication range was large and the area over which message delivery delay was large depended

**Table 1** Performance of $k$-neighbor-BCAST with the parameter $k = 1$ for various communication range $R$.

| $R$ [m] | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 90% delivery time [s] | 1343.8 | 807.1 | 574.7 | 497.1 | 430.8 | 360.3 | 293.1 | 227.5 | 182.3 | 139.9 | 109.5 | 78.7 | 59.9 | 54.1 | 37.8 |
| The total number of forwaridngs | 88.9 | 88.7 | 87.5 | 85.5 | 83.1 | 77.8 | 73.6 | 65.6 | 61.3 | 53.2 | 50.5 | 44.6 | 41.6 | 38.8 | 35.3 |

on parameter $k$. For example, if the communication range is 60 [m], we should set parameter $k$ to 3 or less to prevent large message delivery delay. In contrast, we found that CD-BCAST achieved a message delivery delay close to the minimized value (i.e., the value of $k$-neighbor-BCAST with parameter $k = 1$), because the ratio of the 90% delivery times of each epidemic broadcast mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$ is almost 1. According to Fig. 18, we can find that larger $k$ leads smaller number of message forwardings, and $k$-neighbor-BCAST ($k \geq 2$) achieves a greater reduction of the forwarding number than CD-BCAST when the communication range is small. However, message delivery delay of $k$-neighbor-BCAST ($k \geq 2$) is remarkably large when the number of message forwardings of $k$-neighbor-BCAST ($k \geq 2$) is smaller than that of CD-BCAST (see Fig. 17). In contrast, without parameter tuning, CD-BCAST achieves reduction of the number of message forwardings while maintaining the small message delivery delay. For example, if the communication range is 60 [m], we should set $k$ to 3 to maximize the reduction of message forwardings under the condition of small delivery delay though CD-BCAST achieves almost same reduction as that of $k$-neighbor-BCAST with parameter $k = 3$ without parameter tuning.

We also derived the ratio of 90% delivery times for each epidemic broadcast mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$ and the ratio of the total number of forwardings for each epidemic broadcast mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$, while changing the node density by changing the number $M$ of nodes in the simulation. Figures 19 and 20 show the ratios of 90% delivery time and the total number of forwardings, respectively, when the number of message forwardings is changed from 50 to 150 at an interval of 10. We set communication range as 50 [m] in our simulation. 90% delivery time and the total number of forwardings of $k$-neighbor-BCAST with the parameter $k = 1$ for various $M$ are shown in Table 2. Similar results to that of the simulation in which we changed communication range were obtained.

Finally, we compared the performance of CD-BCAST and $k$-neighbor-BCAST in the case where each infected node managed history of message forwarding to track the infection status of other nodes. In the original version of $k$-neighbor-BCAST, each infected node managed a holding message list and exchanged it to determine whether an encounter node was infected or susceptible. As mentioned above, there are two options here: (1) manage a history of message forwardings; and (2) manage a holding message list. We considered the version of $k$-neighbor-BCAST in which each infected node managed a history of message forwardings. Through simulations, we found that CD-BCAST

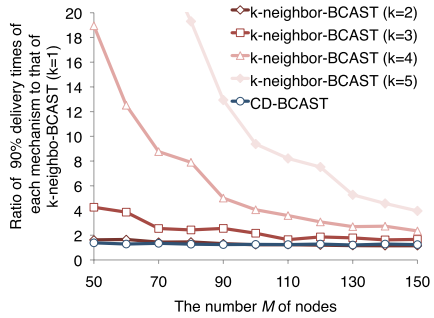


**Fig. 19** Ratio of 90% delivery times of each epidemic broadcasting mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$ with changing the number $M$ of nodes for $k$-neighbor-BCAST and CD-BCAST.

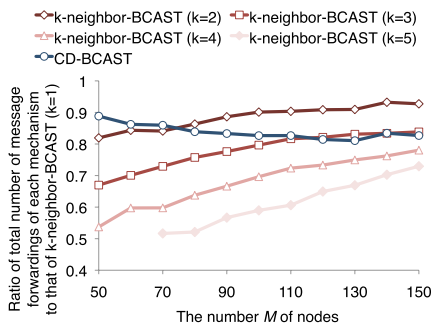


**Fig. 20** Ratio of the numbers of message forwardings of each epidemic broadcasting mechanism to that of $k$-neighbor-BCAST with parameter $k = 1$ with changing the number $M$ of nodes for $k$-neighbor-BCAST and CD-BCAST.

**Table 2** Performance of $k$-neighbor-BCAST with the parameter $k = 1$ for various communication range $M$.

| $M$ | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 90% delivery time [s] | 593.7 | 539.9 | 506.8 | 466.7 | 441.6 | 427.9 | 391.5 | 368.3 | 365.3 | 355.3 | 335.0 |
| The total number of forwaridngs | 43.0 | 51.3 | 59.6 | 67.0 | 74.7 | 81.9 | 88.9 | 96.2 | 104.2 | 109.8 | 115.1 |

provided better performance $k$-neighbor-BCAST, regardless of approaches (1) and (2) above. The simulation setup was the same as the one described in Sect. 3.3, except for the number $M$ of nodes and epidemic broadcasting mechanisms. Figure 21 shows 90% delivery times and the total number of message forwardings. Respective points for CD-BCAST in the figure are related to results for $p_{\text{receive}} = 1$, 0.9, 0.7, 0.5, 0.3, and 0.1 in order from left to right. Similarly, respective points for $k$-neighbor-BCAST in the figure are related to results for $k = 1$, 2, and 3 in order from left to right. Simulation results indicated that CD-BCAST provided performance superior to that of $k$-neighbor-BCAST because all curves for CD-BCAST are lower than that of $k$-neighbor-BCAST. The reason for this is that infected nodes were often mistaken for a susceptible node when we used approach (1) in which a history of message forwardings is maintained; in such case, it repeats inefficient message forwardings. For example, if infected node $I$ forwards a message to $k$ nodes within its communication range and a susceptible node enters the communication range of node $I$, node $I$ forwards the message again to $k + 1$ nodes. Furthermore, every time infected node $I$ encounters a susceptible node, the node forwards message 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 one susceptible node at a time.

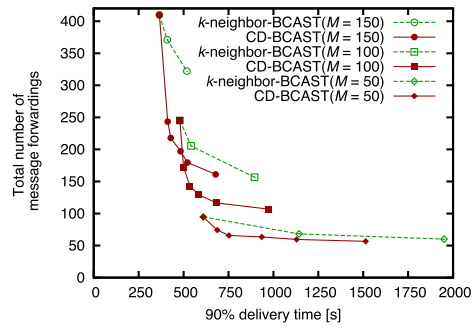


**Fig. 21** Relation between 90% delivery times and the total number of message forwardings for the number $M$ of nodes of 50, 100, and 150 when each infected node manages a history of message forwardings to track infection status of other nodes for $k$-neighbor-BCAST and CD-BCAST.

## 5. Conclusion and Future Work

In this paper, we proposed CD-BCAST, which substantially reduces the number of message forwardings while holding the message delivery delay small without parameter tuning depending on changes in communication range and node density. Through multiple simulations, we showed that CD-BCAST reduced the total message forwarding number by 10%-40% as compared to that of HSA-BCAST, and this reduction was achieved without parameter tuning under varieties of communication ranges and node densities; although, $k$-neighbor-BCAST requires the tuning.

In future, we plan to evaluate the performance of CD-BCAST under more realistic conditions. In real world DTNs, several factors that affect the performance of epidemic broadcasting should be considered including message size, queuing of messages, propagation delay, heterogeneity of nodes, energy and bandwidth consumption, mobility patterns, traffic patterns, and so on. Furthermore, we plan to study how best to determine whether an encountered node is infected or susceptible.

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