On the Impact of Cut-Through Links in Epidemic Broadcasting

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***Abstract*—One of communication mechanisms in DTN is an *epidemic broadcasting* that performs information transmission from a certain mobile node to all other mobile nodes using short-distance radio communications (e.g., WiFi) among mobile nodes. In the literature, it has been shown through simulation experiments that the performance of an epidemic broadcasting improves significantly by not only utilizing ad-hoc communication among mobile nodes but also introducing a small number of cut-through links (i.e., wired communication links connecting several base stations) on the field. In this paper, the effect of deploying cut-through links on the performance (in particular, rapidity of message delivery) of epidemic broadcasting is quantitatively clarified through mathematical analysis. Consequently, we show that the performance of epidemic broadcasting improves significantly by introducing a small number of cut-through links and placing base stations of cut-through links appropriately according to the positional distribution of mobile nodes.**

***Keywords*—DTN (Delay/Disruption-Tolerant Networking), Epidemic Broadcasting, Cut-Through Links, Performance Analysis**

I. Introduction

Delay/disruption-tolerant networking (DTN), which allows end-to-end node communication even when communication links between nodes are not functioning normally, has recently been regarded as a promising communication technology for setting up communication infrastructure at the time of disaster and low-cost communication infrastructure. DTN aims to achieve reliable end-to-end data transfers in communication environments where internode communication links can be temporarily severed, or the transmission delay between nodes can temporarily increase.

Epidemic broadcasting is one form of DTN communication where a node transmits information to all other nodes through internode short-range communication such as WiFi [1], [2]. Each node is mobile and forwards messages to other nodes through store-carry-and-forward communication in epidemic broadcasting. In store-carry-and-forward communication, relay nodes temporarily store messages, and the node is carried while holding the data. The relay node forwards the message from its new location. This makes data transfer possible when end-to-end communication is unavailable. Epidemic-broadcasting messages are diffused over the entire network through being exchanged between nodes; therefore, this is also called gossip-based communication.

Research on DTN applications has become more active in recent years. One potential application of epidemic broadcasting is the transmission of information by short-range communication between nodes when the communication infrastructure cannot be used; for instance during a disaster [3]. Using epidemic broadcasting, information, such as safety information during a disaster, can be transmitted by ad-hoc communication between mobile nodes, even when the communication infrastructure is unusable.

The performance of DTN epidemic broadcasting could be improved by introducing a small number of cut-through links, in addition to using ad-hoc communication between nodes. Cut-through links are communication links connecting multiple points on a field. Examples of cut-through links in DTN are wired networks connecting shelters at a disaster site, long-distance radio networks that connect emergency vehicles, and wired networks connecting base stations at intersections that are part of a vehicular ad-hoc network (VANET). Using cut-through links in epidemic broadcasting would accelerate the diffusion of information and reduce the radio communication bandwidth usage. However, the effect of introducing cut-through links has not been sufficiently evaluated.

The concept of cut-through links itself is not new, and research on cut-through links in asynchronous transfer mode (ATM) and multi-protocol label switching (MPLS) has been carried out for several years [4]–[6]. For instance, [4] uses simulations to compare the performance of five types of adaptive-routing algorithms using cut-through links. Routing algorithms using cut-through links were found to have a better average delay, retransmission rate, and network utilization rate, compared to packet switching. Reference [5] compares the performance of different cut-through methods in three types of networks: multiprotocol over ATM (MPOA), internet protocol (IP), and MPLS.

Many researchers are investigating the effectiveness of epidemic broadcasting in DTN; however, to the best of our knowledge, the effectiveness of cut-through links in epidemic broadcasting has not been well understood. For instance, references [7]–[10] use mathematical analysis to analyze the performance of epidemic broadcasting, and references [1], [2], [11]–[14] investigate the effectiveness of epidemic broadcasting and its variants with simulation experiments. Also, the authors of [15] propose a method for inferring message diffusion dynamics of epidemic broadcasting. However, these works focus on evaluating the speed and performance efficiency of epidemic broadcasting, and do not identify the effects of cut-through links. Reference [16] assesses the validity of cut-through links in epidemic broadcasting with simulations, but the regions where cut-through links are effective and the

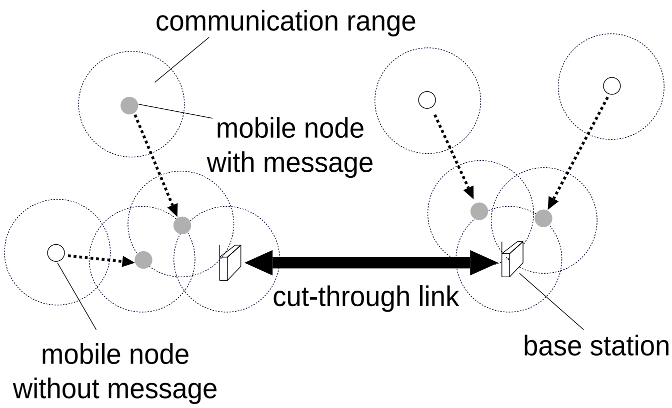

Fig. 1. Example of cut-through links (communication links connecting base stations on a field) in a DTN.

effect of cut-through links on the characteristics of epidemic broadcasting are not sufficiently discussed.

Therefore, this paper quantitatively analyzes, using mathematical analysis, the effect of introducing cut-through links in epidemic broadcasting; in particular, its effect on the speed of message delivery — how the rapidity of message delivery is improved with the introduction of cut-through links. The epidemic broadcasting of various mobile nodes is modeled as a discrete time system. Analyses are carried out on both uniform and non-uniform spatial distributions of nodes. The effect of cut-through links on the speed of epidemic broadcasting is investigated by analytically determining how the virtual contact probability between nodes increases when cut-through links are introduced.

This paper is organized as follows. Section II provides an overview cut-through links for epidemic broadcasting. Section III introduces the analysis model in this paper. Section IV analyzes how cut-through links affect the speed of epidemic broadcasting in both uniform and non-uniform spatial distribution cases. Section V identifies the relation between the speed of epidemic broadcasting, the number of cut-through links, and the base station distribution, based on several numerical examples. Finally, Section VI summarizes this paper and outlines future tasks.

II. Cut-Through Links

Cut-through links are communication links that connect multiple base stations (immobile nodes) on a field. Figure 1 shows an example of a cut-through link. M base stations are positioned on a field, and the base stations are connected by at least $M - 1$ cut-through links. Base stations have interfaces for both wireless and wired communication, and messages received from mobile nodes (hereafter, simply "nodes") through wireless communication can be transmitted to other base stations through cut-through links. Moreover, messages received from other base stations through cut-through links may be transmitted to adjacent nodes using radio transmission.

Although there are several means to use cut-through links, this paper assumes that a base station connected to cut-through links simply forwards the messages between nodes that are within radio communication range of a base station. In other words, if there is a node with a message within radio communication range of a base station, and there is another node that does not have the message within radio communication range of another base station, the message is forwarded through a cut-through link. Here, base stations do not have buffers so that messages are not stored.

The performance of epidemic broadcasting is expected to improve by introducing cut-through links [16]; however, various factors should be adequately designed, including the location of the cut-through links, the message-forwarding algorithm of the base stations, and the management of the buffers.

First, the location of the base stations on a field widely influences the effect of the cut-through links. Intuitively, base stations should be located at even intervals on the field. If base stations are clustered on a field, the area where messages can be diffused through cut-through links will be small; thus, limiting the effect of the cut-through links. Consequently, base station positions on the field must be carefully determined to enhance the effect of the cut-through links.

Second, messages must be appropriately routed if multiple cut-through links exist on a field; or, in other words, deciding which messages should be forwarded to which base stations, on a wired network comprised by cut-through links, should be carefully determined. Naively speaking, the rapid diffusion of messages is possible if a base station that receives a message forwards the message to all base stations connected by cut-through links. Push-based broadcasting (P-BCAST) [1] is rapid but inefficient, as many messages are unnecessarily forwarded. Similarly, simply forwarding messages to all base stations connected by cut-through links could decrease the efficiency of epidemic broadcasting.

Third, if base stations connected by cut-through links have buffers, deciding which messages forwarded by epidemic broadcasting should be retained and which should be discarded (managing base station buffers) is an important task. Generally speaking, base station buffers are finite, and holding all messages that are forwarded by epidemic broadcasting is impossible. Therefore, base station buffer management, i.e., deciding which message should be stored and which should be removed from the buffer, must be appropriately designed.

This paper quantitatively clarifies the effectiveness of cut-through links by analyzing their effect on the efficiency of epidemic broadcasting, and provides the answer to the first problem of base station distribution. However, further analysis of the second and third problems is necessary, but it is beyond the scope of this paper.

III. Analytic Model

Epidemic broadcasting between N mobile nodes is modeled as a discrete time system (Fig. 2). Diffusion of only one type of message is considered for simplicity. The radio communication range of all nodes is set to the same value, r, and ad-hoc communication between nodes is allowed when the distance between the nodes is r or less. All nodes are considered to move at speed v, and the field that the nodes travel is denoted as S.

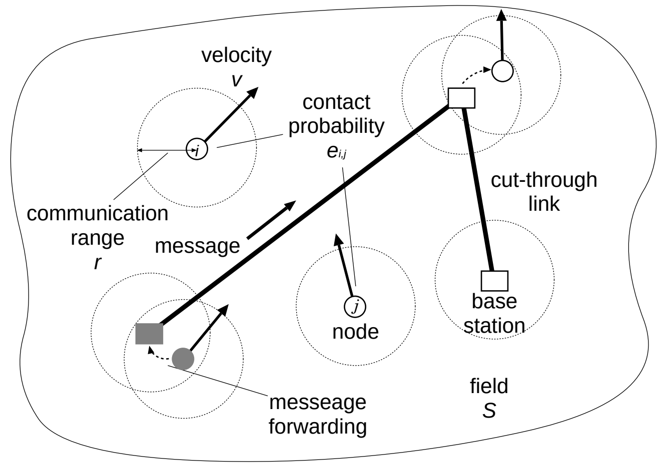

Fig. 2. Analytic model

We assume that the message size is small so that all message forwardings can be completed during a node-to-node encounter with short-range wireless communication. Hence, messages experience no queuing delay at mobile nodes.

Assuming steady node mobility, the probability that nodes i and j will come in contact in a slot (probability that new ad-hoc communication becomes possible) is defined as $e_{i,j}$.

The message-holding rate of node i at slot k is denoted as $\pi_i(k)$, and the message-holding rate vector is expressed as

$$\pi(k)(= {}^t(\pi_1(k), \ldots, \pi_N(k))). \tag{1}$$

P-BCAST [1], where a node containing a message forwards the message at probability 1 when coming into contact with another node, is considered. When $\pi_i(k) \ll 1$, using the contact probability matrix $\mathbf{E} = (e_{i,j})$, the message diffusion dynamics of P-BCAST can be approximated by

$$\pi(k+1) \quad = \quad (\mathbf{I} + \mathbf{E})\,\pi(k). \tag{2}$$

This analysis considers w cut-through links that comprise a tree of $w+1$ base stations on a field. The length of the cut-through links is assumed to be longer than the node radio communication range, r.

IV. Analysis

A. Case of uniform spatial distribution of nodes

Nodes are initially assumed to have a uniform spatial distribution. In other words, the probability density function $p_i(\mathbf{x})$ that node $i\,(1 \le i \le N)$ exists at a point $\mathbf{x} \in S$ is uniform:

$$p_i(\mathbf{x}) = p(\mathbf{x}) = \frac{1}{|S|}, \tag{3}$$

where $|S|$ is the field size.

As the node radio communication range and speed are r and v, respectively, the expected time τ from when a node i comes into contact with another node j to when the node moves out of radio communication range is given by

$$\begin{aligned} \tau &= \frac{1}{2\,r}\left(2\int_{-r}^{r}\sqrt{r^2 - x^2}dx\right)v^{-1} \\ &= \frac{\pi\,r}{2\,v} \end{aligned} \tag{4}$$

The probability that a node $j\,(\neq\, i)$ exists within radio communication range of node i is $\pi\,r^2/|S|$; thus, the contact probability $e_{i,j}$ of nodes i and j for a given slot is given by

$$e_{i,j} \quad = \quad \begin{cases} \frac{\pi\,r^2}{|S|}\,\tau^{-1} = \frac{2\,r\,v}{|S|} & i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Recall that $e_{i,j}$ is defined as the probability that nodes i and j will come in contact in a slot (probability that new ad-hoc communication becomes possible). So, we have $\lim_{v\to 0} e_{i,j} = 0$ and $\lim_{v\to\infty} e_{i,j} = \infty$.

Messages are diffused through the indirect contact of nodes through cut-through links, if cut-through links exist, in addition to the direct contact of nodes using ad-hoc communication. The contact probability matrix which considers the effects of the cut-through links, $\mathbf{E}' = (e'_{i,j})$, is derived below.

A uniform spatial distribution of the base stations is assumed; that is, the probability that a base station $l\,(1 \le l \le w+1)$ exists at a point $\mathbf{x} \in S$ is $q_l(\mathbf{x}) = 1/|S|$.

Nodes i and j can communicate through a cut-through link only when they can each communicate with one of the $w+1$ base stations. Therefore, the contact probability considering the effects of cut-through links, $e'_{i,j}$, is given by

$$e'_{i,j} \quad = \quad \begin{cases} e_{i,j} + (1 - e_{i,j})(\frac{\pi\,r^2}{|S|})^2(w+1)\,w\,\tau^{-1} & i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

B. Case of non-uniform spatial distribution of nodes

Next, we consider the case where the spatial distribution of nodes is not uniform, which means that the probability that node $i\,(1 \le i \le N)$ exists at a point $\mathbf{x} \in S$ is given by an arbitrary distribution $p_i(\mathbf{x})$.

The contact probability $e_{i,j}$ of nodes i and j for a given slot is given by

$$e_{i,j} \quad = \quad \begin{cases} \tau^{-1}\int_S p_i(\mathbf{x})\left(\int_{D(\mathbf{x},r)} p_j(\mathbf{y})d\mathbf{y}\right)d\mathbf{x} & i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where $D(\mathbf{x}, r)$ is the range within radius r around a point $\mathbf{x}$.

In what follows, the probability matrix, considering the effects of the cut-through links, $\mathbf{E}' = (e'_{i,j})$, is derived.

The coordinates of base station $l\,(1 \le l \le w+1)$ are denoted as $\mathbf{z}_l$. Nodes i and $j\,(\neq i)$ can communicate using a cut-through link only when each can communicate with a base station. The probability that nodes i and $j\,(\neq i)$ come into contact through base stations l and $m\,(\neq l)$, respectively, is given by

$$\xi_{i,j}^{l,m} \quad = \quad \tau^{-1}\int_{D(\mathbf{z}_l,r)} p_i(\mathbf{x})d\mathbf{x}\int_{D(\mathbf{z}_m,r)} p_j(\mathbf{x})d\mathbf{x}$$

Therefore, the contact probability accounting for the effects of the cut-through links, $e'_{i,j}$, is given by

$$e'_{i,j} = \begin{cases} e_{i,j} + (1 - e_{i,j}) \sum_{1 \le l,m \le w+1,\ l \ne m} \xi_{i,j}^{l,m} & i \ne j \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

C. Analysis of effects of adding cut-through links

The effect of adding a cut-through link in epidemic broadcasting is analyzed. When the number of cut-through links is increased from w to $w+1$, the diffusion of messages through cut-through links increases and the speed of the epidemic broadcasting improves. Increasing the radio communication range from r to $r + \Delta r$ also improves the speed of epidemic broadcasting, as the probability of nodes coming into contact increases. Therefore, the following analysis derives the increase in radio communication range Δr that is equivalent to increasing the number of cut-through links from w to $w+1$.

The dynamics of epidemic broadcasting are given by Eq. (2). Subsequently, the contact probability (including the effect of cut-through links) when the number of cut-through links is increased from w to $w+1$ (Eqs. (6) and (8)) becomes the same as the contact probability when the radio communication range is increased from r to $r + \Delta r$.

$$e'_{i,j}|_{w \to w+1} = e'_{i,j}|_{r \to r+\Delta r} \quad (9)$$

Solving the above equation for Δr reveals the amount of additional radio communication range that corresponds to adding a cut-through link.

V. Numerical Examples

The following parameters are used in the subsequent numerical examples unless stated otherwise: number of nodes $N = 20$, the radio communication range of nodes and base stations $r = 50$ [m], and the speed of the nodes $v = 4$ [km/h].

A. Case of uniform spatial distribution of nodes

The change in the average message-holding rate at slot k, $E[\pi_i(k)]$, when the number of cut-through links is changed from 0 to 5, is shown in Fig. 3. Here, the field size is $|S| = 250,000$ [m^2] and the slot length is 1 [s]. The initial holding rate is set to $\pi_1(0) = 10^{-4}$ for node 1, and 0 for all other nodes. The result indicates that introducing a few cut-through links significantly improves the information diffusion speed in epidemic broadcasting.

Nodes holding messages will forward them with probability 1 in P-BCAST, which is considered in this analysis. Therefore, messages diffuse rapidly when the average message-holding rate of a node $E[\pi_i(k)]$ becomes sufficiently large. Figure 3 indicates that the average message-holding rate $E[\pi_i(k)]$ increases slowly after epidemic broadcasting starts and then increases rapidly as time passes (number of slots increases). Introducing cut-through links significantly reduces the time before messages diffuse rapidly.

Figure 4 shows the results when the number of nodes is increased from $N = 20$ to $N = 40$. The conditions are the same as in Fig. 3, with the exception that the number of nodes is doubled. This result indicates that the rapidity of epidemic broadcasting significantly increases with the introduction of cut-through links even with many nodes (i.e., field node density is high). The effect of increasing cut-through links on the reduction of message-delivery time in epidemic broadcasting is almost linear.

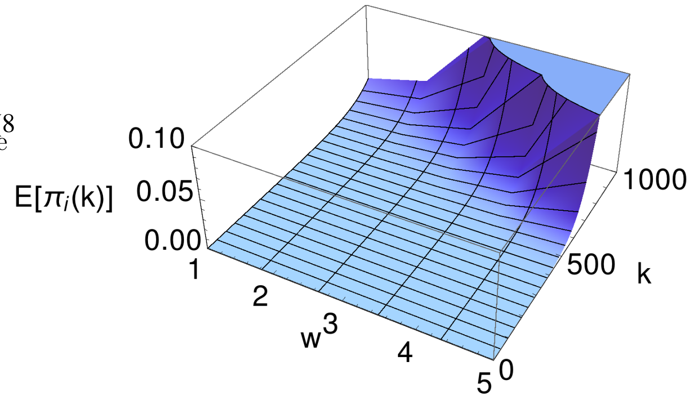

Fig. 3. Change in average message-holding rate when the number of cut-through links w is varied from 0 to 5 (assuming two-dimensional uniform spatial distribution of nodes) ($N = 20$, $r = 50$ [m], $v = 4$ [km/h]).

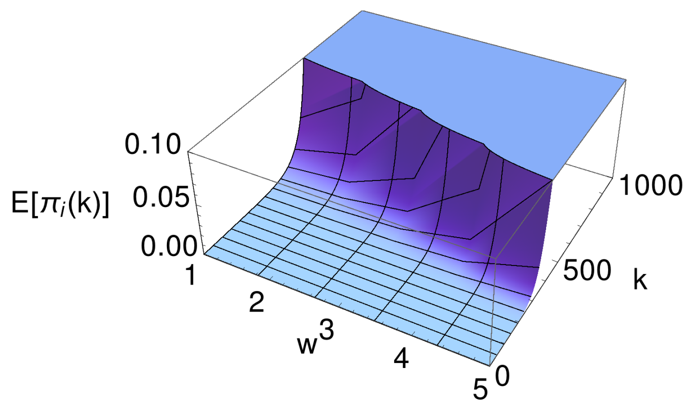

Fig. 4. Change in average message-holding rate when the number of cut-through links w is varied between 0 and 5 (assuming two-dimensional uniform spatial distribution of nodes) ($N = 40$, $r = 50$ [m], $v = 4$ [km/h]).

Figure 5 is the result when the number of nodes $N = 20$, but the radio communication range of the nodes and base stations is $r = 75$ [m]. The conditions are the same as in Fig. 3, except for the increased radio communication range of the nodes and base stations. This result shows that the rapidity of epidemic broadcasting significantly increases with the introduction of cut-through links when the node radio communication range is large.

Figures 6 and 7 show the increase in node radio communication range that corresponds to the addition of one cut-through link, Δr. Figures 6 and 7 are the results for $|S| = 250,000$ [m^2] and $|S| = 1,000,000$ [m^2], respectively. The other conditions are the same as in Fig. 3.

These results indicate that the effect of adding one cut-through link is larger when the node radio communication range, r, is larger, and when the number of cut-through links on the field, w, is smaller. For instance, when the node radio communication range is $r = 100$ [m], the effect of adding

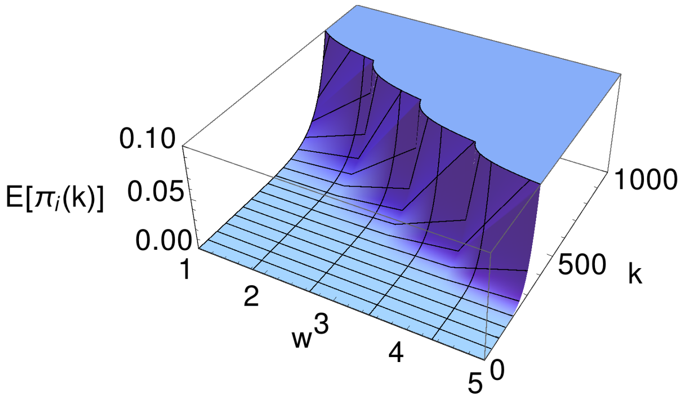

Fig. 5. Change in average message-holding rate when the number of cut-through links w is varied between 0 and 5 (assuming two-dimensional uniform spatial distribution of nodes) ($N = 20$, $r = 75$ [m], $v = 4$ [km/h]).

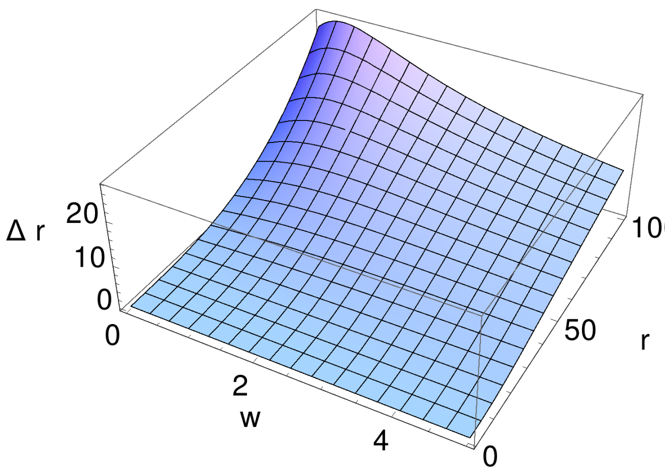

Fig. 6. Increase in node radio communication range equivalent to adding a cut-through link, r ($|S| = 250,000$ [m^2], $v = 4$ [km/h]).

a cut-through link is equivalent to increasing the node radio communication range by about 10 to 20%.

B. Case of non-uniform spatial distribution of nodes

Figure 8 is the change in the average message-holding rate $E[\pi_i(k)]$ at slot k when the number of cut-through links is 0 and 1. Here, the spatial distribution of nodes is a two-dimensional normal distribution centered at the origin (center of the field) with a standard deviation of 200 [m]. Two base stations are positioned at $\mathbf{z}_1$ = (-d, 0) and $\mathbf{z}_2$ = (d, 0) with d taken as 50, 100, or 200 [m] when there is one cut-through link. The initial message-holding rate is the same as in Fig. 3. The result indicates that appropriately placing cut-through-linked base stations according to the spatial distribution of the nodes significantly increases the performance of epidemic broadcasting.

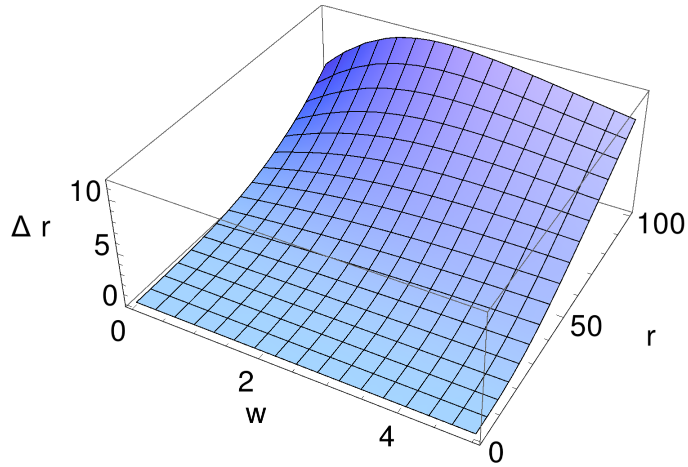

Fig. 7. Increase in node radio communication range equivalent to adding a cut-through link, r ($|S| = 1,000,000$ [m^2], $v = 4$ [km/h]).

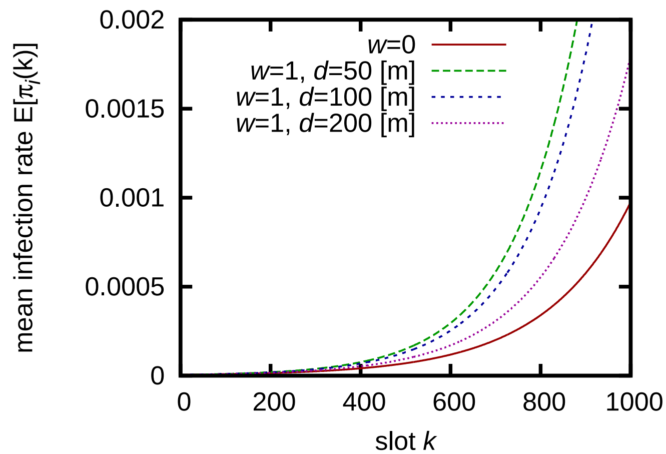

Fig. 8. Change in average message-holding rate when the number of cut-through links w is 0 and 1 (assuming two-dimensional normal spatial distribution of nodes) ($N = 20$, $r = 50$ [m], $v = 4$ [km/h]).

VI. Conclusion

In this paper, we have quantitatively analyzed the effect of introducing cut-through links in epidemic broadcasting; in particular, its effect on the speed of message delivery. Analyses have been carried out on both uniform and non-uniform spatial distributions of nodes. Consequently, we have shown that the performance of epidemic broadcasting improved significantly by introducing a small number of cut-through links and placing base stations of cut-through links appropriately according to the positional distribution of mobile nodes.

Remaining future work includes the performance analysis of epidemic broadcasting algorithms other than P-BCAST, and designing message-routing methods over cut-through links, as well as designing buffer management methods on the basis of the analysis in this paper.

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