Impact of Mobility Constraints on Epidemic Broadcast Mechanisms in Delay-Tolerant Networks

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Abstract

In this paper, we investigate the effect of mobility constraints on epidemic broadcast mechanisms in DTNs (Delay-Tolerant Networks). Major factors affecting epidemic broadcast performances are its forwarding algorithm and node mobility. The impact of forwarding algorithm and node mobility on epidemic broadcast mechanisms has been actively studied in the literature, but those studies generally use unconstrained mobility models. The objective of this paper is therefore to quantitatively investigate the effect of mobility constraints on epidemic broadcast mechanisms. We evaluate the performances of three classes of epidemic broadcast mechanisms — P-BCAST (PUSH-based BroadCast), SA-BCAST (Self-Adaptive BroadCast), and HP-BCAST (History-based P-BCAST) — with a random waypoint mobility model with mobility constraints. Our finding includes that the existence of mobility constraints significantly improves the reachability and dissemination speed of epidemic broadcast mechanisms while degrading their efficiency.

1 Introduction

An epidemic broadcast is a store-and-carry message forwarding for one-to-all communication [6]. In an epidemic broadcast, all nodes perform the same probabilistic message forwarding, and a message is repeatedly forwarded among encounter nodes. Every node generally has very limited knowledge on the network (e.g., existence of neighbor nodes). Hence, an epidemic broadcast is a sort of decentralized autonomous mechanisms; i.e., no centralized controller exists for performing broadcast communication.

Major factors affecting epidemic broadcast performances are its forwarding algorithm (e.g., the forwarding probability, the number of copies, usage of the message history, and usage of knowledge exchange among nodes) and node mobility (e.g., velocity, destination, path selection of nodes, and interference with other nodes) [3]. The impact of forwarding algorithm and node mobility on epidemic broadcast mechanisms has been actively studied in the literature (see, for example, [4, 6, 9]), but those studies generally use unconstrained mobility models such as random walk [3], random waypoint [3], aggregation point [6], and swarm mobility [6]. Hence, the impact of mobility constraints on epidemic broadcast mechanisms has not been well understood.

However, in reality, mobility of a node is usually restricted by several mobility constraints such as path constraints, with which a node has to move along one of predetermined paths (e.g., roads), and area constraints, with which a node cannot cross one or more parts of the field (e.g., no-entrance zones and obstacles).

On the contrary, in VANET researches, several constrained mobility models such as Manhattan mobility model [2], obstacle mobility model [8], and roadmap-based mobility model [5] have been used for performance evaluation of routing protocols. However, to the best of our knowledge, there exist no comparative study on the impact of mobility constraints on the performances of epidemic broadcast mechanisms.

The objective of this paper is therefore to quantitatively investigate the effect of mobility constraints on performances of epidemic broadcast mechanisms. We evaluate the performances of three classes of epidemic broadcast mechanisms [6] — P-BCAST (PUSH-based BroadCast), SA-BCAST (Self-Adaptive BroadCast), and HP-BCAST (History-based P-BCAST) — with a random waypoint mobility model with mobility constraints. Through simulations, we investigate what type of mobility constraints affect the performances of epidemic broadcast mechanisms and how the performances of epidemic broadcast mechanisms are affected by mobility constraints.

The main contributions of this paper are as follows.

- We identify different types of mobility constraints.
- We clarify what type of mobility constraints affect the performances (i.e., reachability, dissemination speed, and efficiency) of epidemic broadcast mechanisms.
- We clarify how the performances of epidemic broadcast mechanisms are affected by mobility constraints.

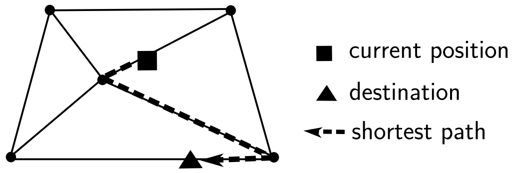


Figure 1: An example node movement with CRWP (Constrained Random WayPoint) mobility model; for a given set of paths (i.e., graph), every node moves according to the RWP mobility model following the shortest-path to its destination.

- We identify a major factor (i.e., path density), which can well characterize the performances of epidemic broadcast mechanisms under a mobility constraint.

The organization of this paper is as follows. Section 2 discusses different types of mobility constraints and introduces a mobility model with constraints called CRWP (Constrained Random WayPoint) mobility model. In Section 3, we evaluate the performances of three classes of epidemic broadcast mechanisms — P-BCAST, SA-BCAST, and HP-BCAST — with the CRWP mobility model. Section 4 concludes this paper and discusses future works.

2 Mobility Constraints and Constrained Random WayPoint Mobility Model

Mobility constraints are classified into two categories: *path constraints* and *area constraints*. Path constraints restrict the trajectory of a node; i.e., a node has to move along one of predetermined paths (e.g., lanes in VANETs). Area constraints restrict the area that a node can move; i.e., a node cannot cross one or more parts of the filed (e.g., no-entrance zones and obstacles). In this paper, we focus on path constraints since they are commonly observed in DTNs, and they can easily approximate area constraints.

We extend the RWP (Random WayPoint) mobility model [3], one of the most popular mobility models, to incorporate path constraints. The extended mobility model is called *CRWP (Constrained Random WayPoint) mobility model* (see Fig.1). In the CRWP mobility model, for a given set of paths (i.e., graph), every node moves according to the RWP mobility model except: (1) the initial position and the destination of a node are randomly chosen on a randomly-chosen path, and (2) every node moves toward its destination following the shortest-path from the current position to its destination.

3 Simulation

3.1 Epidemic Broadcast Mechanisms

In this paper, we evaluate the performances of three classes of epidemic broadcast mechanisms [6] — P-BCAST (PUSH-based BroadCast), SA-BCAST (Self-Adaptive BroadCast), and HP-BCAST (History-based P-BCAST) — with the CRWP mobility model.

P-BCAST is a simple epidemic broadcast mechanism [6, 7]. In P-BCAST, a node forwards the message whenever it encounters other nodes. Namely, a node forwards the message to other nodes, which newly enter the radio communication range of the sending node. P-BCAST achieves the optimal effectiveness (i.e., maximum coverage and minimum message delay) with the worst efficiency under infinite bandwidth [11]. P-BCAST is simple so that it has a clear drawback; i.e., P-BCAST generates an excessive amount of duplicate messages when the node density is high.

SA-BCAST and HP-BCAST are two extensions (i.e., self-adaptation and history) to P-BCAST [6].

In SA-BCAST, the forwarding probability is adjusted based on the number of duplicate messages, N_{dups}, and a node forwards only when a fraction N_{th} of neighbor nodes are changed. The forwarding probability is adjusted to

$$p = \max\left(\frac{1}{c^{N_{\mathrm{dups}}}}, min_p\right).$$

In all simulations, parameters of SA-BCAST are set to N_{th} = 0.5, c = 0.01, and min_p = 0.01.

In HP-BCAST, using the message history, a node refrains message forwarding when the encounter node is in the history (i.e., the message was already sent to or received from the encounter node).

Recall that the objective of this paper is to quantitatively investigate the effect of mobility constraints on epidemic broadcast mechanisms. We therefore intentionally use three simple epidemic broadcast mechanisms, P-BCAST, SA-BCAST, and HP-BCAST, each of which belongs to different classes.

3.2 Simulation Setup

In simulation, we use three types of path constraints: *no constraint*, *grid constraint*, and *Voronoi constraint*. The CRWP mobility model with no constraint is equivalent to the original RWP mobility model [3].

The grid constraint is a set of evenly placed orthogonal paths (see Fig. 2); i.e., all paths are either parallel or orthogonal, and the distance between any adjacent intersections is identical. The grid constraint has been used in the Manhattan mobility model [2, 13]. The total number of paths is denoted by M.

The Voronoi constraint is a set of paths, each of which is an edge of a Voronoi diagram [1] (see Fig. 3). The Voronoi constraint has been used in several mobility models for MANETs [8]. Note that the grid constraint is a special case of the Voronoi constraint. The number of points (i.e., Voronoi sites) is denoted by P. In our simulations, points are uniformly distributed in the simulation field.

Except for the mobility model, our simulation model is almost equivalent to that in [6]. Namely, a fixed number

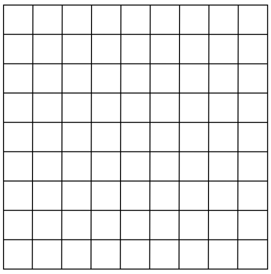


Figure 2: An example of grid constraint ($M = 20$); all paths are either parallel or orthogonal, and the distance between any adjacent intersections is identical.

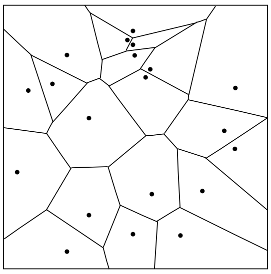


Figure 3: An example of Voronoi constraint ($P = 20$); the Voronoi constraint is a set of paths, each of which is an edge of a Voronoi diagram.

of nodes randomly move according to the CRWP mobility model on 1,000 [m] × 1,000 [m] simulation field. The velocity of nodes are uniformly distributed in $[1, 2]$ [m/s]. The radio communication range of a node is 10 [m]. At the initial state, only a single node (i.e., originating node) has a message and starts its message broadcast.

3.3 Performance Metrics

There are a number of simulation studies on epidemic broadcast mechanisms, and different performance metrics are used in different simulation studies [10, 12, 14, 15]. There is no agreed-upon performance metrics for epidemic broadcast mechanisms in DTNs. Following [11], we define time-varying performance metrics used throughout our simulations as follows.

- Reachability

  Reachability means how many nodes can receive a message with broadcast communication. In broadcast communication, it is important to deliver a message to as many nodes as possible [12].

  We define coverage(t) as the ratio of infected nodes in the simulation area at time t.

- Dissemination speed

  Dissemination speed represents how promptly a message is disseminated with broadcast communication. In broadcast communication, it is usually desirable to deliver information as quickly as possible [14].

  The speed of message dissemination is measured by $p\%$-delivery_time, which is defined as the time elapsed until $p\%$ of all nodes successfully receives the message. In our simulations, we focus on, in particular, 50%- and 90%-delivery_time.

- Efficiency

  Efficiency means how efficiently a node-to-node radio communication is performed. Namely, broadcast communication is efficient if it requires a small amount of communication overhead for a single message delivery. A certain amount of communication overhead is essentially unavoidable in any epidemic broadcast [6, 12]. But if the communication overhead is very high, it results in inefficient radio communication channel utilization, leading poor reachability and dissemination speed.

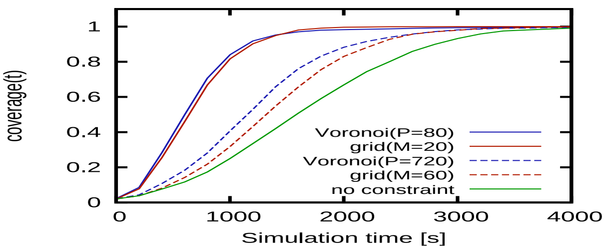
  We define messages_per_delivery(t) as the average number of messages transmitted for making a node to be infected by time t. More specifically, messages_per_delivery(t) is obtained by dividing the total number of message transmitted in the network by the number of newly infected nodes by time t.

3.4 Simulation Result: Reachability

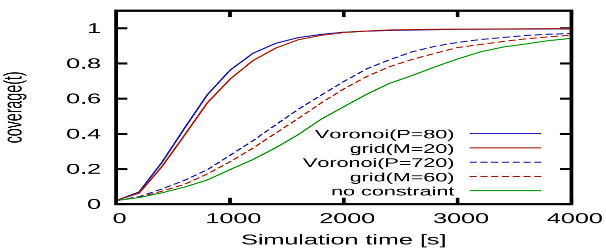
We first measure coverage(t) in epidemic broadcast mechanisms for investigating reachability; i.e., how many nodes can receive a message with epidemic broadcast. Figure 4 shows evolutions of coverage(t) with different mobility constraints in P-BCAST, SA-BCAST, and HP-BCAST. The node density ρ is fixed at 50 [node/km^2].

This figure clearly indicates that existence of mobility constraints significantly improves reachability of epidemic broadcast mechanisms. For instance, cases with the grid constraint ($M = 20$) and the Voronoi constraint ($P = 80$) achieve as 2–3 times large coverage as the case with no constraint on average. The overall performances in P-BCAST, SA-BCAST, and HP-BCAST are quite similar although there are slight differences.

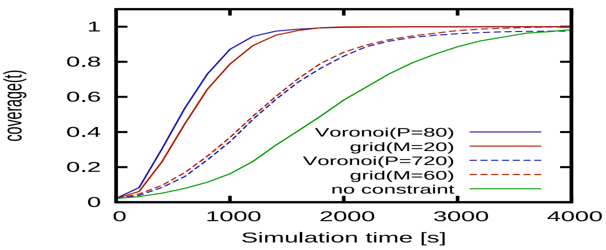
It should be noted that there are three groups of curves in the figure. The case with no constraint shows the narrowest coverage. On the other hand, cases with the grid constraint ($M = 20$) and the Voronoi constraint ($P = 80$) show the widest coverage. Cases with the grid constraint ($M = 60$) and the Voronoi constraint ($P = 720$) are in-between. Namely, the stronger the mobility constraint is, the wider the coverage becomes.



(a) P-BCAST

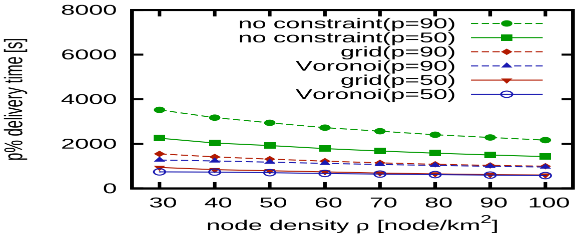


(b) SA-BCAST

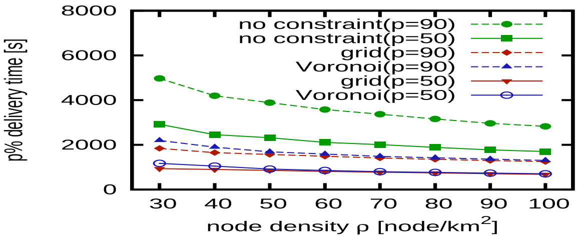


(c) HP-BCAST

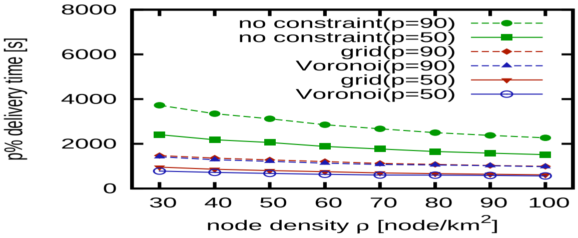
Figure 4. Evolution of coverage(t) with different mobility constraints in P-BCAST, SA-BCAST, and HP-BCAST; these figures clearly indicate that existence of mobility constraints significantly improves reachability of epidemic broadcast mechanisms.



(a) P-BCAST



(b) SA-BCAST



(c) HP-BCAST

Figure 5. 50%- and 90%-delivery_time with different mobility constraints for varied node densities ρ; the speedup factor (i.e., the ratio of p%-delivery_time with and without mobility constraint) is approximately 0.4 regardless of the node density and the value of p.

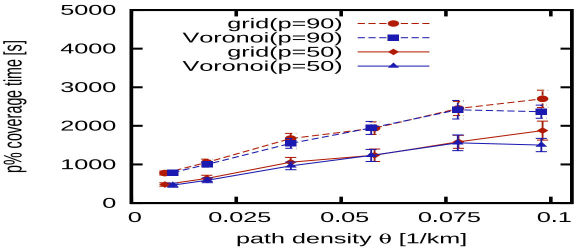
3.5 Simulation Result: Dissemination speed

We then measure 50%- and 90%-delivery_time in epidemic broadcast mechanisms for investigating dissemination speed; i.e., how promptly a message is disseminated with broadcast communication. Figure 5 shows 50%- and 90%-delivery_time with different mobility constraints for varied node densities ρ.

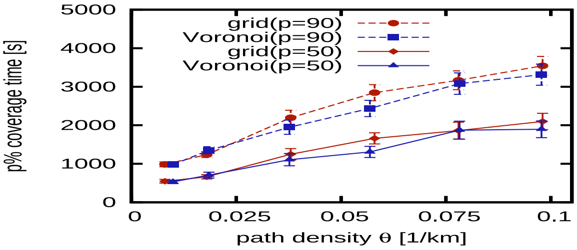
Again, this figure clearly shows that existence of mobility constraints significantly improves disseminated speed of epidemic broadcast mechanisms. It should be noted that the speedup factor (i.e., the ratio of p%-delivery_time with and without mobility constraint) is approximately 2.5 regardless of the node density and the value of p. These observations imply that the existence of mobility constraints is significant, but the effects of mobility constraints on the performances of epidemic broadcast mechanisms are not difficult to predict.

Similarly to Fig. 4, 50%-delivery_time in the cases with the grid constraint and the Voronoi constraint are closely aligned in Fig. 6. Also, 90%-delivery_time in those cases are. These results show that epidemic broadcast mechanisms with grid and Voronoi constraints show similar tendency. Namely, epidemic broadcast mechanisms with the grid constraint ($M = 20$) and the Voronoi constraint ($P = 80$) are almost identical, and epidemic broadcast mechanisms with the grid constraint ($M = 60$) and the Voronoi constraint ($P = 720$) are comparable.

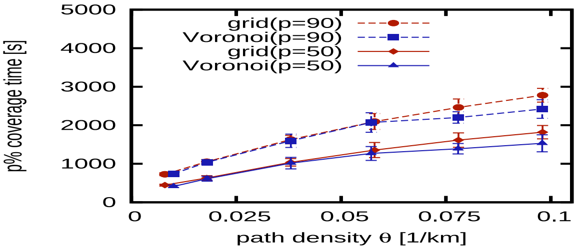
Such resemblance in grid and Voronoi constraints is, however, not surprising. In our simulations, parameters for the grid constraint (i.e., the number of paths, M) and the Voronoi constraint (i.e., the number of points, P) are chosen to match their *path densities*. We define the path density



(a) P-BCAST



(b) SA-BCAST



(c) HP-BCAST

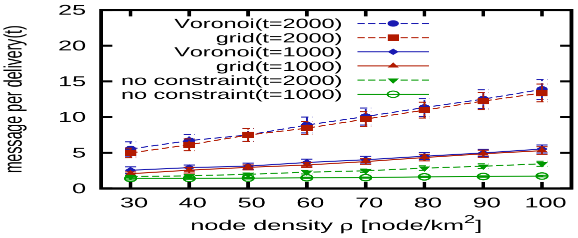
Figure 6. 50%- and 90%-delivery_time are plotted as a function of the path density; the impact of mobility constraints is well characterized by the path density.

θ as the ratio of total path lengths to the size of the field. Values of path densities with grid and Voronoi constraints are shown in Tab. 1. Figures 4 and 5 indicate that the impact of mobility constraints is well characterized by the path density.

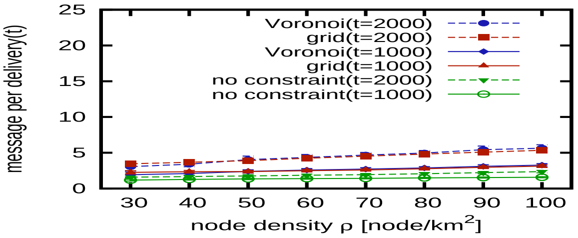
For investigating how accurately the path density can characterize the performance of epidemic broadcast mechanisms, 50%- and 90%-delivery_time are plotted as a function of the path density in Fig. 6. This figure confirms our findings; i.e., the impact of mobility constraints is well characterized by the path density.

3.6 Simulation Result: Efficiency

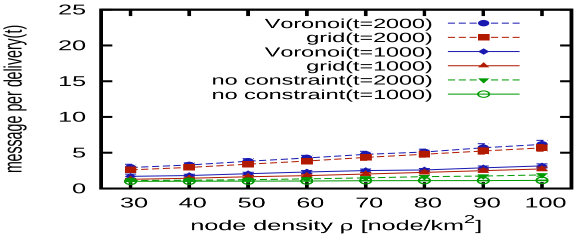
We finally measure messages_per_delivery(t) in epidemic broadcast mechanisms for investigating efficiency; i.e., how efficiently a node-to-node radio communication is performed. Figure 7 shows messages_per_delivery(t) at $t = 1,000$ and 2,000 with different mobility constraints for varied node densities ρ.



(a) P-BCAST



(b) SA-BCAST



(c) HP-BCAST

Figure 7. messages_per_delivery(t) at $t = 1,000$ and 2,000 with different mobility constraints; as the side effects of significantly better reachability and dissemination speed, existence of mobility constraints worsen the efficiency of epidemic broadcast mechanisms.

This figure indicates that, as the side effects of significantly better reachability and dissemination speed, existence of mobility constraints worsens the efficiency of epidemic broadcast mechanisms. With a mobility constraint, a node is more likely to be encountered with others along its path since every node is forced to move along its path. Such a mobility constraint significantly increases the chance of encounters with others as well as the chance of duplicate message transmissions.

We should note that, although the existence of mobility constraints degrades the efficiency of epidemic broadcast mechanisms, the performance of those epidemic broadcast mechanisms are still practically acceptable. For instance, in P-BCAST — the simplest mechanism having no mechanism for suppressing duplicate message transmission —

Table 1. Values of path densities with grid and Voronoi constraints; the impact of mobility constraint is well characterized by the path density.

mobility constraint	parameter	path density θ [1/km]
Voronoi	$P = 80$	0.0184
grid	$M = 20$	0.0180
Voronoi	$P = 720$	0.0571
grid	$M = 60$	0.0580

with mobility constraints is at the order of 10. Also, increases almost linearly against the node density ρ. These observations indicate that the existence of mobility constraints makes epidemic broadcast mechanisms easier to perform their broadcast communications.

4 Conclusion

In this paper, we have investigated the effect of mobility constraints on epidemic broadcast mechanisms in DTNs. We have evaluated the performances of P-BCAST, SA-BCAST, and HP-BCAST with the CRWP mobility model, which was an extension of the RWP (Random WayPoint) mobility model to incorporate path constraints. Our findings include that existence of mobility constraints significantly improves the performance of epidemic broadcast mechanisms, and that the impact of mobility constraints is well characterized by the path density, which is defined as the ratio of total path lengths to the size of the field.

As future work, we are planning to perform more detailed simulations of epidemic broadcast mechanisms with the CRWP mobility model. In particular, effects of several parameters — the number of nodes, the field size, the node velocity, and the radio communication range — on the performances of epidemic broadcast mechanisms need to be examined. Mathematical analysis of epidemic broadcast mechanisms with mobility constraints would be of great value for deeper understanding of epidemic broadcast mechanisms.

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