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Broadcast Delay of Epidemic Routing in Intermittently Connected Networks

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***Abstract*—We analyze the performance of epidemic routing in large-scale intermittently connected networks, under a random geometric graph model and for different mobility parameters (such as the random-waypoint, random walk and Brownian motion models). We derive a generic scaling law on the delay, which provides us with lower bounds: the average delay from a source to a destination and the average broadcast delay are both $\Omega\left(\frac{R_n\sqrt{n}}{v_n}\right)$, where n is the number of nodes in the network, v_n the maximum node speed, and R_n the radio range.**

I. Introduction

Routing protocols for mobile ad hoc networks operate under the assumption that there exists a route from a source to a destination. On the other hand, recent research has highlighted the significance of developing routing protocols for Intermittently Connected Networks (ICNs), where end-to-end multi-hop paths may not exist and communication routes are only available through time and mobility. In this case, the mobile network is almost always disconnected, making packets of information stall as long as the node mobility does not allow them to jump to another connected component. Therefore, in order to overcome the network partitions, nodes communicate by adopting a "store-carry-forward" routing mode.

In analogy with infectious diseases, an algorithm to broadcast a packet of information from a source to all other nodes is called epidemic routing; each node receiving a packet stores and carries it as it moves, passing it on to all new nodes it encounters. Epidemic routing has also been proposed as a feasible approach to forward a packet of information from a source to a destination, when no predictive knowledge on the node movements is available; all nodes behave in this manner, while the destination node receives the packet when it first meets a node carrying the information. In this case, when the traffic is low, epidemic routing can achieve an optimal delivery delay at the expense of increased use of network resources.

In this paper, our objective is to evaluate the delay that is needed in order to deliver a piece of information, using epidemic routing, to all nodes in the network, or alternatively to a given destination. A piece of information is a packet (of small size) which can be transmitted almost instantaneously between two nodes in range. We consider a network made of n nodes moving in a square area of size $\mathcal{A}$, under a random geometric graph model [11], detailed in Section II. We focus on the asymptotic behavior of the delay when the number of nodes n becomes large. In order to study the properties of intermittently connected networks, we are interested in sparse networks, as we will investigate the case where the normalized node density $\frac{nR_n^2}{\mathcal{A}}$ is small (with R_n the maximum radio range). Indeed, due to their potential applications, most of research on ICNs focuses on sparse mobile ad hoc networks (see [10]), a domain where intermittent connectivity is due to node mobility and to limited radio coverage.

The delivery delay of epidemic routing has been analyzed under various modeling assumptions [3], [7], [10], [12]. More recently, some papers have focused on information propagation in large disconnected mobile networks [4], [5], [8].

Our main result is the proof that, when the network density remains small and the radio range is constant, the average broadcast delay cannot be of order smaller than $\sqrt{n}$, as n tends to infinity. This is a considerable deviation from previous results based on Erdös-Rényi models (discussed in Section III-C), that assume a broadcast delay in $O(\log n)$. Our result holds for both the average propagation delay and the broadcast delay. When the radio range R_n and the maximum node speed v_n are not constant as $n \to \infty$, but the normalized node density remains small, our broadcast delay estimate scales in $\Omega\left(\sqrt{n}\frac{R_n}{v_n}\right)$. In particular, if $R_n = O\left(\frac{1}{\sqrt{n}}\right)$, the broadcast delay cannot be smaller than a constant, even if we consider that packet transmissions are instantaneous.

Namely, our main contributions are the following:

- we derive, in Section III, simple and generic lower-bounds on the packet propagation delay distribution in a large but bounded ICN (Theorem 2 and Theorem 3);
- we verify the validity of our analytical results via simulations in Section IV.

In addition, to analyze the broadcast delay of epidemic routing, we adapt and generalize previously computed bounds on optimal unicast routing in mobile ICNs, modeled as unit disk graphs [4], [5] (Theorem 1). Finally, we compare our delay bounds with the results of previous work, derived under the frequently used hypothesis of exponentially distributed meeting times between nodes.

II. Mobile Network Model

We consider a network of n nodes in a square area of size $\mathcal{A} = L_n \times L_n$ and radio range R_n (the index n indicates parameters that are functions of n). We will analyze the case where $n \to \infty$, such that the normalized node density $\nu = \frac{nR_n^2}{L_n^2}$ is bounded by some constant that we will precise.

Initially, the nodes are distributed uniformly at random. Every node follows an i.i.d. random trajectory, reflected on the borders of the square like billiard balls. The nodes change direction at a Poisson rate τ_n and keep a constant speed between direction changes. The maximum mobile speed is v_n. The motion direction angles are uniformly distributed between 0 and 2π. When $\tau_n > 0$, we have a random walk model; when $\tau_n \to \infty$ we are on the Brownian limit; when $\tau_n \to 0$ we are on a random waypoint-like model.

The billiard model is equivalent to considering an infinite area made of mirror images of the original square: a mobile node moves in the original square while its mirror images move in the mirror squares. The fact that a node bounces on a border is strictly equivalent to crossing it without bouncing, while its mirror image enters the square. With this perspective, the trajectory of a node is equivalent to a free random trajectory in the set of mirror images of the original square, while the nodes remain distributed uniformly at random.

We adopt the random geometric graph model [11]: two nodes at distance smaller than a maximum radio range R_n can exchange information. The average number of neighbors per node is therefore smaller than $\pi\frac{nR_n^2}{\mathcal{A}}$.

Since we are interested in investigating the best possible routing delay, we do not consider the effects of buffering or congestion. Indeed, we assume that a piece of information, *i.e.*, a packet of small size can be transmitted instantaneously between two nodes in range; this permits us to capture the fundamental performance limit of intermittently connected networks based solely on the network mobility and topology. Moreover, the previous assumptions do not impact our results, since we deal with lower bounds on the delay. In practice, our lower bounds remain accurate because information transmission occurs much faster than the speed of the mobile nodes.

III. Epidemic Routing Delay

In this section, we analyze the average propagation delay of a packet of information, using epidemic routing.

The nodes are enumerated from 1 to n. We define as T_{ij} the delivery delay, using epidemic routing, of a packet of information from a source node i to a destination j. We also define the average propagation delay $E_{ij}(T_{ij})$, as well as the average broadcast delay $E_i(\max_j T_{ij})$, *i.e.*, the average time needed to deliver a packet of information from a source node i to all other nodes in the network. In the following, we analyze $E_{ij}(T_{ij})$ and $E_i(\max_j T_{ij})$.

We base our analysis of epidemic routing on a probabilistic model of journeys of packets of information that contains all possible shortest journeys originating at the source [4], [5].

As the network is almost surely disconnected, we refer to journeys rather than paths, where a journey is an alternation of packet transmissions and carriages. Journeys are expressed as space-time trajectories, since store-carry-forward routing implies that we must take into account the time dimension. On these journeys, we consider that packet transmissions between two nodes in range take no physical time.

A. Probabilistic Space-Time Journey Analysis

Let $\mathcal{C}$ be a simple journey (*i.e.*, a journey not returning to the same node twice). Let $Z(\mathcal{C})$ be the terminal point. Let $T(\mathcal{C})$ be the time at which the journey terminates. Let $p(\mathcal{C})$ be the probability of the journey $\mathcal{C}$.

Let ζ be an inverse space vector, *i.e.*, with components expressed in inverse distance units. Let θ be a scalar in inverse time units. Considering n nodes in the network, we denote by $w_n(\zeta, \theta)$ the journey Laplace transform, defined by:

$$\begin{aligned} w_n(\zeta,\theta) &= E(\exp(-\zeta \cdot Z(\mathcal{C}) - \theta T(\mathcal{C}))) \\ &= \sum_{\mathcal{C}} p(\mathcal{C}) \exp(-\zeta \cdot Z(\mathcal{C}) - \theta T(\mathcal{C})), \end{aligned}$$

for a domain definition for (ζ, θ).

Notice that $\zeta \cdot Z(\mathcal{C})$ is the dot product of two vectors: a space vector $Z(\mathcal{C})$ and an inverse space vector ζ, so that the product is a pure scalar without dimension.

We call $p_n(\mathbf{z}_0, \mathbf{z}_1, t)$ the normalized density of journeys starting from $\mathbf{z}_0$ at time 0, and arriving at $\mathbf{z}_1$ before time t:

$$p_n(\mathbf{z}_0, \mathbf{z}_1, t) = \frac{1}{R_n^2} \sum_{\|\mathbf{z}_1 - Z(\mathcal{C})\| < R_n, T(\mathcal{C}) < t} p(\mathcal{C}) \ .$$

The journey model contains the full epidemic broadcast. Let us consider that a packet of information is generated at $t = 0$ on a node at coordinate $\mathbf{z}_0 = (x_0, y_0)$. Let us initially consider a destination node which stays motionless at coordinate $\mathbf{z}_1 = (x_1, y_1)$; in this case, $p_n(\mathbf{z}_0, \mathbf{z}_1, t)$ denotes the probability that the destination receives the beacon before time t.

If the destination is mobile, we denote by $q_n(\mathbf{z}_0, \mathbf{z}_1, t)$ the probability that the destination receives the beacon before t, when the source and destination are respectively at position $\mathbf{z}_0$ and $\mathbf{z}_1$ at $t = 0$. We bound this probability using the concept of the information propagation speed, *i.e.*, a probabilistic metric, introduced in [4], [5]. A scalar $s_0 > 0$ is an upper bound for the information propagation speed if, for all $s > s_0$, $\lim_{n\to\infty} q_n(\mathbf{z}_0, \mathbf{z}_1, \frac{\|\mathbf{z}_1 - \mathbf{z}_0\|}{s}) = 0$ when $\|\mathbf{z}_1 - \mathbf{z}_0\| \to \infty$.

With this notation, we now generalize the main theorem of [5], by adapting to epidemic routing and considering a model where the radio range R_n and the maximum node speed v_n are functions of n. Due to space constraints, we give an overview of the proof.

Theorem 1: Consider a network with n mobile nodes with radio range R_n, in a square area of size $\mathcal{A} = L_n \times L_n$, where nodes move at maximum speed v_n, and change direction at rate τ_n. When $n \to \infty$, such that $\limsup \frac{nR_n^2}{L_n^2} < \frac{1}{\pi}$, there is an upper bound s_p of the information propagation speed, which is the smallest ratio of $\frac{\theta}{\rho}$ with:

$$\theta = \sqrt{\rho^2 v_n^2 + \left(\tau_n + \frac{\frac{nR_n}{L_n^2} 4\pi v_n I_0(\rho R_n)}{1 - \frac{nR_n}{L_n^2}\pi\frac{2}{\rho} I_1(\rho R_n)}\right)^2} - \tau_n \ ,$$

where $I_0()$ and $I_1()$ are modified Bessel functions. (see [1])

a) Remark: Notice that quantity ρ is expressed as an inverse of distance, and θ is expressed as an inverse of time.

b) Remark: The expression of θ has meaning when $\frac{nR_n^2}{L_p^2} < \frac{1}{\pi}$. Above this threshold, the upper bound for the information propagation speed is infinite. Such a behavior is expected, since it is known that there exists a critical node normalized density above which the graph is fully connected or at least percolates (*i.e.,* there exists a unique infinite connected component with non-zero probability) [9].

Proof: We consider a random destination, which is first assumed to be motionless. All the other nodes are mobile.

We work with the expression of $w(\zeta, \theta, \lambda)$ which is equivalent to consider that the number of other nodes is given by a Poisson process of rate λ. We have to *de-Poissonize* it, in order to obtain an asymptotic estimate of the journey normalized density when the number of nodes n is large but not random.

According to [5] (with the extension to variable radio range R_n), we have the identity:

$$w(\zeta, \theta, \lambda) = \sum_n \frac{\lambda^n}{n!} e^{-\lambda} w_n(\zeta, \theta) = \frac{1}{\theta D(\|\zeta\|, \theta, \lambda)}, \quad (1)$$

with

$$\begin{aligned} D(\rho, \theta, \lambda) &= (1 - \tfrac{\lambda R_n}{L_n^2} \tfrac{2}{\rho} I_1(\rho R_n)) \left(\sqrt{(\tau_n + \theta)^2 - \rho^2 v_n^2} - \tau_n \right) \\ &\quad - \tfrac{\lambda}{L_n^2} 4\pi R_n v_n I_0(\rho R_n). \end{aligned}$$

In fact, identity (1) is valid for an upper bound of quantity $p_n(\mathbf{z}_0, \mathbf{z}_1, t)$, which allows the journey to be decomposed into independent segments. However, this does not impact on the validity of our result, since we address propagation speed upper-bounds.

In the Poisson model, a journey is decomposed into a sequence where the number of segments follows a Poisson distribution. Hence, we obtain asymptotic estimates on the journey probability densities, by applying an analytical de-Poissonization technique [6].

An upper bound on the information propagation speed is derived from the analysis of the singularities of the Poisson Laplace transform of the journey probability density around $\lambda = n$. In fact, we show that the density of journeys tends to zero, when the ratio $\frac{\|\mathbf{z}_0 - \mathbf{z}_1\|}{t}$ is above a certain threshold (the density tends to zero when the distance from the source increases). Hence, we obtain a bound on the information propagation speed by computing the smallest ratio that has this property. (Notice that the information propagation speed is evaluated to a distance which is a large multiple of the maximum radio range.) Therefore, from the singularity analysis (*cf.* [5]), the upper bound s_p is the smallest ratio $\frac{\theta}{\rho}$ of the non-negative pair (ρ, θ) such that $D(\rho, \theta, n) = 0$.

To finish the proof, we must account for the destination's motion. Therefore, we must multiply the journey Laplace transform $w(\zeta, \theta, \lambda)$ with the Laplace transform of the node excursion from its original position, before computing the new journey probability density. Interestingly enough, as shown in [4] (Section IV-D), this modification does not impact on the information propagation speed bound computed when the destination node remains fixed. Applying the de-Poissonization of the Laplace transform, the same result holds in the case of the bounded network domain [5]. ∎

Corollary 1: The propagation speed s_p is $O(v_n)$.

Proof: Developing the formula in Theorem 1, we have that $\theta(\rho) \geq v_n \sqrt{\rho^2 + H(\rho)^2}$, with $H(\rho) = \frac{\frac{nR_n}{L_n^2} 4\pi I_0(\rho R_n)}{1 - \frac{nR_n}{L_n^2} \pi \frac{2}{\rho} I_1(\rho R_n)}$, and with equality when $\tau_n = 0$. In the latter case, the upper bound speed s_p is proportional to v_n, with a factor of proportionality equal to $\sqrt{1 + \left(\frac{H(\rho_0)}{\rho_0}\right)^2}$, where ρ_0 minimizes $\frac{H(\rho)}{\rho}$. When $\tau_n > 0$, we have $s_p = \min\left\{\frac{\theta}{\rho}\right\} \leq v_n \sqrt{1 + \left(\frac{H(\rho_0)}{\rho_0}\right)^2}$, and the information propagation speed diminishes. ∎

B. Asymptotic Delay Analysis

Based on the probabilistic journey analysis, we derive a lower-bound of the asymptotic propagation delay, when the number of nodes becomes large.

From Theorem 1, we obtain an upper bound on the information propagation speed, which we denote here by s_p. Namely, $s_p = \min_{\rho, \theta > 0} \left\{\frac{\theta}{\rho}\right\}$, with θ and ρ defined in Theorem 1. We recall that the information propagation speed is a probabilistic metric, which applies to asymptotic distances and delays. From this discussion and the journey normalized density analysis, we prove the following lemma on the delay of epidemic routing, focusing first on the simplest case of constant radio range R_n, as n tends to infinity.

Lemma 1: Let a source node i emit a packet at time $t = 0$, at coordinate $\mathbf{z}_i = (x_i, y_i)$ in a network with n nodes and with constant radio range $R_n = R$. Let a destination node j be located at time $t = 0$ at coordinate $\mathbf{z}_j = (x_j, y_j)$. When $\|\mathbf{z}_j - \mathbf{z}_i\| \to \infty$, and the distance of z_j from the border of the network domain also tends to infinity, it holds for the delay T_{ij}:

$$P\left(T_{ij} < \frac{\|\mathbf{z}_j - \mathbf{z}_i\|}{s}\right) \to 0,$$

for all $s > s_p$ such that $s_p = \min_{\rho, \theta > 0} \left\{\frac{\theta}{\rho}\right\}$, with θ and ρ defined in Theorem 1.

Proof: To apply Theorem 1 to a particular source and destination, the destination must be at a large distance from the border of the network domain; in this case, we can ignore the fact that nodes bounce on the borders since the contribution of their mirror images (described in Section II) are negligible to the journey normalized density analysis: they induce an additional density of journeys of the order $\exp(-y)$, where y is the distance of the destination from the border (see [5]).

The definition of the information propagation speed implies that, for all $s > s_p$, $\lim q_n(\mathbf{z}_i, \mathbf{z}_j, \frac{\|\mathbf{z}_j - \mathbf{z}_i\|}{s}) = 0$ when $\|\mathbf{z}_j - \mathbf{z}_i\| \to \infty$, and the destination is sufficiently far from the border. In other words, the probability that the destination receives the information before time $\frac{\|\mathbf{z}_j - \mathbf{z}_i\|}{s}$ tends to 0. ∎

We can now prove the following lower bound concerning the asymptotic propagation and broadcast delays.

Theorem 2: In a network with n nodes, with constant radio range $R_n = R$ and maximum node speed $v_n = v_{\max}$, in a square area $\mathcal{A} = L_n \times L_n$, where the number of nodes $n \to \infty$, such that $\limsup \frac{nR^2}{L_n^2} < \frac{1}{\pi}$, the average delay from a source to a destination and the average broadcast delay are both $\Omega\left(\sqrt{n}\right)$.

Proof: W.l.o.g., we fix $\mathbf{z} = 0$ at the center of the network domain. In the following, we will consider only the source nodes that are located at $t = 0$ in a disk of radius $r_0 = \frac{L_n}{4\sqrt{\pi}}$ centered at $\mathbf{z} = 0$. Since the nodes are distributed uniformly at random, the probability that a source node s is located at $t = 0$ at distance less than or equal to r_0 from the center is $\frac{\pi r_0^2}{L_n^2} = \frac{1}{16}$.

We also consider all destination nodes located inside the annulus defined by the circles of radii $r_1 = \frac{L_n}{\sqrt{2\pi}}$ and $r_2 = \frac{3L_n}{4\sqrt{\pi}}$. Thus, the distance of each destination node from the square domain's borders is at least $\left(1 - \frac{3}{4\sqrt{\pi}}\right) L_n$. The

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probability that a destination node d is located at $t = 0$ inside the annulus is $\frac{\pi n(r_2^2 - r_1^2)}{L_n^2} = \frac{1}{16}$.

Therefore, the probability that a source node s is inside the defined disk and a destination node d inside the defined annulus is $\frac{1}{16^2}$. In this case, the distance between s and d is at least $r_1 - r_0 > \frac{L_n}{4}$.

When $L_n \to \infty$, all conditions of Lemma 1 are met. Therefore, taking the complementary delay probability, we get the convergence:

$$\max_{s,d} P\left(T_{sd} \geq \frac{L_n}{4s_p}\right) \to 1,$$

where s_p is the information propagation speed when $n \to \infty$ (since the distance between s and d is bounded from below by $\frac{L_n}{4} \to \infty$).

Consequently, if i and j are two nodes chosen at random,

$$P\left(T_{ij} \geq \frac{L_n}{4s_p}\right) \geq \frac{1}{16^2}. \quad (2)$$

From (2) and since $T_{ij} \geq 0$, we have for all $x > 0$:

$$E_{ij}(T_{ij}) \geq xP(T_{ij} \geq x) \geq \frac{1}{16^2}\frac{L_n}{4s_p},$$

by taking $x = \frac{L_n}{4s_p}$.

Therefore, using $\Omega()$ notation,

$$E_{ij}(T_{ij}) = \Omega\left(\frac{L_n}{s_p}\right). \quad (3)$$

Finally, from Theorem 1, s_p is upper-bounded by a finite constant, while $L_n = \Theta(\sqrt{n})$, such that the square area grows at the same rate as the number of nodes. Hence, (3) implies that the average propagation delay is $\Omega(\sqrt{n})$. By definition, the same bound holds for the average broadcast delay. ∎

In the more general network model where the radio range and the maximum node speed vary with n, we generalize Theorem 2 in the following theorem.

Theorem 3: For a network with n nodes with radio range R_n, in a square area $\mathcal{A} = L_n \times L_n$, where the number of nodes $n \to \infty$, such that $\limsup_{n\to\infty} \frac{nR_n^2}{L_n^2} < \frac{1}{\pi}$, and the maximum speed of the mobile nodes is v_n, the average delay from a source to a destination and the average broadcast delay are both $\Omega\left(\frac{R_n\sqrt{n}}{v_n}\right)$.

Proof: In the general network model where the radio range R_n and L_n vary with n, it suffices to scale the distances by a factor R_n and to apply the same methodology as in Theorem 2, in order to obtain the same bounds as in (3): the average propagation and broadcast delays are both in $\Omega\left(\frac{L_n}{s_p}\right)$, where s_p is the information propagation speed.

As a result, from Corollary 1, the average propagation delay (and therefore also the broadcast delay) is $\Omega\left(\frac{L_n}{v_n}\right)$.

Since $\limsup_{n\to\infty} \frac{nR_n^2}{L_n^2} < \frac{1}{\pi}$, we have that $R_n\sqrt{n} = O(L_n)$, and the delay bounds are $\Omega\left(\frac{R_n\sqrt{n}}{v_n}\right)$. ∎

These bounds apply for node densities below the percolation threshold. It is therefore important to note that $\frac{R_n}{L_n} = O\left(\frac{1}{\sqrt{n}}\right)$, and Theorem 3 does not mean that the broadcast delay is proportional to the radio range; rather, the delay follows the scaling of the radio range, which is caused by the fact that the network we consider is disconnected.

C. Comparison with Exponential Inter-Meeting Times Model

We now discuss our delay bounds, in comparison with the results of previous work, derived under the frequently used hypothesis of exponentially distributed and independent meeting times [2], [3], [10], [12]. Groenevelt et al. [3] use a Markovian model based on the hypothesis that inter-meeting times for each pair of nodes are i.i.d. and follow an exponential distribution; they evaluate the average delay for epidemic routing and a two-hop routing scheme. Zhang et al. [12] verify and extend these results under the same model, using a fluid approximation and ordinary differential equations. In both papers, the delay bound obtained for epidemic routing is $\Theta\left(\frac{\log n}{\lambda n}\right)$, where n is the number of nodes in the network and λ is the inter-meeting time intensity (the rate at which two nodes meet). Although the analysis is based on the assumption that the inter-meeting time intensity is independent of the number of nodes in the network, a question arising is whether these results can be extrapolated in order to evaluate the scaling behavior of the delay in a more general and realistic network model.

The authors of [10] introduced an Erdös-Rényi graph model, justified by a similar hypothesis on exponentially distributed and independent intra-meeting times, in order to upper bound the delay of epidemic routing. In this case, the intra-meeting intensity (the rate at which any two of the network nodes meet) is assumed constant and independent of the number of nodes in the network, but a tentative generalization (by scaling the radio range or the node speeds) yields roughly the same scaling estimates for the delay as [3], [12].

As stated in Section 4 in [3], in case we have a network of fixed size, with constant node speeds and with a radio range scaling in $O\left(\frac{1}{\sqrt{n}}\right)$, the delay bound obtained for epidemic routing is $O\left(\frac{\log n}{\sqrt{n}}\right)$, where n is the number of nodes in the network. Conversely, our analysis (Theorem 3) suggests that the delay is rather $\Omega(1)$. Similarly, in the extended network model (considered in Theorem 2) the delay of epidemic routing according to [3], [12] would be $O(\log n)$, in contrast to $\Omega(\sqrt{n})$ in our analysis. It is important to note that our results do not contradict the rigorous theoretical analyses of [3], [10], [12]. The discrepancy in the scaling laws comes from the fact that we depart from the modeling hypothesis of independent meeting times or Erdös-Rényi graphs. In fact, when a node mobility model is assumed in random geometric graphs, meeting times are not independent from one mobile node to another. Moreover, in the domain and time-scale we consider, the inter-meeting times cannot be assumed exponentially i.i.d., as shown by a theoretical analysis verified by previous real world measurements in [2] (however, first meeting times are exponential). Therefore, our scaling laws in Theorem 2 and Theorem 3 accurately capture the scaling behavior of the delay of epidemic routing in large networks. Our analysis is also consistent with the results of [8], which show that, in a more restricted mobility model (constrained i.i.d. and

Brownian motion) and when the network is not percolated, the information dissemination latency scales linearly with the Euclidean distance between the sender and the receiver.

IV. Numerical Results

In this section, we perform simulation measurements to compare the scaling behavior of the delivery delay using epidemic routing in an intermittently connected mobile network.

The simulator we use is self-developed and follows the mobility model described in Section II. We simulate epidemic routing of a packet. For each simulation plot, we choose a source node i at random and we measure the average propagation delay $E_{ij}(T_{ij})$, as well as the average broadcast delay $E_i(\max_j T_{ij})$ to all destinations j. Each simulation scenario is run 10 times.

Moreover, we simulate two different mobility parameters (rates of direction change): $\tau_n = 0$ for a billiard model, where nodes change direction only when they bounce on the border, and $\tau_n = 0.1$ for a random walk model.

In Figure 1, we simulate an extended network, which corresponds to the network model described in Theorem 2: we fix the node speed $v = 10$ and range $R = 10$, while the number of nodes n varies from 125 to 2000, in a square network domain of variable size $\mathcal{A} = L_n \times L_n$, such that the normalized node density is constant: $\nu = \frac{nR^2}{L_n^2} = 0.05$. According to Theorem 2, the delay must scale at least as $\sqrt{n}$. To better illustrate this behavior, we normalize the measured delay by a factor $\sqrt{n}$, such that the plots stay above a constant, when n becomes large.

In Figure 2, we simulate a network in a fixed size domain $A = 3000 \times 3000$. Again, the mobile node speed is fixed to $v = 10$, but now we vary the node range R_n with n, and n ranging from 125 to 2000, such that the normalized node density is again constant: $\nu = \frac{nR_n^2}{A} = 0.0444$. According to Theorem 3, the delay scales at least as a constant for large n.

It is interesting to observe in both figures, that the measurements accurately verify the asymptotic behavior derived from our analysis, suggesting that our scaling bounds are tight.

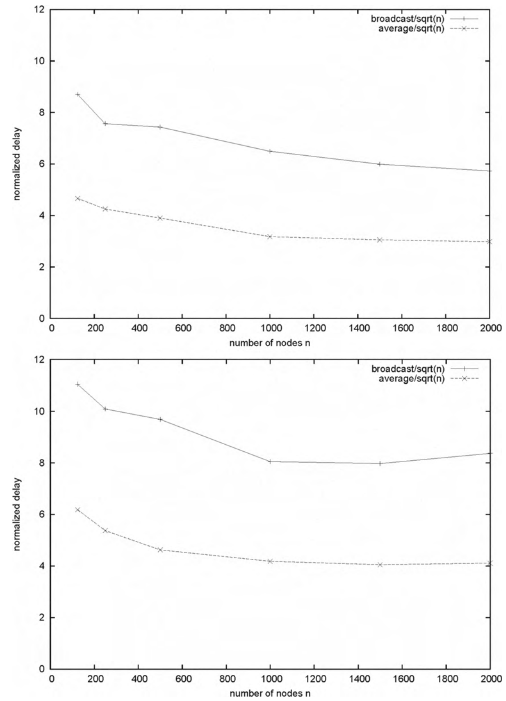

Fig. 1. Normalized average delay between a source and destination and average broadcast delay versus number of nodes n, for billiard (top) and random walk (bottom) mobility, for mobile speed $v = 10$, range $R = 10$ in a square of variable size such that the normalized node density is constant.

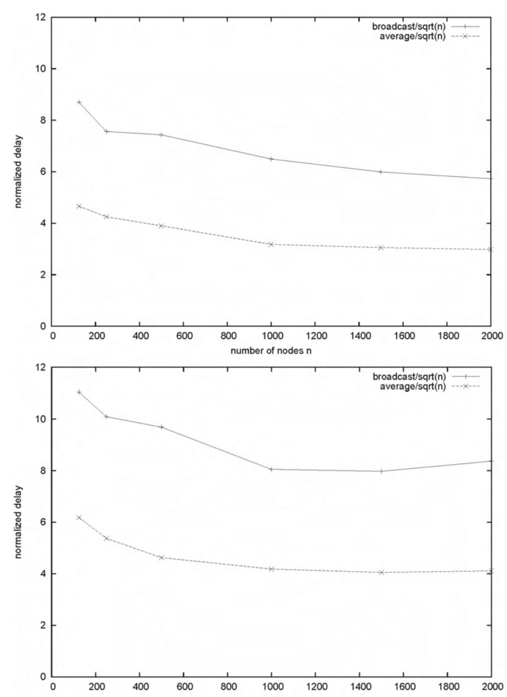

Fig. 2. Average delay between a source and destination and average broadcast delay versus number of mobile nodes n, for billiard (top) and random walk (bottom) mobility, for mobile speed $v = 10$, in a fixed domain $A = 3000 \times 3000$, with variable node range $R_n = \frac{20}{\sqrt{10^{-3} n}}$.

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