Delay-Tolerant Broadcasting

Gunnar Karlsson, Vincent Lenders, and Martin May

***Abstract*—There are many asynchronous communication situations for which the prevalent continuous connectivity paradigm is not needed. Communication with a fair delay tolerance may instead be provided by intermittent store-and-forwarding between nodes. This paper proposes a design for an open, receiver-driven broadcasting system that relies on delay-tolerant forwarding of data chunks through mobility of wireless nodes. The system provides public broadcast channels, which may be openly used for both transmission and reception. We show by analysis and simulation under benchmark mobility models that a delay-tolerant broadcast channel has both a sufficiently high throughput and reach to be interesting as a competitive alternative to the regulated wireless broadcast channel. The analysis is based on a queuing model to study the interactions among the mobile nodes in a street. The simulations complement this analysis for mobile nodes moving on a square according to benchmark mobility models. Finally, we present the design of, and experiences with, a proof-of-concept prototype.**

***Index Terms*—Broadcasting, communication systems, computer networks, mobile communication, networks, personal communication networks, routing.**

I. Introduction

COMMUNICATION networks have traditionally provided continuous end-to-end connectivity. This is natural when the primary service is interactive voice conversations. The continuous connectivity paradigm has also been assumed for asynchronous services with generous tolerance of delay in the delivery of data. The paradigm might be unnecessary for such services, but it comes at a low cost for wired networks. This is not the case for wireless networks for which it might be infeasible or uneconomical to provide uninterrupted connections everywhere. As a consequence, there will be intermittencies occurring due to insufficient coverage of areas where there are mobile nodes roaming.

Delay and disruption tolerant communication does not assume that the network consists of more than a set of disjoint point-to-point connections at any given point in time [7]. The data move from one node to the other, and are spread by the mobility of the nodes. Such a loosely connected network might still be of good use for many asynchronous services. In particular, our interest is in a generic service for disseminating contents to an arbitrarily large group of receivers, without any assurance on the completeness or order of the delivery; in other words, we wish to provide a delay-tolerant broadcasting service.

How well this service performs depends on its availability and the movements of the nodes that participate in the contents dissemination. As an illustration of the capability of such a system, consider the case where pedestrians are walking in the same direction along a 100-meter long pathway, each with a velocity of one meter per second; the radio transmission supports a constant bit rate of 1 Mb/s within a coverage range of 10 meters forward and backward of the node. If people enter the pathway according to a Poisson process with an average distance of 20 meters between two adjacent persons, then a person makes a pair-wise contact with a person in front or behind with probability 0.56. They share the link capacity so the bit rate is 0.5 Mb/s per node. The contact lasts 95 seconds on average and is sufficient for transferring up to 3.3 MB during the walk. That is sufficient for more than 200 seconds of music, played back at a rate of 128 kb/s. This simple calculation indicates that it might even be possible to support continuous streaming of audio by delay-tolerant broadcasting since the expected play-out of the data exceeds the time it takes to walk down the street (see Section IV for the detailed derivation of these numbers).

Our main motivation for developing a delay-tolerant broadcasting scheme is to have an alternative to terrestrial and satellite broadcasting systems. We expect the system to be of most use where there is denser population of users, such as urban areas, beaches, camping sites, sports fields, and in public transportation. We believe that an unlicensed public broadcasting system fills a need since the terrestrial wireless broadcast channels are highly regulated. Not only is the spectrum allocation strictly guarded, but also the concession rights to send programs are severely limited and awarded on politically decided criteria and commercial terms. In addition, the broadcast contents may be subject to regulation and sometimes also to censorship. It is therefore interesting to design a wireless broadcast system for the unlicensed ISM bands to support asynchronous and delay-tolerant applications. The system would be open for public transmission from anyone, similar to broadcasts on the fixed Internet.

We define broadcast to be a dissemination mode of data for which the group of receivers is completely open; any node that wishes to receive data from a particular broadcast channel is allowed to do so. This is the same definition as that for regular wireless public broadcasts. The distinction between multicast and broadcast might be artificial: we use the term broadcast here only to mean that the group of receivers is undefined and that contents spread indefinitely from node to node. The broadcast is organized in channels (this is analogous to a multicast group), where each channel provides a particular type of content that is selected by a producer. A novelty of the system is a receiver-driven broadcasting scheme; there is no flooding of contents as

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in epidemic dissemination schemes [27]. A node may entreat contents for a channel from a peer node that it meets, but does not have the obligation to do so.

The following are the contributions that we report in this paper. We present the concept of the broadcast system and three feasibility studies: (i) an analytic study for mobility in one dimension for a street; (ii) a simulation-based study with mobile devices on a plane; (iii) an implementation study of the development of a prototype system based on Bluetooth.

The paper is structured as follows. The next section reviews important related works that have influenced our design, and it discusses our contributions in relation to the prior art. Section III describes the concept and the system design in more detail. Section IV describes the analytic performance model and the results we get from it. The evaluation based on simulations is presented in Section V. A first prototype of a broadcast system for Bluetooth is described in Section VI. Section VII summarizes our contributions, presents our conclusion, and outlines further issues of study for making delay-tolerant broadcasting a reality.

II. Related Work

The area of delay-tolerant networks is gaining attention and the research is progressing in many different directions. The Delay Tolerant Network Research Group (DTNRG) [1] has proposed an architecture [4] to support messaging that may be used by delay tolerant applications. The architecture consists mainly of the addition of an overlay, called the bundle layer, above a network transport layer. Messages are transferred in bundles in an atomic fashion between nodes, using a transport protocol that ensures node-to-node reliability. These messages can be of any size. Nodes are assumed to have buffers in which they store the bundles. In contrast to this approach, we do not aim at providing reliable data transfer.

Routing in delay-tolerant networks has been addressed recently in [2], [10], [13], [14], [27]. Our system does not require a routing infrastructure. The idea of our system is to use a pure interest-based pull approach where nodes only download content from one-hop neighbors. Multicast routing in DTN has been addressed in [32]. While the goal of our system is also to deliver data to a group of people, our approach is decoupled from any multicast semantics (such as group memberships, et cetera). The work by Choudhury [6] also concerns data dissemination, albeit it assumes a random push mode (gossip).

Data collection in partially connected sensor networks has been addressed in [16], [26], [31]. The basic idea of these works is similar to ours, namely exploiting mobility to forward data in the network. The main difference is that sensor networks aim at pushing information out of the network to data sinks, whereas our system is designed to pull content down to the mobile user. Khelil *et al.* [17] suggest several metrics for quantifying the impact of mobility at large time-scale on the performance of delay-tolerant networks. We have used some of those metrics in our work. Hui *et al.* have conducted measurements with real human mobility in [12]. Lenders *et al.* [18], [19] measured human mobility in an office environment. Such traces could be used to validate our system for real situations.

The "drive-through internet" is based on WLAN coverage along roads to provide intermittent network access; there is no relaying of data between cars [24]. The concept of mobile infostation networks is equivalent to delay-tolerant networks; the work presented in [28]–[30] lends support to our design. Also, it has been shown that the long-term throughput for an ad hoc network with mobile nodes can remain constant as the density of nodes increases [9]. And finally, Peoplenet has some similarities with our approach in the way information propagates on a contact basis between mobile users [22]. However, Peoplenet heavily relies on a fixed infrastructure and is targeted at seeking information in contrast to broadcasting information.

A note on the modeling. There has not been much use of space-time queuing models for mobile communication to capture the number of users in an area and the mobility between areas. The Markovian highway PALM model is one example [20]. It is a sophisticated model for car traffic on a highway and is used for dimensioning cellular telephony. Hence, it is made for a different communication mode than our delay tolerant peer-to-peer mode. The mobile infostation concept has also been analysed for a high-way scenario and the analysis parallels our street model [30]. Serfozo's book treats the theory of spatial models in depth [25].

III. New Broadcasting System

A. Concept

The broadcasting system consists of mobile-user nodes in a loosely defined network. Nodes wishing to receive contents on a chosen channel solicit them from nodes they encounter as they move around. They might in return be asked for contents of the same or any other channel. Nodes also solicit contents in order to redistribute it, without the user having a desire to receive it. The solicitation strategy allows a node to adapt its caching strategy to its storage and energy resources, or any other local policy; the node may implement various strategies for soliciting contents to improve the performance of the system, to solicit contents that is requested the most or that the user has most interest in forwarding, for instance.

Taken together, the broadcast and delay-tolerant paradigms simplify the system: there is no group to be maintained and there is no explicit routing in this communication mode; routing is in fact replaced by mobility as nodes come to places where data are available. All data transfers are one-hop long and the link layer thus resolves contention for the data transmission between nodes. Our system architecture leverages all types of wireless data-link protocols, for instance IEEE 802.11 and Bluetooth.

Contents are brought into an area of interest by the mobile nodes, or, alternatively, they are generated by the mobile nodes in the area. The mobile nodes could retrieve contents when they "dock" at places where they are connected to the Internet (for instance, by means of podcasting). The content retrieval could also be over a wireless network, such as a wireless local-area network or a wide-area cellular network. Our broadcasting system adds the following advantages to podcasting and to multicasting over infrastructure-based wireless networks:

1) It provides contents to mobile nodes between the docking opportunities (which could be hours apart).
2) It extends the reach of the dissemination of data in the infrastructure-based wireless network.

3) Contents that originate from the mobile nodes could be broadcast without any infrastructure.

Hence, the delay-tolerant broadcast complements infrastructure-based broadcasts, and offers a new mode of ad hoc broadcasting between mobile nodes for any content they generate and that should be openly disseminated (such as for example still images, video, and voice clips). The connection between the delay-tolerant broadcast and the infrastructure is not in the focus of this work, and we do not further discuss how contents are initially brought into the wireless domain in this paper.

The data is delivered in "chunks" which are delivered in arbitrary order, without assured completeness. Order can be imposed at the receiving end either by soliciting chunks in a given order or, better, by soliciting them in any order, followed by sorting. We will therefore be concerned with the possible reception rate for a mobile node, as well as the dissemination rate and reach of an individual chunk of data. Note that there are many applications for which order and completeness are not necessary: the distribution of a mixture or music, news, traffic and weather information, as done by most radio stations today, would not require complete nor orderly delivery, as long as the data chunks correspond to meaningful parts of contents, a song or a news item for example.

A mobile node that has associated with a peer node may solicit contents for the particular broadcast channels that it listens to, or for any channel for which it is willing to carry contents. Since there is no connected network in the wireless domain, there is no need for routing. The application is hence based either on UDP over IP for which the packets are broadcast with TTL set to one (the broadcast could be for a specific sub-network, if appropriate), or on the data-link protocol directly (as in our prototype). The UDP/IP suite might be useful for docking, but places where the node remains resident for longer times could equally well provide systems running the broadcasting protocol so that the docking is at the application layer.

We assume that nodes connect pair-wise and that neighboring pairs do not disturb each others, e.g., they use different channels for 802.11 or different sequences for the frequency hopping for Bluetooth. The data link association is established according to the specification of the particular link layer being used, and the MAC protocol resolves contention when nodes meet; a node does not associate with more than one other node. The reason is to economize on the limited connections to maximize the amount of data transferred (it is also supported by the optimal transmission range [28]). The system could use robust header compression, provided that it actually speeds up the transfer when the association times are short. We do not address problems at the physical layer, such as interference, decay or fading. If the radio conditions are good, a connection is established, otherwise it is not; interference is dealt with through the proper design of the link layers. The design issues for the broadcast lie instead at the application layer: the solicitation protocol and the naming schemes for contents and broadcast channels.

B. System Design

In the following, we describe our system design. We first describe how broadcast channels are structured. Then, we introduce how nodes discover and request contents from channels. We also discuss how our delay-tolerant broadcasting system could be improved by deploying fixed caching nodes at strategic locations.

1) Channels and Chunks: A broadcast channel is defined by a name, an identifier, some metadata about its contents, and the name of the producer, followed by a list of chunk names including their sequence numbers. This definition is provided in a file that is available through a URL. All broadcast channels and data chunks have unique universal resource identifiers (URI) [3]. Given a channel name, it is possible to locate the definition file of the channel through any search engine.

A chunk is defined by its name, its file type, and some metadata. The metadata may for example include artist and title to be displayed at playback, and can also be used for queries. An important issue is to determine what constitutes official contents for a channel: for instance music of a certain genre, or from a selected group of artists. This is the decision of the producer for the channel. However, our system also allows for channels where any contents of a specific media type is allowed: for instance a music channel for which everybody may provide contents.

2) Channel Announcements: In order to bootstrap the listening, one channel is pre-defined: the *discovery channel*. This channel announces the names of available broadcast channels and is carried by all nodes. A node that does not know what channels to ask for sends a request for this particular channel and, as reply, would get a chunk containing the list of channels known by the corresponding node. The user then selects a set of channels from this list and asks for contents in this set.

3) Request for Contents: The protocol for requesting contents is straightforward: a node simply requests contents from a set of channels, or it requests any of a set of specified chunks of data. The following should apply:

- A named chunk may be requested with a given offset to allow the completion of a previously interrupted transfer.
- Requests for contents from a channel may specify chunks that are not of interest (for instance those that are already retrieved).
- If node A solicits contents for channel i and node B only stores contents for channel j, then B should provide A with any chunk that appears on both channels i and j.
- A chunk of data may be requested based on its metadata.

A request is issued as a list:

$$< \mathtt{id}\ 1, \mathtt{offset} >; < \mathtt{id}\ 2, \mathtt{offset} >; < \mathtt{id}\ \mathtt{N}, \mathtt{offset} >$$

Each id is a URI for either a chunk, in which case the offset is measured in bytes within the data volume, or for a channel where the offset is the lowest sequence number of interest for a chunk (or the lowest time stamp) on the channel. Requests for channels and chunks might be mixed in a request and the list may be of arbitrary length; it should ideally fit into a single packet. Contents may also be requested based on meta-data. The third bullet point is difficult to ensure: it would require chunks to carry all the channel names where they appear, but the channel contents are selected by producers who are not coordinated with one another. We cannot solve this currently.

The associations when nodes meet might be short and it is vital to economize on the connection time. The most efficient implementation is to embed the requests for data in the MAC-layer beacons. However, it would require a cross-layer design that might be difficult to have accepted for MAC layer standards; it would for instance cause more overhead since the beacon frames would be longer than otherwise.

4) Fixed Caching Nodes: The performance of the broadcasting system depends on the node density, on the mobility, but also on the availability of contents at the nodes. To improve the performance in general, we propose the use of dedicated fixed nodes acting as content caches. These caching nodes would typically not run an application for the stored data and would only serve to disseminate the content. Since fixed caching nodes do not need to have an Internet connection, they may easily be placed in public transportation systems and throughout the built environment. Note however, that the fixed caching nodes are optional in our design, and only introduced to improve the overall performance of the broadcasting.

IV. Analytic Evaluation

With the mixing of data among the mobile nodes and the fetching of data from fixed nodes, it is clear that nodes receive some subset of the available data chunks in a random order. We describe here a model of the broadcast system that allows us to study some basic performance measures:

- *Data rate*: The average data rate for the exchange via the intermittent connections.
- *Rate of contacts*: The average rate of contacts that a node makes.
- *Contact duration*: The expected duration of the connections a node establishes while traveling.

The performance depends on the number of users in an area and their mobility patterns, whether they are resident or disappear from the area, and the rate of data transmission when nodes exchange data. The performance also depends on the number of chunks a node caches for delivery to others (and for its own consumption). The latter is however not captured in the model; it represents the subset of all mobile nodes that posses content to share with each other (they listen to the same channels for instance).

We are going to study a limited region in this section: a street. We will also present how the street model can be combined to model arbitrarily large networks of streets. The feasibility of the concept for mobility on the plane is studied by means of simulation in the subsequent section.

The model takes as its input a renewal process of arriving nodes. The particular process and its average arrival rate may be estimated from measurements, albeit the Poisson arrival process is a reasonable default choice. Measurements may also provide the probability distribution for the node velocities. The length of the street as well as the transmission range and bit rate are considered to be given parameters. Since the system does not exist, there is no possibility to estimate parameters for it at this time but we would like to stress that it is feasible to model an actual street. Our purpose at this time is to study if the broadcast concept appears workable for reasonable assumptions. We are mostly concerned with densely populated areas where the number of mobile nodes in an area is high, and where the nodes move with pedestrian speeds (note however that this is not assumed by the model itself).

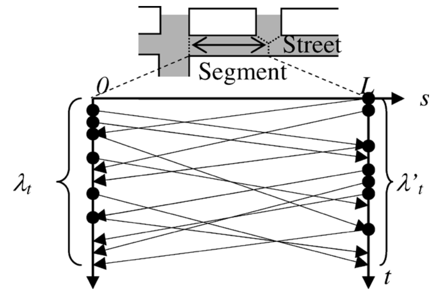

Fig. 1. A street is modelled in segments. Nodes arrive at the end points of an L-meter long segment at average rates λ_t nodes per second from the left and λ'_t from the right. The axes denote space (s) and time (t).

A. The Street Model

We model the street for pedestrian nodes as a one-dimensional topology. This is reasonable if the width of the sidewalk (or the pedestrian alley) is narrower than the transmission range of the radio. An actual street may be cut into segments, where each segment is such that the arrivals to, and departures from, only occurs at its endpoints (see Fig. 1). The sidewalks on the two sides of a street may be modelled independently of one another, if we assume that the crossings occur at the endpoints of the street segment and the driveways are wider than the transmission range.

We impose the following restrictions in order to get a tractable and illustrative model that still retains a measure of realism:

- We assume that nodes do not change direction on the segment; hence they enter at one end and depart from the other.
- The speed of walking is constant for each node. Velocities are independently assigned to the nodes from one and the same distribution. The sojourn time for a node is simply the length of the street segment divided by its speed.
- The data exchange between two nodes that meet is proportional to the length of time that they remain in contact, which is determined by their relative velocity to one another and the time that both remain in the street.
- All mobile nodes are identical with respect to transmission and storage capabilities. Storage is not limited.

The rate into a street segment from the left is denoted by λ and correspondingly λ' denotes the rate of arrivals from the right, as shown in Fig. 1 (the apostrophe is used on other parameters in an analogous fashion). The time rate is indicated by λ_t when needed and the spatial rate by λ_s; they are related through the velocities of the nodes.

B. Probability of Contacts

Consider nodes moving only in one direction along an L-meter long street. Fix a time t and let the distance between two consecutive nodes be denoted by the random variable X. These internodal distances are independently drawn from one and the same distribution $F_X(x) = P(X \leq x)$, with average distance λ_s^{-1}. The probability that two nodes are within transmission range Δ is $q(\lambda_s) = F_X(\Delta)$. We hence transform the arrival process into a discrete Bernoulli process where an interval is connected with probability q and disconnected with probability $1-q$. However, we only use pair-wise communication and therefore transform this process into a new one: Let $x_i = 1$ denote a connected interval in the Bernoulli process where $p(x_i = 1) = q$. The output process is defined by $y_i = x_i(1-y_{i-1})$, where y_i is 1 or 0 for connected and unconnected intervals respectively; it has never two consecutive intervals connected. (It is a two-state discrete Markov process with transition probabilities p_{ij} for going from state i to state j: $p_{00} = 1-q$, $p_{01} = q$, $p_{10} = 1$.) Taking expectations of the expression for y_i and letting i grow large gives the expected probability of pair-wise connected nodes as $E(y) = q/(1+q)$, since x_i and y_{i-1} are independent.

The probability that a node is connected at time t is hence

$$r(\lambda_s) = 2E(y) = \frac{2q}{1+q} = \frac{2F_X(\Delta)}{1+F_X(\Delta)}. \quad (1)$$

The expected number of connected nodes in the street at t is $L\lambda_s r(\lambda_s)$. The transferred volume of data is given by b, the bit rate of a connection, times the total contact duration for a node on the street. The contact duration depends both on the arrival rates of nodes into the street from the two ends and on the distribution of node speeds.

1) Inter-Arrival Time Distribution: Assume that nodes move at a fixed speed on the street, which is the same for all nodes moving in the same direction. The internodal distances on the street have therefore the same distribution as the inter-arrival times. Fig. 2 shows the probability of a contact, $r(\lambda_s)$, for three different inter-arrival distributions of nodes, all with average λ_s: an exponential distribution, an Erlang distribution with four phases and a two-phase hyper-exponential distribution with arrival rate $0.35\lambda_s$ in phase 1 selected with probability 0.31 and $5.7\lambda_s$ in phase 2 selected with probability 0.69. The Erlang distribution has a coefficient of variation 1/2 and the hyper-exponential distribution has a coefficient of variation 2.

We see in the figure that the hyper-exponential arrival process, which is burstier, gives higher contact probabilities at low arrival rates, but lower at high arrival rates, compared to the other two distributions. This is expected since there will be contacts within the bursts also at low rates, but it requires higher arrival rates to have contacts between bursts. An Erlang distribution tends towards a constant arrival rate when the number of stages increases and the probability of contact is hence low at small rates ($r \to 0$ for $\lambda_s < 1/\Delta$ as the number of stages $\to \infty$).

The conclusion we draw is that bursty arrivals of mobile nodes is advantageous; the more constant the distances between nodes become, the higher the rate must be in order for the probability of connectivity to be high. We believe that the Poisson arrival process represents the most realistic case, since it arises from people independently arriving to the street (groups of people would only yield better results, and we do not see a mechanism that would reduce the variance of the arrival process so that an Erlang model would be appropriate).

Hence we will in the remainder of the Section assume that arrivals of nodes into the street are modelled as Poisson processes with intensity λ_t and λ'_t for the two ends, respectively.

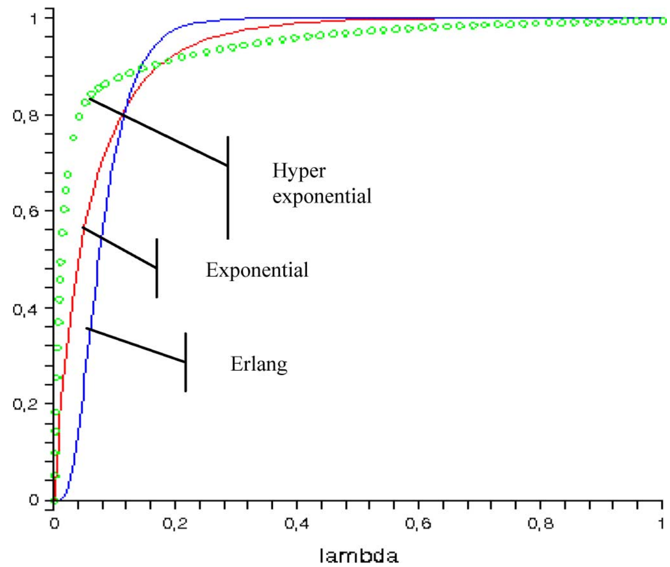

Fig. 2. The probability of a node being connected for a transmission range of 10 m and average arrival rate of nodes, λ_s $[m^{-1}]$. The inter-arrival distances have exponential, four-phase Erlang and two-phase hyper-exponential distributions. All nodes move with the same speed.

2) The Distribution of Node Velocities: The node velocities are randomly distributed in a range $[v_{min}, v_{max}]$, where $v_{min} > 0$ to avoid indefinite accumulation of nodes, and $v_{min} \le v_{max} \le \infty$ (we assume a finite mean). The distribution of nodal velocities is $F_V(v) = P(V \le v)$; we assume that the probability-density function exists and is denoted by $f_V(v)$. The temporal and spatial arrival rates are related through

$$\lambda_s = \lambda_t \overline{1/v}, \quad (2)$$

where

$$\overline{1/v} = \int_{v_{min}}^{v_{max}} \frac{1}{v} f_V(v) dv. \quad (3)$$

Note that if the temporal arrival process of nodes to the street is Poisson with rate λ_t nodes per second, then the spatial distribution of nodes in the street becomes Poisson as well with average rate λ_s ($f_V(v)dv \times \lambda_t/v$ is a thinned spatial Poisson process, consisting only of nodes moving at speed v; the spatial process is a superposition of all such processes for all v; the superposition of Poisson processes is still Poisson).

The speed distribution impacts the spatial distribution. These are some examples, all with average velocity of one meter per second ($\mathbf{U}$ means a uniform distribution over the stated range, and $\mathbf{exp}(0.9)$ is an exponential distribution with mean 0.9 m/s).

1) $V \in \mathbf{U}[0.5, 1.5] : \lambda_s = 1.1\lambda_t$
2) $V \in \mathbf{U}[0.1, 1.9] : \lambda_s = 1.6\lambda_t$
3) $V \in [\mathbf{exp}(0.9) + 0.1], v_{min} = 0.1 : \lambda_s = 0.9\lambda_t$

The resulting contact probabilities are plotted in Fig. 3 for Poisson arrivals. It is clear that slow velocities result in higher contact probabilities since nodes are located close to one another, while higher velocities lead to short contact durations. The wider the support for the distribution, in the uniform case,

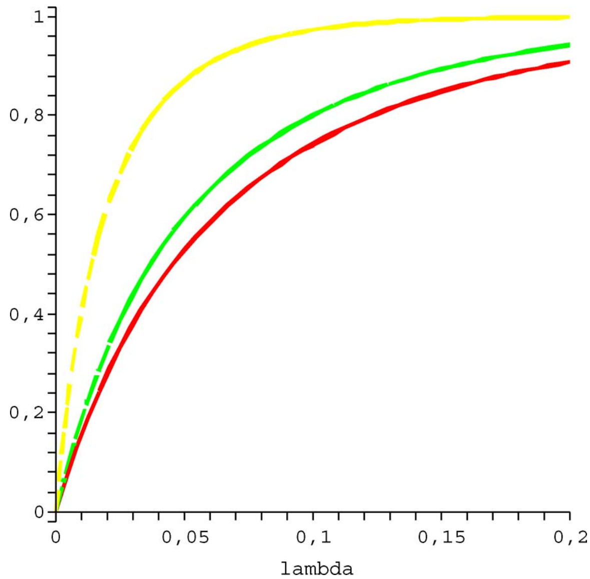

Fig. 3. The contact probability as a function of the temporal arrival rate, $r(\lambda_t)$, for three different speed distributions; the ordering is from below: the shifted exponential distribution, uniform distribution with support [0.5, 1.5] and with support [0.1, 1.9].

the higher the contact probability for a given arrival rate. However, a wider range of speeds will certainly affect the contact durations. We will therefore study the expected contact duration in Section IV-C to see whether speed kills the performance. Before that, we study the contacts with a fixed node.

3) Contacts With a Fixed Node: The street model could include one or more fixed caching nodes. Since the connection probability is growing fast when the average distance between nodes shrinks, it is expected that a fixed node improves the performance mainly at long inter-arrival distances of nodes. It is evident from Fig. 2 that the fixed node is most needed when the arrival rate is low.

We place the fixed node in the interior of the street so that it covers Δ meters in either direction. We make the following approximation: unconnected nodes arrive in range of the fixed node from the two directions as Poisson processes with rates $(1-r(\lambda_s))\lambda_s$ and $(1-r(\lambda'_s))\lambda'_s$ respectively (in reality there is a dependence between the inter-arrival distances given by the transformation from x_i to y_i above, but it is low for low arrival rates). We then see the fixed node as a spatial queue with Poisson arrivals and with a fixed sojourn distance of 2Δ meters for the nodes; it is thus an $\mathrm{M/D/\infty}$ model. An unconnected mobile node makes contact with the fixed node if it is the only unconnected node in the coverage region.

We use the property that Poisson arrivals see time averages, so that the probability of a mobile node establishing a contact with the fixed node is the probability that the $\mathrm{M/D/\infty}$ queue is empty, which is simply $e^{-\rho}$, where $\rho = ((1-r(\lambda_s))\lambda_s + (1-r'(\lambda'_s))\lambda'_s)2\Delta$ [8].

We plot the contact probability in Fig. 4 for the case that the arrival rates are equal to λ_s in the two directions so that $\rho = 4\Delta\lambda_s(1-r(\lambda_s))$. We see that most mobile nodes are unconnected at very low arrival rates and there is no contention for the fixed node since it is mostly unused. The usefulness of the fixed node decreases with higher arrival rates because the

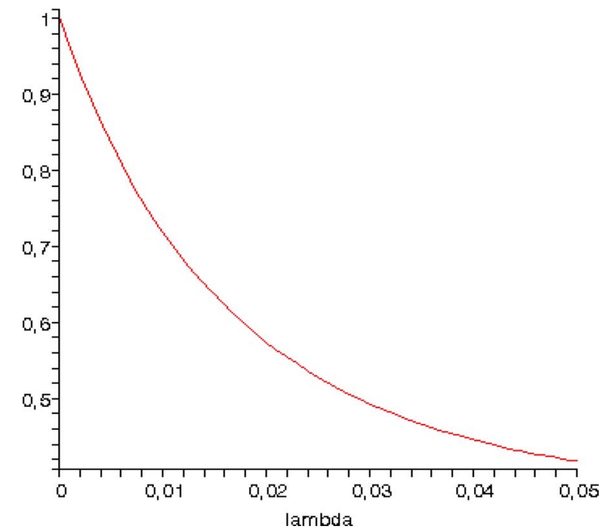

Fig. 4. The probability that a node connects to a fixed node. The arrival rates of nodes is $\lambda_s[m^{-1}]$ in both directions with Poisson arrival processes. The fixed node covers 20 meters of the street.

mobile nodes connect to one another instead. The contacts with the fixed node last for $2\Delta\overline{v^{-1}}$ and $2\Delta\overline{v'^{-1}}$ seconds, respectively for the two directions (see (3)). This corresponds to 2.5 MB of transferred data when all nodes have a transmission range of 10 meters and move with a fixed velocity of one meter per second, given that they only fetch data from the fixed node at its full capacity of 1 Mb/s.

Remark that the analysis above is not entirely accurate. There will also be a contact when an unconnected node moves into the coverage of an initially busy fixed node that becomes available during the time the mobile node remains in range. However, it only increases the contact probability over what we have shown.

C. Contact Durations

1) Same Direction: There are two cases for contacts between two nodes moving in the same direction with speeds v_1 and v_2, respectively, where $v_1 > v_2$. In the first case, the faster node is initially behind the slower node and overtakes it; the second case is when the contact occurs with the faster node ahead. The two cases happen with equal probabilities; they are illustrated in Fig. 5.

The contacts occur when either a node arrives to the street, or when its contact breaks; in either case it finds an unconnected node less than Δ meters away. The average distance when a contact occurs is $\bar{x}_\Delta$. It is the average length of an interval when a connection occurs, i.e., it is the average of the inter-arrival distance distribution, $F_X(x)$, truncated at Δ and re-scaled; it is for example 5 meters for an exponential distribution with arrival rate of one node per 20 meters and a transmission range of 10 meters.

The contact duration on an unlimited street is therefore

$$T_\infty = \frac{\pm\bar{x}_\Delta + \Delta}{v_1 - v_2}. \tag{4}$$

The sign of $\bar{x}_\Delta$ is positive when the faster node overtakes the slower node, and it is negative otherwise. The two cases have

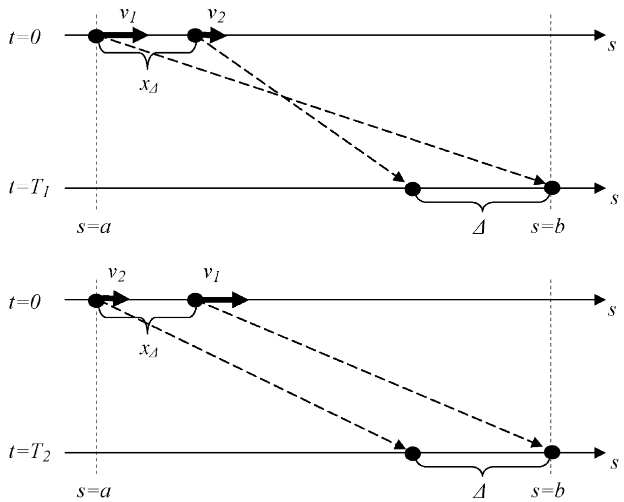

Fig. 5. Contacts between two nodes moving at different speed: (top) the faster node overtakes a slower node, (bottom) a slower node gets left behind a faster node ($x_\Delta \leq \Delta$). The maximum length of the contacts occurs when $a = 0$ and $b = L$.

equal probability since the velocities are drawn independently from the same distribution. The average contact duration is therefore $\bar{T}_\infty = \Delta/(v_1 - v_2)$ for given v_1 and v_2, where $v_1 > v_2$.

A street of length L restricts the contact so that it may at most be equal to the time that the fastest node spends on the street:

$$T_L = \min\left(\bar{T}_\infty, \frac{L}{v_1}\right). \quad (5)$$

We want to find the average of T_L. T_L is given by the first term of the min when $v_1 - v_2 \geq (\Delta/L)v_1$. Hence, for given v_1 and v_2, we get $\bar{T}_L$

$$\bar{T}_L = \bar{T}_\infty P\left(v_2 \leq v_1 \frac{L-\Delta}{L}\right) + \frac{L}{v_1} P\left(v_2 > v_1 \frac{L-\Delta}{L}\right). \quad (6)$$

For a street length L of 100 meters and a transmission range Δ of 10 meters, $P(v_2 > v_1(L-\Delta)/L)$ is 0.60 and the average of L/v_1 is 90.9 seconds for $\mathbf{U}[0.5, 1.5]$ and 0.56 and 62.5 seconds, respectively for $\mathbf{U}[0.1, 1.9]$. Remaining is to find the average of the term $\bar{T}_\infty$ over all allowed values of v_1 and v_2:

$$\Delta \int_{v_{min}\frac{L}{L-\Delta}}^{v_{max}} \int_{v_{min}}^{v_1 \frac{L-\Delta}{L}} \frac{1}{v_1 - v_2} f(v_2) f(v_1)\, dv_2\, dv_1. \quad (7)$$

The two distributions above yield averages of $\bar{T}_\infty$ equal to 14.0 and 11.6 seconds for $\mathbf{U}[0.5, 1.5]$ and $\mathbf{U}[0.1, 1.9]$, respectively, when $\Delta = 10$ meters, $L = 100$ meters; hence, $\bar{T}_L$ becomes 60.1 and 41.4 seconds, respectively, for the two distributions and these parameter values.

Finally, for a Poisson arrival rate of 1 node per 20 second, we get by using (1) and the relationships in Section IV-B-2 that the speed distribution $\mathbf{U}[0.5, 1.5]$ yields 3.3 expected number of simultaneously connected nodes in a 100 meter long street, while the distribution $\mathbf{U}[0.1, 1.9]$ yields 5.7 connected nodes. The total expected connection time for the nodes in the street are 198 and 236 seconds, respectively, for the two distributions. Calculated this way, we may conclude that the higher density of nodes, resulting from the wider speed distribution, compensates for the shorter average duration per contact.

2) Opposite Direction: Now consider traffic in the opposite direction with a rate λ'_s and inter-node intervals distributed as $F'_X(x)$. We limit this case to fixed velocities of v and v' meters per second, for the two directions. The rate of contacts among nodes moving in the opposite direction is then $r'(\lambda'_s)\lambda'_s$, where r' is defined as r in (1), but with respect to the distribution of X'. Two nodes moving in opposite directions make contact if they both are unconnected and the contact lasts for $T' = (\bar{x}_\Delta + \Delta)/(v + v')$ (again, $\bar{x}_\Delta$ is the average distance between the nodes when the contact occurs; it is computed as stated above, but for the total arrival rate of $\lambda_s + \lambda'_s$). The average number of contacts for a node moving from 0 to L is

$$n = (1 - r'(\lambda'_s))\, \lambda'_s (v + v') \frac{L}{v}. \quad (8)$$

Explanation: a node sees unconnected nodes coming against itself at speed $v + v'$ and at a rate of $(1 - r(\lambda'_s))\lambda'_s$ nodes per meter; it observes this for L/v seconds. Hence, the duration of the contacts with nodes in opposite direction is the product of these two expressions, $T' \times n$. The expected contact duration is

$$\bar{T}' = (1 - r'(\lambda'_s))\, \lambda'_s (\bar{x}_\Delta + \Delta) \frac{L}{v}. \quad (9)$$

The expected connection duration for a node that travels with constant velocity v on the street with *two way* traffic is therefore

$$\bar{T} = \frac{1}{v}\left(r(\lambda_s)(L - \bar{x}_\Delta) + (1 - r(\lambda_s)) \times (1 - r'(\lambda'_s))\, \lambda'_s (\bar{x}_\Delta + \Delta) L\right). \quad (10)$$

The first term is the probability of contact in the forward direction times the length of the contact; the second term is the probability of contact with nodes in the opposite direction times the length of those contacts. (The first term is used in the example in Section I.)

The contact duration is plotted in Fig. 6 for Poisson arrivals. Note that it is not symmetric in the two arrival rates and that the latter term in (10) is convex in λ'_s. The contact duration given by nodes moving in the opposite direction goes down simply because they are more likely to be connected to a node moving in their own direction.

D. Networks of Streets

The model of a single street allows for a larger network of streets to be modelled. We do not model mobility explicitly and rely instead on a queuing network model that captures the random roaming of the nodes from street to street; the roaming within a street is captured by the street models above. This network model allows mapping of a particular topography and user-movement patterns of a given area, for instance a part of a city.

The resulting model is as follows: The network is composed of interconnected streets. Each street is modelled internally as

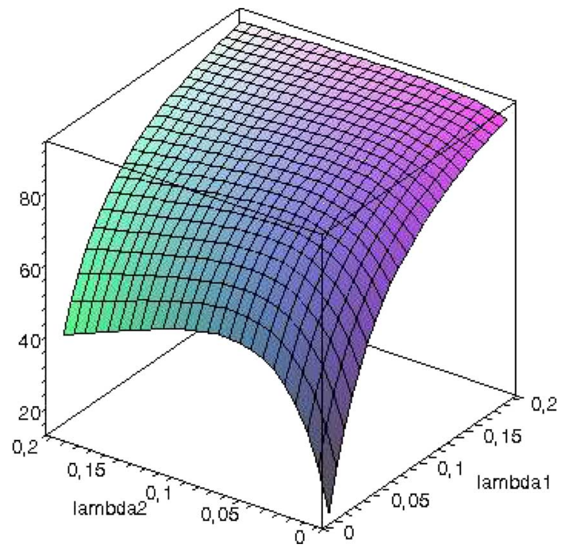

Fig. 6. The average contact duration in seconds for a node with transmission range of 10 m and average arrival rate of nodes λ_s (lambda1 in legend) and λ'_s (lambda2 in legend) in the two directions of the street; velocity of movement is 1 m/s and the arrival process is Poisson.

described above and is modelled as an $\mathrm{M/G/\infty}$ queue in the network. The stationary distribution of number of customers is Poisson and the transient distribution is non-homogeneous Poisson [8]. The sojourn time in each queue is given by the length and the speed distribution for the street. Nodes move into the modelled network from the outside world according to a Poisson process at an average rate of λ_0 nodes per second and are randomly routed from street to street. The arrival rate from area i into area j is λ_{ij} (λ_{0j} and λ_{i0} represent the arrivals from and to the outside world). The total arrival rate into area j is $\lambda_i = \lambda_{0j} + \ldots + \lambda_{Mj}$ and $\lambda_{ij} = \lambda_i p_{ij}$. The network of streets is therefore modelled as a queuing network that may be either open or closed, depending on whether the number of users is fixed or not (it is open if λ_0 is independent of the number of users in the network).

The distribution over the number of users in the network has a product form (see Chapter 8 of [25]). This gives us the distribution of nodes per street, given the time the nodes spend in each one. And given the arrival rate of nodes into a particular street, we find the rate of contacts that nodes experience when they move there. Thus, we may construct a model of an arbitrarily large network of streets that are interconnected according to the map of the area we wish to model. The real topography determine the lengths of the streets, and measurements result in the branching probabilities when nodes move from street to street. The model may then be used to determine how well the delay-tolerant broadcasting works for a given arrival rate of users to the city area, as well as where fixed nodes would be best placed. We intend to address these modeling issues in our continued work.

E. Conclusion and Discussion

The one-dimensional topology might appear limited, but urban areas are where we see that delay-tolerant broadcasting would function best. We draw some conclusions from the study in this section. First, burstier arrival processes of nodes give higher contact probabilities at low arrival rates; we have therefore chosen the Poisson arrival process in most examples. The distribution of velocities for the nodes have an impact on the probability of contacts through the mapping of the temporal arrival rate to the spatial rate. However, a large span of speeds also results in a wide range of contact durations. We have shown that a wider distribution of velocities has a lower expected duration per contact, but since it has a higher rate of contacts we find that the total contact duration becomes longer. When adding two-way traffic, the performance improves. So, the peer-to-peer distribution only dips at low arrival rates. We have shown the usefulness of adding fixed nodes to handle connectivity for streets at times when the rate is low. For instance, a node picks up 2.5 MB of data with certainty in a deserted street, since there is not competition for the fixed node, and the probability of doing so is still over 0.4 at a rate of 0.05 when the expected number of nodes in the coverage is one. The probability to make contact with other mobile nodes is about as high at that rate, and it increases rapidly with further rate increase.

We conclude this part with a positive outlook on the feasibility of delay-tolerant broadcasting.

V. Simulation Study

In the previous section, we introduced a model for the broadcasting system for a one-dimensional street model. In this section, we analyse the system with simulations in a two-dimensional topology where people are moving on a square. Again, the goal of the study is to examine if the system obtains good performance for reasonable system parameters. The remainder of this section is structured as follows. We first describe our simulation model and the assumptions. Then, we look at the distribution of the association times and inter-association times. The performance of the system is finally evaluated, using the average bit rates per node and the content dissemination rates as metrics.

A. Simulation Model

We used our own simulator with a very simple communication model: nodes communicate with each other at a nominal bit rate b if their geometric distance is smaller than a threshold value Δ (the wireless range of the radio devices). More sophisticated simulation tools, such as GloMoSim or ns-2 which incorporate lower layer protocol details, are not necessary for our study; we do not aim at analyzing protocol performance details, but we rather aim at identifying the feasibility of delay-tolerant broadcasting.

We assume an environment where humans carry Bluetooth enabled devices and are moving on a square. The mobile nodes are moving with a speed v of 1 m/s (this represents approximately the average speed of humans), the radio range of each device, Δ, is 10 meters (the wireless range of class 3 Bluetooth devices), and the wireless channel bit rate b is of 1 Mb/s. The square size is set to 300 by 300 meters and the number of nodes in the square is fixed during the whole simulation time. In our simulation setup, the nodes are not in range of each other most of the time. Nodes only occasionally come into wireless proximity and associate. Each node associates with only one neighbor at a

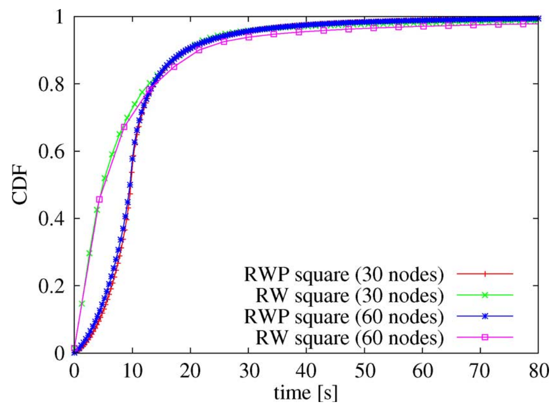

Fig. 7. CDF of the association duration.

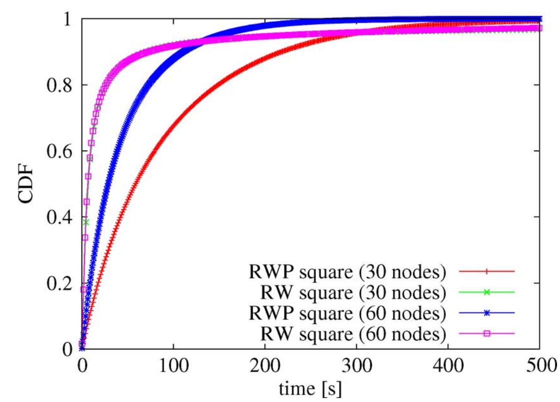

Fig. 8. CDF of the inter-association time.

time. Therefore, an already associated node declines any additional association request from another node.

The time required to setup an association is referred to as the setup time T. It includes the time (i) to awake the nodes from sleeping mode; (ii) to synchronize the two devices; and (iii) to setup a connection. No data is transferred during the setup. Two nodes stay associated with each other until all desired data has been exchanged, or until the nodes move apart so that they are outside the communication range. We simulate user mobility with two benchmark models: the random way point (RWP) [15] and the random walk (RW) [5].

Note that for the metrics we are interested in, a group mobility model delivers the same results as for a single node mobility model since the group has synchronized its content after some time and behaves as one larger node with a slightly increased transmission range. Afterwards, the group mobility model has similar properties as a single node mobility model such as the RWP or the RW model and hence, groups of nodes do not contribute to faster content spreading. Note further that we initially place the nodes with the RWP model on the square according to [23] to make sure that the node distribution is in steady state over the whole simulation time.

B. Association Durations and Rates

First, we analyse the durations and the rates of associations for both mobility models. These values help in understanding the average bit rates and the data dissemination rates we discuss later in this section.

We assume that the nodes stay associated with each other until they move apart (this is the case when associated nodes have content to share during the whole association time). We consider two different node densities (30 and 60 nodes) to examine the effect of the population density in the square area (these densities result in a maximum wireless coverage of approximately 10% and 20% of the area, respectively).

The cumulative distribution functions (CDF) for the durations is plotted in Fig. 7. The duration of an association is defined as the time interval between the moment two un-associated nodes come into wireless range until the moment they leave. We observe that the mobility models produce quite different distributions of the contact durations.

In the RWP model, the most probable duration is of about 10 seconds. This corresponds to the association time of two people moving in opposite directions $(2\Delta/2v = 10\ [s])$. Larger time values arise when two nodes move in the same direction for a certain amount of time. In contrast, the RW mobility model produces most contact durations in the range between zero and ten seconds. Regarding node density, we conclude that the node density does not have a major impact on the duration of associations for either benchmark mobility models.

We next look at the rate of associations. For this, we plot in Fig. 8 the CDF for the time interval from the moment a node looses an association until it re-associates with another (or the same) node. We observe that the time period is on average shorter for the RW model. Thus, we conclude that associations with the RW model are shorter than with the RWP model, but occur more frequently. The open question, we address later in this section, is if this leads to higher average bit rates compared to those obtained with the RWP model.

An additional interesting issue becomes visible when comparing the inter-association rates with different node densities (30 vs. 60 nodes). One would expect that the rate of intermittent associations increases when the node density increases. This is indeed the case for the RWP model. However, for the RW model, the difference is only marginal and hardly visible in the plot. This is due to the more localized mobility pattern of the RW model.

It is unrealistic to assume that people are constantly moving without pausing from time to time. Therefore, an important aspect we investigate is how the node pause times impact the association rates and durations. We plot the results of our simulations for the RWP model with various pause times in Figs. 9 and 10. We assume that each node waits for a fixed pause time when it arrives at a way point. We see that the pause time significantly affects the duration and rates of associations. Pausing nodes produce longer contact durations but less frequent associations. Consider for example the curve with a pause time of 1000 seconds. Many associations last for around 20 seconds compared to 10 seconds for 0 seconds pause time; 20 seconds occur when one device is pausing and another device passes straight across its transmission region. We also see relatively many associations which are larger than 20 seconds for pause times of 1000 seconds when comparing to simulations with smaller pause times.

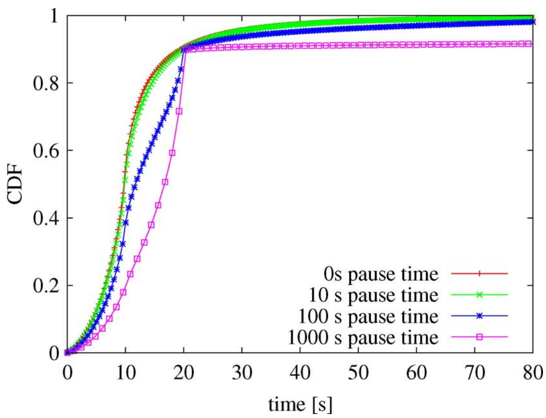

Fig. 9. CDF of the association duration for different pause times with the RWP model.

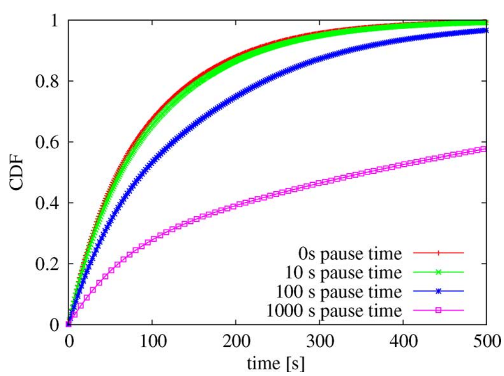

Fig. 10. CDF of the inter-association time for different pause times with the RWP model.

These occur mainly when two nodes pause at the same time while being within wireless range. Again, an open question is how the pausing of nodes impacts the average bit rate and the dissemination rate of content. We answer this in the next subsections.

C. Average Bit Rates

So far, we examined how the mobility model, the node density, and the pause time affect the association durations and inter-association times. Now, we discuss how these parameters affect the average transmission bit rates between the nodes. The specific metric we look at, is the maximally achievable average bit rate per node for content downloads. For this analysis, we assume the following scenario:

- Two nodes share the wireless capacity of an association in a fair manner. The maximal capacity per node is 0.5 Mb/s when downloading simultaneously.
- In all associations, both peers download content at full data rates (0.5 Mb/s in both directions).
- There is no interference between associations. Since we only consider sparsely connected networks, the assumption that associations are not considerably interfering with each other is sound.

The bit rates, averaged over all nodes, for both mobility models are plotted in Fig. 11. The bit rates are plotted against the setup time on the x-axis. Recall that the setup time T is

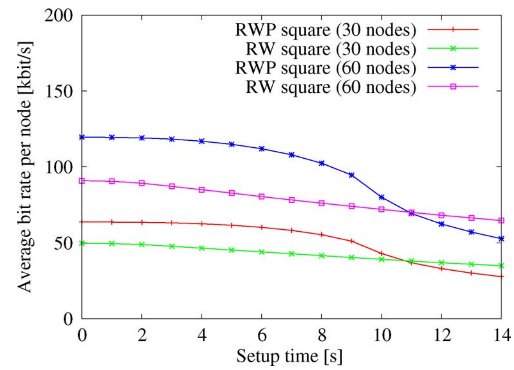

Fig. 11. Average bit rate for both mobility models.

the time interval from the moment when two nodes come into wireless range until the association is ready to transmit data. Note that in our Bluetooth-based prototype system (see Section VI), we frequently measured setup times mostly up to 10 seconds, but sometimes even larger.

From the figure, we draw three main conclusions: First, even in a sparsely populated network (30 nodes in the 300 by 300 meters square), the nodes achieve reasonable average bit rates around 50 kb/s for both mobility models. Second, the performance with both mobility models decreases slightly for setup times between 0 and 8 seconds. For setup times larger than 10 seconds, the bit rates with the RWP drop down sharply, even below the bit rates obtained with the RW mobility model. Last, the node density has a large influence on the per node bit rates. By doubling the density, the average per node bit rates increase by almost 90% for both mobility models.

We also examined how the pausing of nodes affects the average bit rates. For this, we determined the bit rates for pause times of 0, 10, 100 and 1000 seconds with the RWP model for 30 nodes. The results are plotted in Fig. 12. For small setup times, the bit rates are largest when the nodes are constantly moving. This is because nodes even profit from short associations which occur frequently with high mobility. However, as the setup time increases, the achieved bit rates decrease to a similar value for all four pause times (between 9 and 10 seconds). For very large setup times, the longer the pause time, the better is the achieved average bit rate.

The reason is that it is no longer possible to profit from small associations which occur when the nodes are moving in opposite directions. Data is transferred mainly between node pairs where one of the two nodes is pausing. The nodes then profit from the increased contact duration. We also see that, in contrary to what one would expect, large pause times do no degrade the bit rates significantly even for very small setup times. For an ideal setup time of 0 seconds, the bit rates with 1000 seconds pause time are only 25% smaller than those obtained with 0 second pause time.

D. Content Dissemination Rate

We now discuss the other of the key metrics of delay-tolerant broadcasting systems: the content dissemination rate. This metric captures the time required until a fraction of the nodes receive a new piece of content over the broadcast channel. In

TABLE I
TIME REQUIRED IN SECONDS TO BROADCAST CONTENT (200 kB AND 2 MB) TO 10%, 50%, 90%, AND 100% OF ALL NODES

	10%		50%		90%		100%	
	200k	2M	200k	2M	200k	2M	200k	2M
RWP 30 nodes	193 ± 10	1283 ± 31	400 ± 11	1583 ± 28	593 ± 12	1801 ± 28	783 ± 16	2011 ± 33
RWP 60 nodes	128 ± 6	848 ± 26	258 ± 7	996 ± 25	388 ± 8	1129 ± 26	563 ± 10	1300 ± 28
RW 30 nodes	4810 ± 1148	9958 ± 1920	13850 ± 1176	22531 ± 2382	23848 ± 2156	35024 ± 2789	34317 ± 2819	44061 ± 3490
RW 60 nodes	2011 ± 146	3598 ± 480	5766 ± 224	8441 ± 533	9484 ± 269	13061 ± 671	13240 ± 369	17577 ± 846
RW 150 nodes	751 ± 119	1306 ± 51	2199 ± 228	3177 ± 75	3450 ± 277	4840 ± 83	4305 ± 328	6029 ± 99

TABLE II
TIME REQUIRED IN SECONDS TO BROADCAST CONTENT (200 kB AND 2 MB) WITH THE RWP MODEL TO 10%, 50%, 90%, AND 100% OF ALL NODES

	10%		50%		90%		100%	
	200k	2M	200k	2M	200k	2M	200k	2M
0s pause time	193 ± 10	1283 ± 31	400 ± 11	1583 ± 28	593 ± 12	1801 ± 28	783 ± 16	2011 ± 33
10s pause time	190 ± 11	1331 ± 36	409 ± 12	1642 ± 33	611 ± 13	1870 ± 33	810 ± 17	2090 ± 36
100s pause time	313 ± 19	1565 ± 61	631 ± 22	2031 ± 56	918 ± 25	2373 ± 56	1218 ± 32	2701 ± 61
1000s pause time	1461 ± 110	5560 ± 441	2755 ± 134	7459 ± 409	3988 ± 150	8671 ± 484	5216 ± 187	10133 ± 572

TABLE III
TIME REQUIRED IN SECONDS TO BROADCAST CONTENT (200 kB AND 2 MB) TO 90% OF ALL NODES FOR DIFFERENT PAUSE TIMES AND DIFFERENT SETUP TIMES T

	T=0s		T=5s		T=10s	
	200k	2M	200k	2M	200k	2M
0s pause time	593 ± 12	1801 ± 28	770 ± 23	2765 ± 146	2015 ± 40	6496 ± 150
10s pause time	611 ± 13	1870 ± 33	788 ± 19	2897 ± 88	1965 ± 38	6367 ± 144
100s pause time	918 ± 25	2373 ± 56	1094 ± 35	3252 ± 108	1843 ± 39	5635 ± 163
1000s pause time	3988 ± 150	8671 ± 484	4245 ± 187	10835 ± 1222	5521 ± 113	16439 ± 571

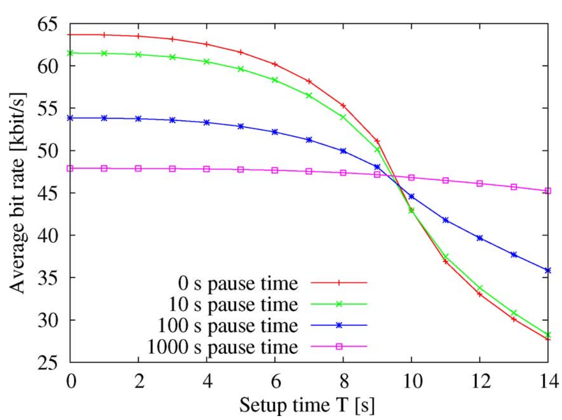

Fig. 12. Average bit rate against setup times for different pause times, RWP mobility, and 30 nodes.

sparsely populated areas, as those used in our studies, the dissemination rate is determined mainly by the node speed, the node movement (determines the area covered and the order of the node encounters), as well as the per node average bit rates we studied before.

In this simulation scenario, we assume data chunks with a size of 20 kB. A data chunk is the smallest data unit. If an association breaks before a complete chunk is received, the whole chunk must be re-sent in a following association (note that a 20 kB transfer only takes 320 ms at a bit rate of 0.5 Mb/s as used in the simulations). We determine the time necessary to broadcast 200 kB (10 chunks) and 2 MB (100 chunks) respectively. While the probability that 200 kB are sent over a single association is high for both mobility models, the probability that 2 MB are sent over a single association is very low. Therefore, the 2 MB broadcasts setup aims at studying the dissemination rates involving multiple consecutive associations. We start by analyzing the dissemination rate in an ideal case where the setup time T is zero seconds, and the nodes do not pause. The results in seconds with a 95-percent confidence interval are given in Table I.

We distinguish between the average time to broadcast the content to 10, 50, 90 and 100 percent of the nodes with the RWP and RW models. We identify three main trends: (i) as expected, larger node densities help disseminating the content faster; (ii) due to the rather local mobility patterns of the RW model, the time to broadcast is much larger than with the RWP model. Indeed, transmission delays are one order of magnitude higher than with the RWP model, even for large data quantities (2 MB) to a small fraction of nodes (10%). This result is surprising since the average bit rates are in the same order of magnitude for both mobility models. (iii) As foreseen, the small amounts of contents are disseminated much faster than large ones.

In Table II, we analyse the impact of the pause time with the RWP model on the dissemination time. The table entries are in seconds with a 95-percent confidence interval. Here, the main finding is that large transfers profit most with longer pause times. The impact of the setup time on the dissemination performance is illustrated in Table III (again in seconds with a 95-percent confidence interval). As expected, the shorter the setup time, the better the dissemination rate. Surprisingly, the dissemination rate with longer setup times $(T = 10\ s)$ is better with long pause times. Recall that long pause times result in longer average contact durations and hence, the longer setup time can thus be compensated.

E. Conclusion and Discussion

We simulated the performance of the delay-tolerant broadcasting system for sparsely populated squares. We have shown that for a pedestrian node speed (v of 1 m/s), the per node download bit rates with both mobility models are fairly high (between 50 and 120 kb/s). Even when the setup times of associations become so large that small contacts of two nodes moving in the opposite direction can no longer be used, the average bit rates do not decrease too extensively.

Regarding content spreading, we have seen that for rapid dissemination among the nodes, it is necessary that some nodes move frequently over large distances as it is the case with the RWP model. Then, it is for example possible to disseminate 200 kB to 90% of the nodes within less than 7 minutes. Note that in the optimal case, contents are spread with the speed of the mobile nodes, hence 5 minutes from one side of the square to the opposite side. For a more local mobility pattern as the RW model, much larger node densities are required to achieve similar dissemination rates.

Pausing nodes reduce the amount of small contacts and increase the amount of large contacts. In total, the effect is minimal for both the average bit rates and the dissemination rates. For large setup times, the performance is slightly better when the nodes are pausing, whereas for small setup times, the performance is slightly better when the nodes are constantly moving. (Fixed caching nodes may be seen as mobile nodes with indefinite pause times and their usefulness are indicated by the results for the 1000-seconds pause time.)

VI. Proof-of-Concept Prototype

In order to assess the feasibility of a delay tolerant broadcasting system, we developed a prototype application for mobile phones called *Bluetella*.

A. Basic Concepts

Bluetella is an application that runs on mobile devices. To exchange data, two Bluetella devices establish a point-to-point connection via wireless Bluetooth communication. To participate in a Bluetella network, a node simply has to run the Bluetella application and announce a Bluetella specific profile UUID. Bluetella communication is divided in three phases: environment scanning, state synchronization, and data transfer. First, simultaneously with the profile announcement, the device starts scanning the environment for other Bluetella enabled devices.

Whenever two Bluetella nodes are in transmission range, they establish a connection and start synchronizing. In this second step, both nodes send the list of channels or content they are interested in to the neighbor node. If content of the requested channel is available, the node starts transmitting data back to the requesting device (phase three). Even if the requested content is not available, the nodes keep track of the requested channels/content, maintaining a global hit list of the most popular channels/content. During the synchronization phase, after the exchange of the search lists, the nodes also exchange these global hit lists and re-compute, with their own list, an updated global hit list. After the regular content is downloaded, devices with larger storage capacities then may download additional content from the global hit list if available. This function is of particular interest for fixed nodes serving as content caches, as described in Section III.

B. Experiences With the Bluetella System

The prototype application is implemented on the Java 2 Micro Edition Platform (J2ME). To run the application on the cell phones, they have to support MIDP 1.0, as well as the Bluetooth API specified in JSR-82 [21]. We tested Bluetella on multiple cell phones, such as the Nokia 6630 and the cell phones of the Siemens S-Series. Based on the specific phone hardware, the size of the application was about 70 kB and the application allocated between 700 kB and 1500 kB memory, depending on the number of connections and the size of the request and hit lists. The major problem we encountered with our application was the lengthy discovery time of Bluetooth. According to the Bluetooth specification, "the inquiry substate may have to last for 10.24 seconds unless the inquirer collects enough responses and determines to abort the inquiry substate earlier" [11].

If multiple devices are scanning the environment for devices, the scanning time might even increase to higher values. In theory, Bluetooth provides bandwidth up to 721 kb/s on an asymmetric channel. In practice, the throughput is considerably less once protocol overhead and error control are taken into account. In the measurements we conducted, we achieved download speeds between 39.2 kb/s and 70 kb/s. There are three lessons we learned form this prototype implementation: (i) delay tolerant broadcasting systems are easy to develop and deploy; (ii) the main concern with Bluetooth communication for delay-tolerant broadcasting is the long communication setup time; and (iii) the communication rates are high enough for small data transfers; for larger files, data/header compression is beneficial.

VII. Conclusion

We have proposed the concept of delay-tolerant broadcasting to allow wide and public dissemination of data over radio communication. It enhances broadcasting based on an infrastructure, and offers a new ad hoc distribution mode for contents that originate from mobile nodes. Our approach is purely receiver driven. There is no flooding or explicit routing in the network. Content for broadcast channels is spread through node mobility and peer-to-peer contact between pairs of neighbor nodes. The system for achieving this is not complex; as our prototype implementation shows, the program is small and runs on mobile phones. The feasibility is rather connected to the performance of the system. We have studied it for mobility in one dimension analytically, and in two dimensions through simulations. We find the results encouraging and expect the concept to be workable in urban areas and other places where the node density is reasonably high. We will hence continue with the design of the system and evaluate it further by also considering traces from measurements [12], [18], [19]. The study will also address the solicitation and caching strategies for the nodes.

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