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# A framework for performance analysis of geographic delay-tolerant routing

Erik Kuiper<sup>1\*</sup>, Simin Nadjm-Tehrani<sup>2</sup> and Di Yuan<sup>3</sup>

## Abstract

A major tool used for evaluating routing protocols in ad hoc and delay-tolerant networks is simulation. Whereas the results from simulations give good insights, they are limited to the specific scenario set-up that is used. If the scenario changes, new and often time-consuming simulations have to be run. Moreover, the simulation time in packet-level simulators with fairly realistic physical layer implementation, such as ns-2, generally grows rapidly in the number of nodes. This practically limits the number of nodes in a simulation, even if the limit can be extended by the use of simulation federations. Larger scenarios can also be facilitated by the use of more abstraction in the physical layer; abstractions that may impact the validity of the results. In this article, we present the forward-wait framework—a mathematical model describing the packet movements for opportunistic geographic delay-tolerant routing protocols. By describing packet movements as a sequence of alternating forwarding and waiting phases, the framework can accurately predict the routing performance. Key input parameters to the framework are random variables describing the forwarding and waiting phases. We show how the properties of the random variables can be derived, both via abstract modeling and small scale ns-2 simulation data. The model is then used to demonstrate the prediction capabilities of the framework in providing results that are close to the (much slower) packet-level simulations.

**Keywords:** geographic routing analysis, routing performance, delay-tolerant networks, opportunistic routing

## 1. Introduction

Simulation is the most common method for evaluating routing protocols in infrastructure-free wireless communication networks. Using detailed network modeling, simulation enables us to examine the performance of routing protocols without incurring the high costs associated with practical experiments. However, with high fidelity simulations, the simulation time grows rapidly with the number of nodes. Scaling up simulations in terms of number of nodes typically requires the use of a more abstract physical layer or simulation federations.

Instead of relying on a simulator to provide routing performance, we propose the forward-wait mathematical framework to provide key performance properties of geographic routing protocols. The framework is suitable for intermittently connected mobile ad hoc networks (IC-MANETs) where the routing consists of alternating forwarding and waiting phases. In the forwarding phase,

a packet is forwarded towards the destination by a partial path, and in the waiting phase a packet is stored at a node awaiting the formation of a new partial path that can forward the packet further towards the destination. The model is applicable to all protocols characterized by alternating forwarding and waiting phases. As an example, we use the Location-Aware Routing for Delay-tolerant networks (LAROD) [1] for numerical performance evaluation.

For opportunistic delay-tolerant networks (DTNs), the inter contact time (ICT) model [2-4] is the most widely used approach for mathematical characterization. The ICT model describes the time between node encounters. This works well for very sparse networks with unguided or random routing protocols. The ICT model is intrinsically limited to forwarding packets at the start of an encounter, and multi-hop partial paths are not a component of the model. If the network density is high enough for nodes to form connected islands (partitions), and a routing protocol tailored for such topologies is used, the ICT model is not suitable for describing the routing.

\* Correspondence: erik.kuiper@saabgroup.com

<sup>1</sup>Saab Aeronautics, Linköping, Sweden

Full list of author information is available at the end of the article

The reason is that the model does not describe the routing options within a partition; that is, the possibility to route to nodes currently reachable through an encountered node.

The forward-wait framework models the movement of a packet as a sequence of alternating forwarding and waiting phases. A packet is forwarded towards the destination as far as the topology allows it within a partition. When the packet reaches the edge of the partition, it waits until node movements have restructured the topology in such a way that forwarding becomes possible again in a newly formed partition. In order to deal with a large multiplicity of network scenarios and mobility factors, we describe each phase using random variables.

For the forwarding phase and the waiting phase, respectively, we model the distance a packet moves towards (the presumed location of) the destination until it has to wait, and the time a packet has to wait before the next forwarding opportunity arises. The characteristics of the forwarding and waiting random variables depend on both node mobility and the routing protocol. It is thus important to correctly establish the properties of the random variables to obtain accurate predictions from the framework. A feature of the framework is that the characteristics of the forwarding and waiting phases can be derived from multiple sources: models, small scale simulations, or practical data.

We can combine the models of the forwarding and waiting phases to determine the packet delivery probability as a function of source-destination distance and maximum allowed delivery time (time-to-live, TTL). By adding a description of the Euclidian distance from the source to the destination for a given scenario, the packet delivery ratio can be computed for any given value of the TTL parameter. Alternatively, an appropriate TTL can be set to satisfy a given delivery probability. These results are provided more efficiently by the framework than by running packet-level simulations.

To summarize, the contributions of this article are as follows:

1. A general framework for analysis of geographical routing protocols in opportunistic DTNs with locally connected partitions.
2. Two methods to derive the characteristics of forwarding and waiting phases: (1) abstract mobility and routing models, and (2) actual simulation data for arbitrary mobility models and geographic delay-tolerant routing protocols.
3. An illustration of the application of the framework, which includes deriving the forwarding and waiting properties for the pheromone reconnaissance

mobility model and the LAROD routing protocol [1].

The article is organized as follows. The next section relates our work to other proposed models for routing analysis in opportunistic DTNs. The main contribution, the forward-wait framework, is presented in Section 3. This is followed by deriving the properties of the forwarding and waiting phases in Section 4. In Section 5, the mathematical framework is validated against simulation results. Section 6 discusses the validity of the assumptions made by the model. In Section 7, we illustrate how the forward-wait framework can be used. Finally, the article ends with concluding remarks in Section 8.

## 2. Related studies

The benefit of using partial paths in IC-MANETs has formally been proven by Heimlicher et al. [5]. Under some simple and reasonable assumptions, they have shown that the forward-wait paradigm will outperform end-to-end forwarding. While their results do not provide mechanisms to predict the routing performance, they confirm the intuition that partial paths should be used by routing protocols in IC-MANETs.

For predicting routing performance in DTNs, the most commonly used model is the ICT model. The ICT model describes when nodes encounter each other and are capable of exchanging data. Combined by a description of the routing protocol and the properties of the node encounter time, routing performance can be predicted. The two most commonly used metrics to describe the node encounter time are the inter-meeting time and the next encounter time. The inter-meeting time is the time between encounters of two specified nodes, and the next encounter time specifies when a node next encounters any other node. It is very common to characterize these encounter times using exponentially distributed random variables. It has been shown that, for several popular synthetic mobility models, assuming exponential distributions is indeed a reasonable choice [6,7]. Examples of analyses using exponential distributions are those by Spyropoulos et al. [4], Small and Haas [3], Groenevelt et al. [2], and Resta and Santi [8].

The exponential distribution has been contended by Chaintreau et al. [9] in a study of actual encounter data from humans carrying mobile devices. They have found that the encounter distributions exhibit a power law distribution with a coefficient less than one. The work has been continued by Karagiannis et al. [10]. They showed that the power law distribution is only valid up to a certain time after which the distribution decays

exponentially. The power law distribution with exponentially decaying tail can also be found in some synthetic mobility models [10-12]. Another perspective on the ICT distributions comes from Zhang et al. [13] who have studied encounter properties in a network of scheduled buses. One important observation they made was that the delivery delays between bus pairs can differ quite significantly. The forward-wait model proposed in this article has a waiting component similar to the delay distributions used in ICT analyses, and for our illustrative scenario we have found that the wait distribution has an exponentially decaying tail.

An extension of the ICT model has been presented by Resta and Santi [8]. In their framework, they compute the distribution of the packet delivery delay, not only the expected mean. While this is a result similar to the one we present, their analysis is limited to very sparse systems where the ICT model assumptions hold. An additional characteristic of their framework is that they analyze monotone relaying schemes, i.e., once a node has received a copy of the packet it will keep a copy until the packet reaches the destination.

Due to the discrete nature of the ICT model, its application in large systems is computationally complex. To overcome this problem, Zhang et al. [14] have proposed to model the routing using ordinary differential equation, and Altman et al. [15] have proposed to describe packet spreading among nodes using a fluid model. Both approaches study epidemic and limited epidemic schemes. This means that, for a single-copy routing protocol, such as the one we consider, these models are not suitable. Additionally, our approach is to provide the option to use a detailed analysis of small-scale scenarios as a foundation to enable the analysis of large systems.

The above works have provided an analysis of how long time it takes to reach the destination, an outcome that analysis with the forward-wait framework also provides. In addition to the delivery delay, an analysis of geographic routing protocols can also study the time-distance relationship in packet forwarding. For this, Jacquet et al. [16] have presented an upper bound on the information propagation speed in very sparse networks. While we use the time-distance relationship in our analysis, the results by Jacquet et al. cannot be used since we describe systems with significantly higher node densities.

The assumption of sparse network is, in fact, a major limitation of the previously described models. With this assumption, connected groups of nodes are not taken into account. If the node movements and node density are such that nodes normally do have neighbors, then these models are not appropriate for predicting routing performance. A concept that accounts for connected partitions and non-uniform node mobility is delay expansion, introduced by Asplund [17]. Delay expansion

enables us to determine bounds on worst-case latency for a wide class of broadcast protocols. The key idea is to describe the least number of uninformed nodes that will meet an informed node during the time period of interest. By having the number of informed nodes as a function parameter, non-uniform mobility can be handled. However, the results in [17] are not directly applicable to unicast routing.

When location information is available many works attempt to optimize network connectivity by actively adapting transmission power. Some research within the area of MANET topology control focuses on mathematical studies that trade-off the degree of connectivity against energy efficiency (interested reader may refer to a survey by Santi on the topic [18]). This is a different problem compared to the one addressed in this article, where we focus on studies of delivery probability towards a given distance and within a given time using some abstraction of node mobility and routing.

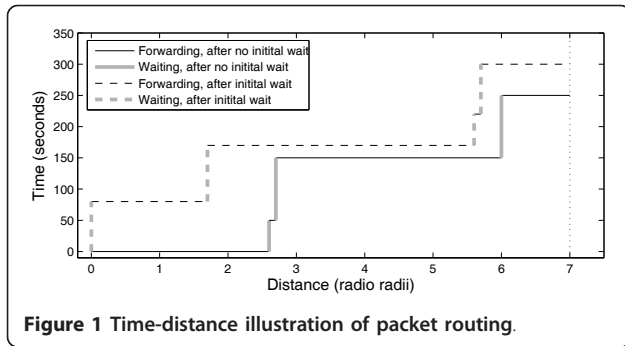
### 3. The forward-wait framework

In the forward-wait framework, the movement of a packet towards the destination is modeled by two phases: forwarding and waiting. The forwarding phase is used to characterize how much closer a packet gets to the destination when it can be forwarded within a connected partition of the network. Once forwarding is not possible, the waiting phase accounts for how long time a packet has to wait until it can be forwarded again. While the model is developed for geographical routing, it is agnostic to the routing mechanism used to forward the packet. However, the model does make the following assumptions.

1. Only one copy of a packet is routed at any time.
2. The delivery latency is dominated by the waiting time, and thus the forwarding time can be neglected.
3. Packet movement is dominated by the forwarding, and thus in the waiting phase, packet movement due to node mobility can be neglected.

In Section 6, we will discuss the validity of these assumptions. There we will show the impact of violations of these assumptions, and that the impact can be compensated for to some extent. The reason to defer the discussion until then is the need for delay and forwarding data for the purpose of determining the impact of the assumptions.

Figure 1 visualizes assumptions 2 and 3 with two packets moving from source to destination. In a forwarding phase, a packet is routed from one node to another until it has to wait. While forwarding, the elapsed time is ignored by the second assumption above, which is depicted by the horizontal lines in the



**Figure 1** Time-distance illustration of packet routing.

figure. The waiting phases, on the other hand, ignore node movements, as indicated by the vertical lines. The two cases in the figure illustrate that when a packet is generated by the source, it either has to wait if the source node is at the frontier of a partition (upper track) or it can be forwarded immediately, within the current partition, until it reaches the edge (lower track). Thus, a packet will travel in time and space in a manner similar to one of the two tracks depicted in Figure 1.

The forwarding and waiting components of the framework are described by means of independent random variables. In the forwarding phase, the corresponding random variable describes how far a packet can be forwarded until it reaches the edge of its current partition. In the waiting phase, we use a random variable to describe how long time it takes until node movements have restructured the topology in such a way that the packet can be forwarded again. The reason that independence between the random variables can be assumed is that, as a packet is forwarded, it is handled by new nodes whose movements are independent of the nodes previously holding the packet. Examples of how the properties of the random variables can be derived for a specific scenario are provided in Section 4. In the same section, we show why it is important to separate the two cases, depending on whether or not a packet had to wait at the source or not before it could be forwarded. The mathematical description of the framework will be presented in a bottom-up fashion. As a final outcome, we will have the probability of reaching the destination at a (Euclidian) distance  $d$  within time  $t$ ,  $P_d(t, d)$ , and two random variables  $X(t)$  and  $T(d)$ ; the former variable describes how much a packet has reduced the distance to the destination at a specific time, and the latter describes the time it took to move towards a (presumed) destination at the specific distance from source. All results are derived based on the random variables describing the forwarding and waiting phases. In Table 1, we summarize the key notation and terms.

To describe the packet forwarding distance we create auxiliary variables that describe (as random variables)

the reduction of distance to the destination after  $n$  forwarding phases. The reduction in distance in forwarding refers to the difference between the Euclidean distances between the packet location and its destination before and after a forwarding phase. Note that the first forwarding phase is different from the later forwarding phases, since in the latter cases there are no nodes ahead of the custodian in the direction towards the destination. In the first forwarding case, we may or may not have nodes to route through in the current partition. Due to this difference in the forwarding characteristics, we need one auxiliary variable for each of the two cases ( $D_n$  and  $D'_n$ ). These variables are the sum of the independent random variables that make up the separate forwarding phases, and they are defined in Equations (1) and (2). For the case where the packet has to wait at the source before it can be forwarded,  $D'_n$  is zero with probability one before the first forwarding phase ( $n = 0$ ). This is denoted by means of a random variable  $I$  that always takes the value 0.

$$D_n = \begin{cases} L & n = 1 \\ D_{n-1} + L_n & n > 1 \end{cases} \quad (1)$$

$$D'_n = \begin{cases} I & n = 0 \\ L'_n & n = 1 \\ D'_{n-1} + L'_n & n > 1 \end{cases} \quad (2)$$

The probability that a packet is in its  $n$ th forwarding phase when the distance to the destination has been reduced by  $d$ , measuring from the original source location, is then given by Equation (3). Probability  $P_{fw}(d, n)$  is defined in the same way using  $D'_n$ . It is important to note that while  $P(D_n \geq d)$  is the probability of having moved *at least* a distance  $d$  using exactly  $n$  forwarding phases,  $P_{fi}(d, n)$  is the probability of being in the  $n$ th forwarding phase when the distance to the destination has been reduced by  $d$ .

$$P_{fi}(d, n) = \begin{cases} P(D_1 \geq d) & n = 1 \\ P(D_n \geq d) - \sum_{m=1}^{n-1} P_{fi}(d, m) = P(D_n \geq d) - P(D_{n-1} \geq d) & n > 1 \end{cases} \quad (3)$$

Similar to the derivation of the random variables for the forwarding phase, Equation (4) computes the random variable describing the time of waiting after exactly  $n$  waiting phases. Analogous to the definition of  $D'_n$ ,  $W_n$  is defined also for the case where no waiting has occurred. In Equation (5), we give the probability of being in the  $n$ th waiting phase at time  $t$ .

$$W_n = \begin{cases} I & n = 0 \\ V_n & n = 1 \\ W_{n-1} + V_n & n > 1 \end{cases} \quad (4)$$

**Table 1 Key notation and terms**

Notation	Description
$d$	Euclidian distance
$t$	Time
$L$	Random variable describing the reduction of distance to the destination during the first forwarding phase, if the packet could be forwarded immediately when it was generated
$L_n$	Random variable describing the reduction of distance to the destination at the $n$ th forwarding phase after waiting, if the packet could be forwarded immediately when it was generated
$L'_n$	Random variable describing the reduction of distance to the destination at the $n$ th forwarding phase after waiting, if the packet had to wait at the source before forwarding
$I$	Random variable that with 100% probability takes the value 0
$D_n$	Random variable describing the reduction of distance to the destination after $n$ forwarding phases, if the packet could be forwarded immediately when it was generated
$D'_n$	Random variable describing the reduction of distance to the destination after $n$ forwarding phases, if the packet had to wait at the source before forwarding
$V_n$	Random variable describing the time that a packet is in the $n$ th waiting phase until it can be forwarded
$W_n$	Random variable describing the time that a packet has waited after $n$ waiting phases
$X(t)$	Random variable describing how much a packet has reduced the distance to the destination at time $t$
$T(d)$	Random variable describing the time taken to reach distance $d$ from the source
$S_{wi}$	Random variable describing if there was an initial wait or not. $S_{wi} = 1$ if there was an initial wait and 0 if there was no initial wait
$S_w(t)$	Random variable describing the index number of the current wait phase at time $t$ , assuming that the packet was forwarded immediately when it was generated
$S'_w(t)$	Random variable describing the index number of the current wait phase at time $t$ , assuming that the packet had to wait at the source before forwarding
$S_f(d)$	Random variable describing the index number of the current forwarding phase when the packet has reduced the distance to the destination by $d$ , assuming that the packet could be forwarded immediately when it was generated
$S'_{fw}(d)$	Random variable describing the index number of the current forwarding phase when the packet has reduced the distance to the destination by $d$ , assuming that the packet had to wait at the source before forwarding
$P(\text{expr})$	Probability that the expression $\text{expr}$ is true
$P_f(d, n)$	Probability of being in the $n$ th forwarding phase when the packet has reduced the distance to the destination by $d$ (measured from the source), assuming that the packet could be forwarded immediately when it was generated
$P'_{fw}(d, n)$	Probability of being in the $n$ th forwarding phase when the packet has reduced the distance to the destination by $d$ (measured from the source), assuming that the packet had to wait at the source before forwarding
$P_w(t, n)$	Probability of being in the $n$ th waiting phase at time $t$
$P_d(t, d)$	Probability of delivery of a packet within time $t$ to a destination at a distance $d$ from the source
$P_{wi}$	Probability that a packet has to wait before it can be forwarded from the source

$$P_w(t, n) = \begin{cases} P(W_1 \geq t) & n = 1 \\ P(W_n \geq t) - \sum_{m=1}^{n-1} P_w(t, m) = P(W_n \geq t) - P(W_{n-1} \geq t) & n > 1 \end{cases} \quad (5)$$

Using the above results, we can now define expressions predicting routing performance. The main result is presented in Equation (6) where we compute the probability that a packet has, within time  $t$ , been delivered to a node that was a distance  $d$  from the source. The two terms in the equation consider the cases where a packet initially waits before being forwarded, and the case where it is immediately forwarded from the source, respectively. These two cases correspond to the two tracks in Figure 1. Each term is a sum of the probabilities of the possible sequences of forwarding and waiting at the evaluation point. This equation will be used to compute the packet delivery ratio.

$$P_d(t, d) = P_{wi} \cdot \sum_{n=1}^{\infty} (P_{fw}(d, n) \cdot P(W_n \leq t)) + (1 - P_{wi}) \cdot \sum_{n=1}^{\infty} (P_f(d, n) \cdot P(W_{n-1} \leq t)) \quad (6)$$

The probabilistic answer provided by (6) might not be enough if a more detailed analysis of the routing performance is to be conducted. To complement  $P_d(t, d)$ , we define how much a packet has reduced its distance to the destination at time  $t$  by stochastic variable  $X(t)$  in (7), and the time required to reach a distance  $d$  from the source by stochastic variable  $T(d)$  in (8). To describe these two properties, we use stochastic variables defining the indices of the forwarding or waiting phase that the packet is in. For the selection of distribution for a particular case, we use the Kronecker delta defined as follows.

$$\delta(n) = \begin{cases} 1 & n = 0 \\ 0 & n \neq 0 \end{cases}$$

Equations (7) and (8) have the same structure as (6), but instead of probabilities, we operate on random variables. Equation (7) describes how much a packet has reduced its distance to the destination at time  $t$ . The first term describes the case when the packet was forwarded after an initial wait, and the second term describes the case for a sequence of forwards without an initial wait. The equation uses selection elements ( $S_{wi}$ ,  $S_w(t)$ , and  $S'_w(t)$ ) defined by the following probabilities described earlier.

$$\begin{aligned}
 P(S_{wi} = 1) &= P_{wi} \\
 P(S_w(t) = n) &= P(S'_w(t) = n) = P_w(t, n) \\
 X(t) &= \delta(1 - S_{wi}) \cdot \sum_{n=1}^{\infty} (\delta(n - (S'_w(t) - 1)) \cdot D'_n) \quad (7) \\
 &+ \delta(S_{wi}) \cdot \sum_{n=1}^{\infty} (\delta(n - S_w(t)) \cdot D_n)
 \end{aligned}$$

Equation (8) has the same structure as (7), but instead computes the time taken to move towards the destination with distance  $d$  from the source. In addition to  $S_{wi}$ , the equation uses the selection elements  $S_{fw}(d)$  and  $S_{fi}(d)$  defined by the following probabilities described earlier.

$$\begin{aligned}
 P(S_{fw}(d) = n) &= P_{fw}(d, n) \\
 P(S_{fi}(d) = n) &= P_{fi}(d, n) \\
 T(d) &= \delta(1 - S_{wi}) \cdot \sum_{n=1}^{\infty} (\delta(n - S_{fw}(d)) \cdot W_n) \quad (8) \\
 &+ \delta(S_{wi}) \cdot \sum_{n=1}^{\infty} (\delta(n - (S_{fi}(d) - 1)) \cdot W_n)
 \end{aligned}$$

The forthcoming sections will be devoted to deriving the properties of the forwarding and waiting random variables in a given context, and validating the model using simulation data. In addition, we will show how  $P_d(t, d)$  can be used in a practical application of the framework.

#### 4. Characterizing forwarding and waiting

In order to use the framework presented in Section 3 for estimating the routing performance with a given mobility model and routing protocol, we need a description of the properties of the random variables for forwarding and waiting. We explore two alternatives: (1) using abstract models for mobility and routing in Section 4.2, and (2) using data from a protocol simulation, i.e., LAROD ns-2 simulations [1], in Section 4.3.

The first alternative is useful if the properties of a mobile scenario and routing protocol are well known and can be modeled. The second alternative can capture

the distributions of *any* routing protocol and mobility scenario, including protocols for which the characteristics are not well known. For illustration of the process of creating the abstract model based on a known mobility and routing algorithm, we use the knowledge about LAROD routing protocol, the characteristics of which will briefly be described in Section 4.1.

In ad hoc wireless networks, distances have little meaning, unless the range capabilities of the chosen radio technology are also specified. For this reason, we have chosen to express distance in the nominal radio range. Moreover, we will treat node densities by the *average node degree*. The average node degree,  $c$ , is the average number of nodes per area covered by the nominal radio range, defined as  $\rho\pi r^2$ , where  $\rho$  is the average node density and  $r$  is the nominal radio range. For Poisson distributed nodes in an infinitely large system, the average node degree equals the average expected number of neighbors of a node [19].

#### 4.1. Abstract mobility and routing model

In this section, we detail the mobility and routing models that will be used in Section 4.2 to derive the model-based forwarding and waiting properties. The model is intended to capture the mobility and routing in the LAROD ns-2 simulations used in Section 4.3, but still be manageable so that using the model is significantly simpler than using simulations.

##### 4.1.1. Poisson-based mobility

For the abstract mobility model, we choose the Poisson distribution [19] to describe the statistical distribution of the nodes. The Poisson distribution describes the statistical location properties of independent nodes that are equally likely to be in all locations in an infinite space. The choice of using Poisson distribution is justified by three reasons. First, it is a commonly used abstraction and mathematically attractive. Second, it is a reasonable simplification of the pheromone mobility model that we have used in the ns-2 simulations. Third, it describes the location properties of nodes in some commonly used synthetic mobility models [20,21].

The Poisson distribution only describes how the nodes are statistically distributed, not how they move. To derive the properties of the waiting phase, we need to characterize how the nodes move during a limited time period. To this end, we assume that the nodes move independently at a common constant speed, and that for short time periods the movements can be regarded rectilinear. The common constant speed reflects the speed used in the LAROD ns-2 simulations.

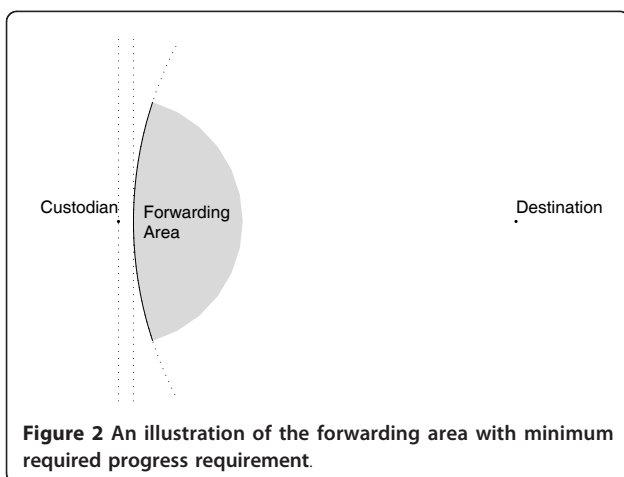
##### Modeling geographic forwarding

Many geographic opportunistic forwarding algorithms are based on forwarding areas, a notion that we use in the abstract routing model. Since we will demonstrate

the use of the wait-forward framework by predicting the performance of LAROD [1], we will use its parameters when modeling routing behavior. LAROD is a delay-tolerant geographic single-copy routing protocol. At each hop, the protocol selects the node providing the most routing *progress*. Here, progress refers to the reduction in distance to destination. As a packet is forwarded, the custody of the packet is transferred from one node to another, guaranteeing that there always is a node responsible for the packet. If there is no node that can provide a pre-defined minimum progress, LAROD waits until node movements have changed the nodes' positions in such a way that forwarding becomes feasible. The area in which the next custodian can be selected is called the forwarding area; see Figure 2 for an illustration. The protocol periodically attempts to detect new nodes in the forwarding area. The time period of two successive attempts is referred to as the retry interval,  $t_r$ . Setting the value of  $t_r$  involves a trade-off between the latency in detecting new nodes and protocol overhead. In LAROD ns-2 simulations,  $t_r$  is set randomly and uniformly between 8 and 12 s.

Modeling custodian selection in the geographic routing protocol with a minimum progress requirement leads to Equations (9) and (10), for which the terms are defined in Table 2. Equation (9) defines the forwarding area, and (10) describes the position of the next custodian. The forwarding operation is characterized by the reduction in distance to destination as measured from the current custodian. When a forwarding phase starts, the packet is routed without delay, until forwarding is no longer possible, because the current custodian's forwarding area is empty. In the waiting phase, the protocol regularly attempts to start a new forwarding.

$$X \in fa(X_c \rightarrow X_d) \mid |X - X_d| \leq |X_c - X_d| + p, |X_c - X| \leq r \quad (9)$$



**Table 2** Terms in custodian selection

Notation	Description
$fa(X_c \rightarrow X_d)$	Forwarding area for a custodian at $X_c$ and destination at $X_d$
$r$	Nominal radio range
$p$	Minimum-required progress. The parameter is set to $0.04r$
$X$	Two-dimensional Euclidian position
$X_c$	Position of the current custodian
$X_d$	Position of the destination
$X_n$	Position of node $n$
$X_x$	Position of the next custodian

$$X_x = X_n \mid \min(|X_n - X_d| \mid X_n \in fa(X_c \rightarrow X_d)) \quad (10)$$

### Framework inputs based on models

In this section, we will derive the properties for the forwarding and waiting random variables based on the mobility and forwarding models described in Section 4.1. The random variables will be described using distributions [19]. To describe the probability density function (pdf) and cumulative distribution function (cdf) we use the notations  $\text{pdf}(X, x)$  and  $\text{cdf}(X, x)$  where  $X$  is a random variable and  $x$  is the value of the random variable. To see the impact of node density, we will evaluate four different node densities within a relevant range.

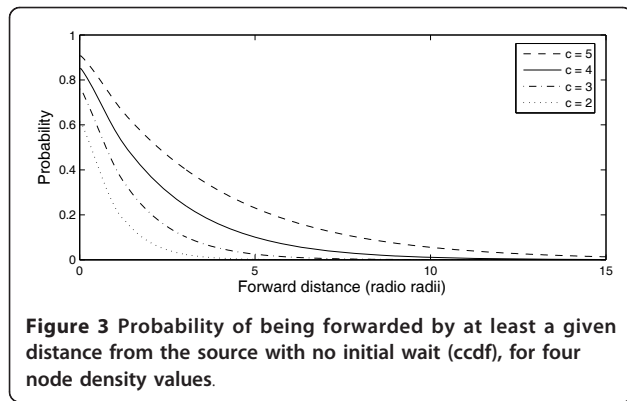
#### Forwarding distribution based on models

Even for the ideal disk-based transmission model, determining the forwarding distribution analytically for Poisson distributed nodes is unfortunately too complex to be practically tractable. For details, please see Appendix 1. For this reason, we have derived the forwarding cdfs using Monte Carlo simulation.

For determining the reduction of distance to the destination that a packet achieves while approaching the destination from the source ( $L$ ), the Monte Carlo simulation is set up as follows. A number of nodes drawn from a Poisson distribution are placed in a rectangular area. The area is large enough so that at most 0.1% of the packets will reach the area boundary. Each node's coordinate is set randomly following a rectangular distribution. A packet is sent towards a destination located infinitely far away, and the forwarding progress, measured along the line connecting the source and destination, is determined. Custodian selection is performed according to (10), until an empty forwarding area is encountered.

The result is shown in Figure 3 using the complementary cdf (ccdf) for four different values of node density (where  $c$  denotes the node degree described earlier). The ccdf in the figure is  $(1 - \text{cdf}(L, d)) \cdot (1 - P_{wi})$ , as the Monte Carlo simulation also records the occasions





when no node is present in the forwarding area and the packet has to wait. In order to derive a well-behaved density function, the distribution from the Monte Carlo simulation has been fitted to a curve described by (11), where  $G$  is a gamma-distributed random variable with shape parameter  $r$  and scale parameter  $\lambda$ . The transition points in (11) are selected to achieve an optimal match between the measured distribution and the fitted curve.

Using the assumption of Poisson distributed nodes, the measured probability that a packet could not be forwarded from the source ( $P_{wi}$ ) obtained from the Monte Carlo simulations can be verified theoretically. Knowing the node density and forwarding area size the theoretical probability for not forwarding is trivial to determine (this is the probability that there are no nodes in the forwarding area). For our definition of the forwarding area, the results are presented in Table 3. These values are closely matched by the Monte Carlo simulations.

$$\text{cdf}(L, d) = \begin{cases} 0 & d < 0.04 \\ k_0 + k_1 \cdot d + k_2 \cdot d^2 + k_3 \cdot d^3 & 0.04 \leq d \leq 1.3 \\ \text{cdf}(G(r, \lambda), d) & d > 1.3 \end{cases} \quad (11)$$

When the packet is forwarded to the edge of a partition, it has to wait until further forwarding can take place. When at least one node enters the forwarding area this wait ends, and forwarding can continue. The property of this forwarding will not be the same as the forwarding experienced by the source node when the

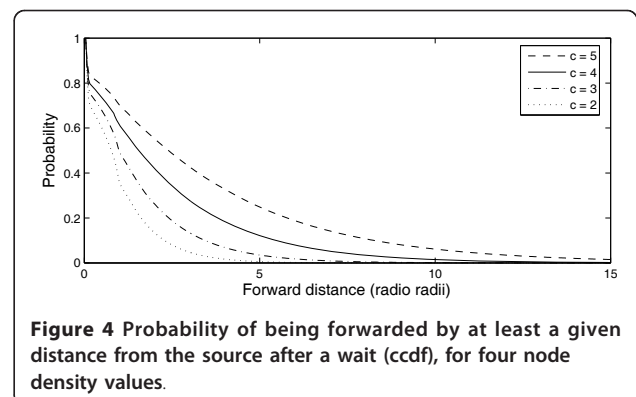
**Table 3** Probability of having an initially empty forwarding area

Avg. node degree $c$	$P_{wi}$ (%)
2	38.7
3	24.1
4	15.0
5	9.3

packet was generated. The reason is that a custodian candidate in the forwarding area after a wait will be found close to the edge of the current custodian's forwarding area. This is due to the fact that the node movements are small during a retry interval compared to the size of the forwarding area. We will see that this will have significant implications for the forwarding distribution.

The Monte Carlo simulations used to determine the distance forwarded after a wait ( $L_p, L'_n$ ) are set up similar to the ones used for analyzing packet forwarding from the source ( $L$ ). A simulation run starts by placing a number of nodes, drawn from a Poisson distribution, in a rectangular area. Searching through the nodes, the first node having an empty forwarding area is selected to be the custodian of a packet. If no node with an empty forwarding area exists, the simulation run is aborted. Provided that a custodian is found, the next step is to move all the nodes (including the custodian) in random directions with a distance randomly selected to correspond to the retry interval employed between forward attempts (in the abstract model we have used the same interval, 8-12 s, as in LAROD ns-2 simulations). If a node has entered the forwarding area after the retry interval, the forwarded distance of the packet is recorded; otherwise the simulation run is discarded.

The resulting distribution is shown in Figure 4 using its ccdf. The figure leads to several interesting observations. The steep drop at the beginning of the curves corresponds to the scenario that a node enters the forwarding area from the rear. In this case, the forwarding areas of the initial and new custodians have a large overlap. As a result, the probability of making another hop is low. Similar to the cdfs for initial forwarding at the source, the cdfs corresponding to the ccdfs in Figure 4 have been curve-fitted to derive well-behaved pdfs. The curve fitting is done according to Equation (12), where the transition points are selected based on a maximum match between the measured distribution and the fitted curve. In the



equation, parameters  $d_4$  and  $d_5$  are density dependent, and selected to achieve an optimal fit.

$$\begin{aligned} \text{cdf}(L_n, d) &= \text{cdf}(L'_n, d) \\ &= \begin{cases} 0 & d \leq 0.04 \\ k_0 + k_1 \cdot d + k_2 \cdot d^2 + k_3 \cdot d^3 & 0.04 < d \leq 0.16 \\ k_{10} + k_{11} \cdot d + k_{12} \cdot d^2 + k_{13} \cdot d^3 & 0.16 < d \leq 0.85 \\ k_{20} + k_{21} \cdot d + k_{22} \cdot d^2 + k_{23} \cdot d^3 & 0.85 < d \leq d_4 \\ k_{30} + k_{31} \cdot d + k_{32} \cdot d^2 + k_{33} \cdot d^3 & d_4 < d \leq d_5 \\ \text{cdf}(G(r, \lambda), d) & d > d_5 \end{cases} \quad (12) \end{aligned}$$

### Waiting distribution based on models

A wait period starts when a packet reaches the edge of a partition where it has to wait until mobility makes further forwarding possible. To determine the distributions for the waiting phase based on the modeled mobility and routing, we consider the periodic forward attempts employed by LAROD. After waiting a time  $t$  the probability of successful forwarding is described by  $P_f(t)$ . With the knowledge of when a forward attempt is made, described by  $R$ , the waiting distribution can be established. For the LAROD simulations,  $\text{pdf}(R, t)$  is a rectangular distribution as specified in (13).

$$\text{pdf}(R, t) = \begin{cases} 0.25 & 8 \leq t \leq 12 \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

For  $P_f(t)$ , we note that it is zero at  $t = 0$  and equals  $P_{wi}$  as  $t$  approaches infinity. Therefore,  $P_f(t)$  is expected to have an exponential-type shape. Since we are only interested in  $P_f(t)$  when  $\text{pdf}(R, t)$  is non-zero, a linear approximation is considered. An analysis of the data points used to establish  $P_f(t)$  has shown that this is a reasonable approximation over the relevant interval.

The probability of forwarding after a given waiting time ( $P_f(t)$ ) is not trivial to determine analytically, and for this reason we have used Monte Carlo simulations. In each simulation run, a number of nodes are placed in a rectangular area, following a Poisson distribution. The size of the area is selected such that the expected number of nodes with an empty forwarding area is 100. All nodes are then randomly moved. Whether or not nodes have entered forwarding areas that initially are empty is then recorded. The simulation has been run for 100 times for each of the time values 8, 9, 10, 11, and 12 s, giving approximately 10,000 samples per point. The collected data are then fitted to a linear function to represent  $P_f(t)$ . The coefficients in the linear function and two sample values are provided in Table 4, and the linear function itself is given in (14).

$$P_f(t) = k \cdot t + o \quad (14)$$

What remains to compute is the waiting time  $V_n$  based on  $R$  and (14). To this end, we first determine the

**Table 4 Average probability of forwarding after a retry interval**

Avg. node degree $c$	$k$	$o$	$t = 8$ (%)	$t = 12$ (%)
2	0.0059	0.013	6.0	8.3
3	0.0080	0.023	8.7	11.9
4	0.0127	0.008	11.0	16.1
5	0.0167	-0.002	13.2	19.9

probability that a forward attempt is a success or a failure (see Equations 15 and 16). Next, we use two random variables,  $E_n$  and  $A_n$ , to describe the waiting times for a successful or a failed forward attempt, respectively. The density functions of  $E_n$  and  $A_n$  are defined in (17) and (18). Based on these and the failed wait time described by (19), a random variable describing the time when a successful forward attempt is made after  $n - 1$  failed attempts is defined in (20). The random variable  $V_n$  is then defined in (22) using the selection element  $S_f$  (21) and the Kronecker delta. The notation is summarized in Table 5. In Figure 5,  $\text{cdf}(V_n, t)$  is illustrated.

$$P_f = \int_0^{\infty} \text{pdf}(R, t) \cdot P_f(t) dt = \int_8^{12} 0.25 \cdot (k \cdot t + o) dt = 10 \cdot k + o \quad (15)$$

$$P_a = \int_0^{\infty} \text{pdf}(R, t) \cdot (1 - P_f(t)) dt = 1 - P_f = 1 - 10 \cdot k - o \quad (16)$$

$$\text{pdf}(E_n, t) = \frac{\text{pdf}(R, t) \cdot P_f(t)}{P_f} \quad (17)$$

$$\text{pdf}(A_n, t) = \frac{\text{pdf}(R, t) \cdot (1 - P_f(t))}{P_a} \quad (18)$$

$$B_n = \begin{cases} A_n & n = 1 \\ B_{n-1} + A_n & n > 1 \end{cases} \quad (19)$$

$$F_n = \begin{cases} E_n & n = 1 \\ B_{n-1} + E_n & n > 1 \end{cases} \quad (20)$$

$$P(S_f = n) = P_f \cdot P_a^{n-1} \quad (21)$$

$$V_n = \sum_{n=1}^{\infty} (\delta(n - S_f) \cdot F_n) \quad (22)$$

### Distributions from ns-2 data

In this section, we present the alternative approach to deriving probability distributions for the framework for

**Table 5 Notation and terms in deriving distributions for the waiting phase**

Notation	Description
$P_f$	Probability that a forward attempt is successful
$P_f(t)$	Probability that a forward attempt at time $t$ is successful
$P_a$	Probability that a forward attempt fails
$A_n$	Random variable describing the waiting time of the $n$ th failed forward attempt
$B_n$	Random variable describing the waiting time of $n$ failed forward attempts
$E_n$	Random variable describing the waiting time for a successful forward attempt after $n-1$ failed attempts
$F_n$	Random variable describing the waiting time if the $n$ th forward attempt is successful
$R$	Random variable describing time to the next transmission attempt
$S_f$	Random variable describing the index number of the wait attempt when a packet was successfully forwarded

an arbitrary protocol and mobility model, provided that some detailed simulation traces are available. As an example, we compute numerically the forwarding and waiting distributions from ns-2 simulations of LAROD under the pheromone reconnaissance mobility model. The idea is to compare the results to the distributions derived in the previous section, in which mobility and routing are modeled more abstractly. We do not expect that the results will match each other perfectly due to the following reasons. First, the ns-2 simulator has a more realistic radio model. Second, the pheromone reconnaissance mobility model does not produce Poisson distributed nodes. Third, the location of a destination is assumed to be known in the abstract model, i.e., a perfect location service is assumed in our derivation of the distributions. This is however not the case in the ns-2 simulations.

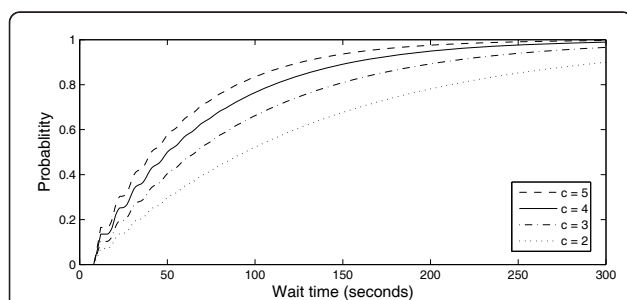
**Forwarding distribution based on simulations**

Extracting forwarding distributions from simulation traces calls for some methodological considerations, because distance measurements in the simulations can only provide finite values. The consequence of a finite distance is that a packet might reach its destination during a forwarding operation, and in this case it is impossible to tell how much further the forwarding could have continued. Consider a packet transmitted by its custodian. If the packet reaches the edge of the partition before reaching its destination, the simulation data give

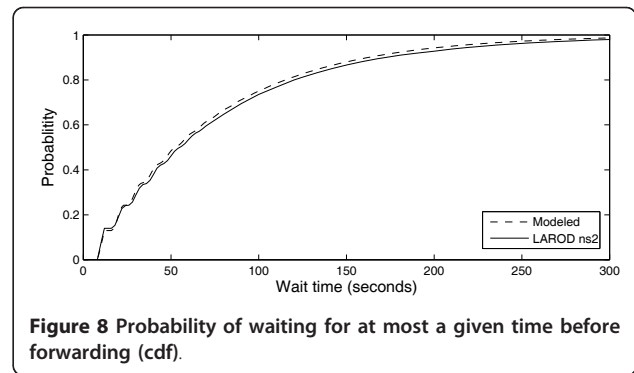
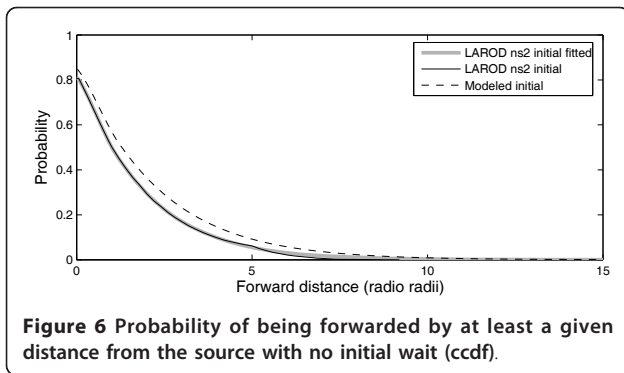
relevant distance information for deriving the distributions. On the other hand, if the packet reaches the destination, then one cannot tell how much further it could have been forwarded. To limit the impact of this issue when establishing the simulation-based  $\text{cdf}(L, d)$ ,  $\text{cdf}(L_n, d)$ , and  $\text{cdf}(L'_n, d)$ , we only consider simulation data where forwarding takes place to destinations for which the distance from the custodian is above a pre-defined threshold. Thus, the computed forwarding distribution will be representative for the true distribution up to the distance threshold. A problem with setting a high distance threshold is that the number of data points available for establishing the distribution becomes very low. For the LAROD ns-2 simulations, a distance threshold of 5 radio radii is used. In order to obtain a smooth distribution over this value, we apply an extrapolation technique.

A second issue in deriving forwarding distributions via simulations is packet duplication. This can happen due to LAROD routing logic, e.g., when a custodian forwards the same packet to two nodes that are not within the radio range of each other. To deal with the issue, the consideration is limited to the copy that has reached furthest towards the destination. In the LAROD simulations, the average node degree equals 3.93. Throughout the article, the data extracted from simulations are based on a TTL value of 1,000 s.

In Figures 6 and 7, we provide the ccdfs of forwarding, obtained by trace data from the LAROD simulations. The modeled (dashed) curve is based on the equations in Section 4.2.1. For the solid black curve representing the LAROD ns-2 data, we see a drop after 5 radio radii. After this value, some packets have reached their destinations, and hence they only provide a truncated forwarding distance. The LAROD ns-2 curves have been extrapolated and curve-fitted using the functions given in Section 4.2.1. The modeled curve uses the same node density level (3.93) to ease the comparison. From the simulation results, the probability of having an initial waiting phase,  $P_{wis}$  is 19% for an average node degree of 3.93. This is considerably higher than the value of 15%



**Figure 5 Probability of waiting for at most a given time, for four node density values.**

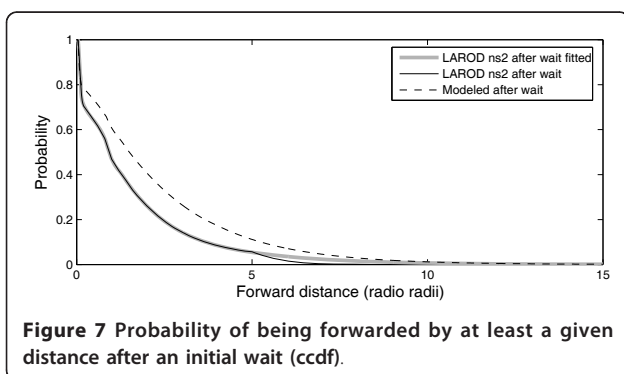


derived for the similar node degree level under Poisson distribution (see Table 3). From these results, we see that the model we use does not exactly describe the forwarding properties experienced in the simulations. Some probable causes were discussed at the beginning of Section 4.3.

The lower ccdf curves from LAROD ns-2 compared to those derived for Poisson distributed nodes reveals lower average forwarding distance. Consequently, more waiting phases are required before the destination is reached. Whether or not this means a longer delivery time depends on the characteristics of waiting — an aspect that we will study in the next section.

#### Waiting distribution based on simulations

We now turn our attention to characterizing waiting time using LAROD ns-2 simulations. Processing waiting data is less problematic compared to the case of forwarding data. Yet some caution is necessary, because some packets may time out while waiting to be forwarded. In data processing, such packets are discarded. Hence, only packets for which forwarding does occur after waiting are considered. Consequently, information associated with very long waiting times is not available, meaning that the distribution derived from simulations is slightly optimistic. The results are presented in Figure 8, and compared to the curve computed by the modeling approach (Section 4.2.2) under the same node density level. From the



figure, it is apparent that the distribution derived from the Poisson distributed nodes yields a very good approximation; the waiting time obtained from the LAROD simulations is only slightly longer than the one derived in Section 4.2.2. The study in Section 4 has thus demonstrated that with carefully constructed models the model-based and simulation-based distributions can be fairly close to each other. The challenge is to know when the models are good enough.

### 5. Validation of the framework

Having presented the forward-wait framework in Section 3, and its parameters in terms of random variables in Section 4, we are now in a position to evaluate the validity of the framework. We compare the predictions by the framework to those given by LAROD ns-2 simulations, and if they are reasonably similar we conclude that the framework accurately can predict the routing performance. While this only proves that the framework can predict the routing performance for this specific case, it strengthens our belief that its use can be extended to previously unexplored scenario configurations.

For the framework, we consider both the model-based input from Section 4.2 and the simulation-based input from Section 4.3. Due to the difference between the two sources of input, the routing performance predictions should somewhat differ. What we hope, however, is that when simulation-based input is used, the predictions by the framework come close to the simulation results. Differences in the results, if any, should originate from the assumptions made in the framework and data extraction issues.

We need a final part of the puzzle before the framework predictions can be compared to the simulation results. The output from the ns-2 simulations is the packet delivery ratio for various maximum packet life times, whereas the output from the forward-wait framework is the probability that a packet has reached a destination located at distance  $d$  from the source within time  $t$ . To make them comparable, we need a description of

source-destination distance. This aspect is addressed first, followed by results of the comparison.

**Distance to destination**

The source-destination distance differs for each packet. This variation will be described by the random variable  $Y$ . We determine properties of  $Y$  along two lines, one based on a mathematical description of the source and destination locations, and the other based on LAROD ns-2 simulations.

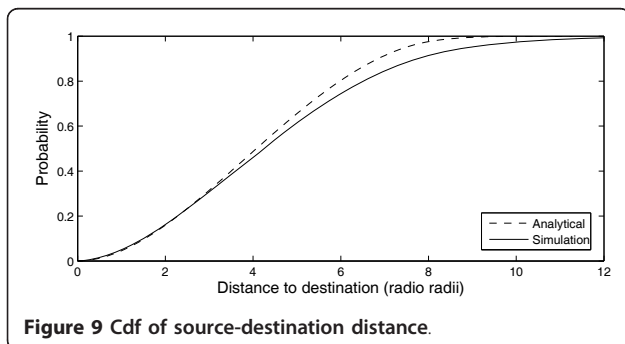
In the mathematical description, we assume that the nodes are evenly and independently distributed in a square area. Denoting the side length of the area by  $k$ , the density function of  $Y$  follows (23). For the derivation of the equation, the reader is referred to Appendix 2.

The corresponding results obtained from LAROD ns-2 simulations are illustrated in Figure 9 for the  $8 \times 8$  radio radii square. The source-destination distance from the ns-2 simulation is somewhat higher than that from the mathematical description. We conjecture that non-uniform node placement, movement of the destination during packet routing, and location service inaccuracies have all contributed to the difference between the curves.

$$\text{pdf}(Y, d) = \begin{cases} 2d \cdot \left( \frac{\pi}{k^2} - \frac{4d}{k^3} + \frac{d^2}{k^4} \right) & 0 \leq d \leq k \\ 2d \cdot \left( \frac{2}{k^2} \tan^{-1} \left( \frac{2k^2 - d^2}{2k\sqrt{d^2 - k^2}} \right) - \frac{2}{k^2} + \frac{4\sqrt{d^2 - k^2}}{k^3} - \frac{d^2}{k^4} \right) & k < d < \sqrt{2}k \\ 0 & \text{otherwise} \end{cases} \quad (23)$$

**Delivery predictions**

With the tools and data previously presented, we can now estimate the delivery ratio using the forward-wait framework, and compare the prediction to the delivery ratio obtained by LAROD ns-2 simulations. The delivery ratio based on  $P_d(t, d)$  and  $Y$  is computed according to (24). The equation models the fact that when a packet is within the radio range of the destination, the last hop is a guaranteed success.



$$P_{TTL}(t) = \int_0^r \text{pdf}(Y, x) dx + \int_r^\infty \text{pdf}(Y, x) \cdot P_d(t, x - r) dx \quad (24)$$

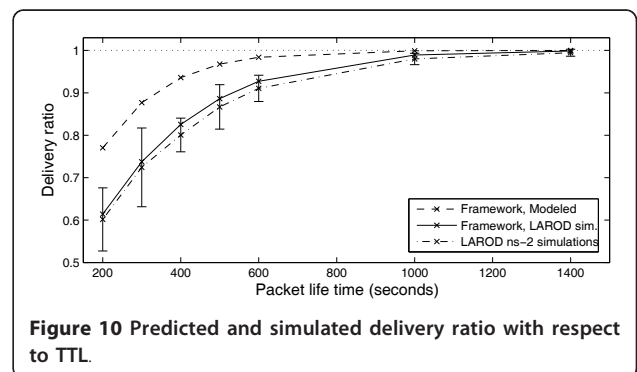
The delivery ratio predicted by the forward-wait framework, using input from the modeling approach and the LAROD ns-2 simulations, is presented in Figure 10. The figure also shows the delivery ratio from the LAROD ns-2 simulations with a 95% confidence interval.

Two major observations follow from the figure: (1) the predicted delivery ratio can differ significantly, depending on the type of input, and (2) providing the framework with key input parameters from simulations leads to highly accurate predictions of the delivery performance. The remaining gap can be attributed to simplifications made in the framework, and the fact that it is difficult to estimate long forwarding chains and delays from the simulation data, as described earlier in Section 4.3.

The first observation illustrates the importance of using a relevant data source when predicting routing performance. Assuming idealistic conditions, predictions become too optimistic in comparison to the simulation results, even though the latter may not necessarily represent real-world performance.

**Distance and time predictions**

In addition to validating the model in terms of the final delivery ratio, it is also of interest to validate the distance and time distributions predicted by Equations (7) and (8) against data from the LAROD ns-2 simulations. From the simulations, it is easy to extract how far a packet has traveled from the source at some specific time, as well as at the time taken for achieving a given reduction in the distance to packet destination. The measurements are however performed only for packets that have not yet been delivered to their destinations. For the time for having reached a distance from the source (Equation 8), the data from the simulations can directly be compared to the predictions made by the forward-wait framework.



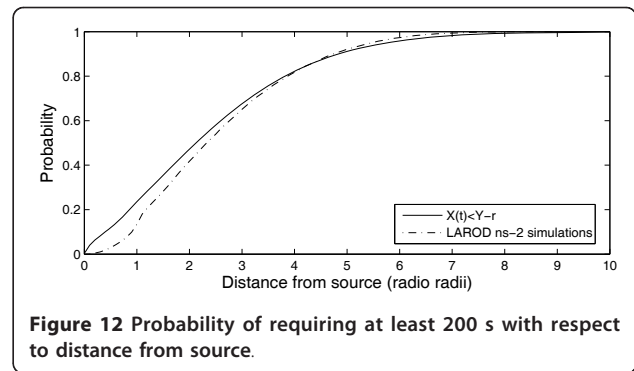
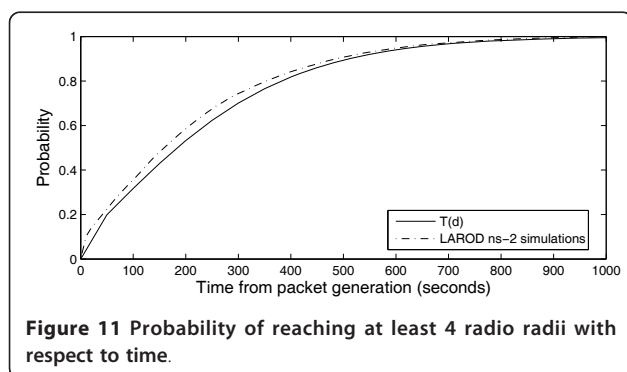
**Figure 10** Predicted and simulated delivery ratio with respect to TTL.

The reason for this is that while we cannot extract data for packets having reached their destinations before the measurement point, all packets have the same distribution regarding time of passing the measurement point.

For the time to reach a certain point analysis, we have chosen a measurement point 4 radio radii from the source. In Figure 11, the distribution function from the ns-2 simulations is compared to the one computed by the forward-wait framework using the ns-2-based distributions. As can be seen from the figure, the two distributions are very close to each other. The distribution from the framework is slightly more optimistic on how fast a packet travels, an effect also reflected in the slightly optimistic results from the framework in the previous section.

The direct validation of Equation (7) is not possible due to the following reason. In practical, simulations packets are delivered to their destinations, and if a packet reaches its destination before the time used for measurement, data for that packet cannot be gathered. Thus, we only measure packets for which the following is true,  $X(t) < Y - r$ , where  $Y$  is the distance to destination, and  $r$  is the radio range. As in the previous section, we assume that when a packet is within radio range of the destination, the last hop is a guaranteed success.

In Figure 12, we have plotted the distributions of  $X(t) < Y - r$  and the data from the ns-2 simulations at time  $t = 200$  s. We observe a visible difference between the framework prediction and the ns-2 data. The main reason for the difference is that the forward-wait framework assumes that the node holding the packet does not move while it waits. The ns-2 data on the other hand includes node movements during waiting. Obviously, node movements can be in any direction, both towards and away from the source, but since we measure the absolute distance from the source we cannot tell if the packet has advanced towards the destination or not. What we clearly see is that the impact on node mobility while waiting cannot be ignored. A further discussion regarding the validity of the forward-wait framework due to this effect is provided in the next section.



From the results in this and the previous section, we conclude that the forward-wait framework can reasonably accurately predict the routing performance for LAROD, provided that representative forward and wait distributions are used. We believe that these results extend to other geographic routing protocols in IC-MANETs.

## 6. The validity of the framework assumptions

In the previous section, we have shown that the forward-wait framework can successfully predict simulation results. Let us now examine how well the assumptions used for building up the framework (see Section 3) are met. We consider first the assumption that forwarding takes no time and that packet movement is minimal in the waiting phase. Table 6 shows the mean values of waiting times and forwarding distances, obtained from the mobility model in Section 4.1.1 and the LAROD ns-2 evaluations, respectively.

It is striking to observe the significant amounts of distance that packets traveled during waiting in relation to the forwarding distance. An immediate question is how much this result influences the validity of the model. The answer is that the impact is in fact not significant—whereas some nodes move closer to the destination of a packet waiting to be forwarded, other nodes will move away from the destination. Assuming directional uniformity of the movements, they cancel each other's effect in the infinite case. In the finite case, the distance to a static destination will somewhat increase (on average) during a waiting phase. However, this increase is typically small enough to be negligible.

We now consider the related assumption that time for forwarding is negligible. The time that a forwarding phase takes depends greatly on the communication technology and packet size. As the modeling approach in Section 4.1.2 does not include these aspects, we look in more detail into LAROD ns-2 simulations. From the simulation results in Table 6, we observe that the time consumed by forwarding is small ( $\approx 1.5\%$ ) in comparison to the waiting time. This confirms that the assumption

**Table 6 Average waiting times and forwarding distances**

Avg. node degree	Avg. wait time (s)	Dist. traveled in waiting (radio radii)	Avg. fwd. dist. initial (radio radii)	Avg. fwd. dist. after wait (radio radii)	Avg. time fwd. (s)
<i>Modeled mobility</i>					
2	144	0.81	1.0	0.9	-
3	97	0.54	1.6	1.3	-
4	74	0.42	2.4	2.0	-
5	60	0.34	3.7	3.1	-
<i>LAROD ns-2 simulations</i>					
3.93	78.1	0.47	1.9	1.4	1.2

in the framework holds. If this was not the case, Equation (5) would have been adapted to include forwarding time.

Another assumption in Section 3 was that, at any given time, only one copy of a packet is routed. For LAROD, however, occasionally this is not true in our ns-2 simulation data. For such cases, we use the copy that reaches furthest towards the destination for deriving the forwarding distributions. Hence, the assumption can be respected by extraction of suitable traces from simulations (at the expense of being more or less optimistic). To analyze the delivery ratio of a routing protocol that routes multiple copies of a packet, the forwarding and waiting distributions can be extended by considering the first copy arriving at the destination and modeling the routing decisions made for those packets.

### 7. Practical application of the forward-wait framework

In Section 5, we showed that the forward-wait framework can accurately match the results by simulations. This establishes some trust in the capability of the framework in predicting routing performance. In this section, we illustrate how the framework can be used in connection with a large-scale deployment. For the illustrations, we require data for multiple node densities. Since these data are only available for the model of routing and mobility from Section 4.1, we will in this section use the distributions derived in Section 4.2.

A first natural use of the framework is to predict the packet delivery ratio for large scenarios. In Figure 13, we show the delivery ratio for different scenario sizes at a constant average node degree of 4. With the random selection of destination in the used scenario and the constant node density, more nodes means longer source-destination distances. This is reflected in the figure by lower delivery ratio for larger scenarios for the same packet life time.

In addition to being predictive, the framework can be used to enable a source node to dynamically set the packet TTL to achieve a desired delivery probability. To illustrate this, in Figure 14 we plot the relationship

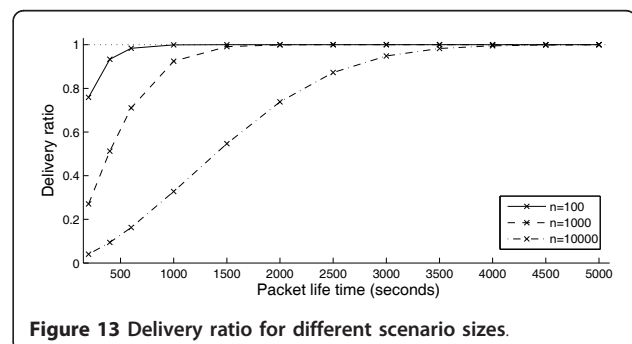
between distance to destination and TTL for various density levels with a 95% delivery probability.

If the TTL is fixed,  $P_d(t, d)$  can be used to determine whether a packet shall be transmitted or not for the required delivery probability. Figure 15 shows  $P_d(t, d)$  for the mobility and routing models for an average node degree of 4. For example, if the requirement of delivery probability is 95% or higher, then the packets to destinations that are over 6.5 radio radii away can be discarded if the TTL is set to 600 s.

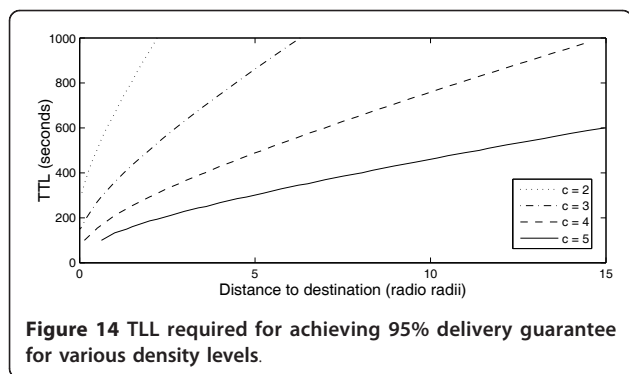
### 8. Conclusions and further study

We have presented and validated the forward-wait mathematical framework for geographic routing. The framework describes the probability of delivery as a function of the maximum allowed delivery time and the distance to destination. As input, the framework uses scenario- and protocol-specific random variables characterizing the forwarding and waiting phases. Combined with a description of the distance to destination, the delivery ratio can be computed for any scenario size. The framework can also be used to dynamically assess delivery probabilities based on different packet life time settings. A first application of the framework in the context of a military reconnaissance scenario has already provided useful insights [22].

A major challenge in modeling routing performance is that the routing performance is scenario- and protocol-dependant. For the proposed forward-wait framework,



**Figure 13 Delivery ratio for different scenario sizes.**



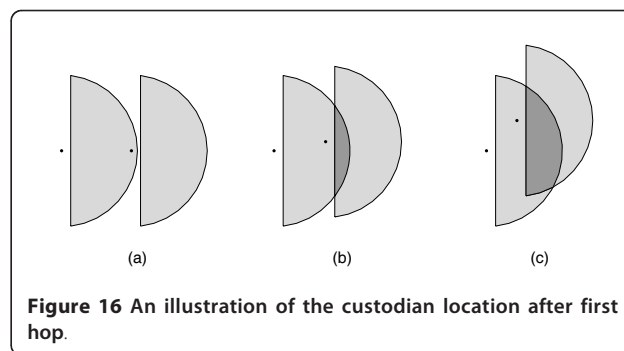
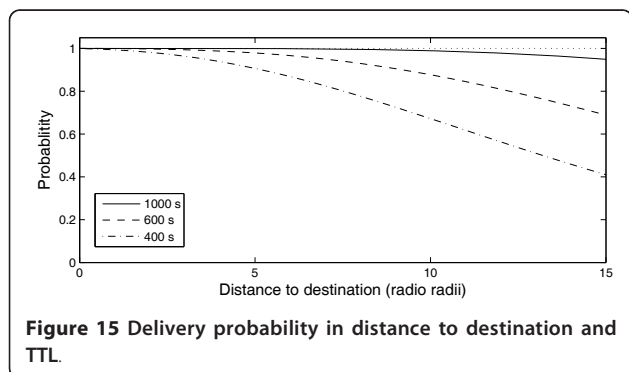
the scenario- and protocol-specific elements are captured by the properties of the forwarding and waiting phases. For a specific scenario evaluated in ns-2, we determined these properties using two methods: (1) an abstract mobility model with Poisson distributed node placement and a routing protocol model, and (2) basic routing data from the ns-2 simulations. Comparing the two approaches, we observed that only with the latter input the forward-wait framework could accurately predict the routing results from the ns-2 simulations. This illustrates the difficulty of accurately describing node mobility and routing protocol using simple abstractions, and that if simplistic models are used, then the performance results are generally not reliable.

While the proposed framework is believed to be general enough to apply to other geographic routing algorithms, further study is needed to provide the evidence for this. In addition to the validation of the framework to broaden its usefulness, the prediction accuracy could be improved by explicitly considering both time and motion in the models describing forwarding and waiting.

### Appendix 1

#### Complexity of deriving the distribution of forwarding distance

In illustrating the complexity of determining forwarding distance analytically, it is instructive to make a couple of



major simplifications. First, nodes are Poisson distributed. Second, the destination is infinitely far away. With these assumptions, the forwarding area has a constant shape. Yet, an analytical derivation of the forwarding distance is still practically unfeasible. For the first hop from the source, it is trivial to establish whether or not a packet can be forwarded, and the probability distribution of the progress if forwarding takes place. For the possible second hop, the distribution becomes harder to derive. Depending on the location of the custodian after the first hop, there are three different cases, as illustrated in Figure 16. Under the assumption of perfect custodian selection, the intersection of the two forwarding areas does not contain any other node. Although the process is cumbersome, it is feasible to derive analytical expressions on a case-by-case basis. However, with a chain of forwarding operations, the derivation becomes overwhelmingly complex and practically unfeasible. This justifies the use of determining the distributions of the forwarding phase by means of Monte Carlo simulations.

### Appendix 2

#### Source-destination distribution

In this section, we derive the source-destination distance density function, by considering two nodes being placed randomly with a uniform distribution in a square area. Let the positions of the two nodes  $A$  and  $B$  be represented by random variables defined below, where  $k$  is the side length of the square.

$$A = (X_A, Y_A)$$

$$B = (X_B, Y_B)$$

$$\text{pdf}(X_A, x) = \text{pdf}(Y_A, x) = \text{pdf}(X_B, x) = \text{pdf}(Y_B, x) = \begin{cases} 1/k & 0 \leq x \leq k \\ 0 & \text{otherwise} \end{cases}$$

The random variable representing the distance between the two nodes has the following expression.

$$Y = |A - B| = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2}$$



In determining the density function of  $Y$ , we make use of the below relationships.

$$\text{pdf}(A + B, t) = \iint \text{pdf}(A, x) \cdot \text{pdf}(B, y) \cdot \delta((x + y) - t) dx dy$$

$$\text{pdf}(A - B, t) = \iint \text{pdf}(A, x) \cdot \text{pdf}(B, y) \cdot \delta((x - y) - t) dx dy$$

$$\text{pdf}(f(X), y) = \text{pdf}(X, x) \cdot \left| \frac{dx}{dy} \right|, \text{ where } f(x) \text{ is a continu-}$$

ous and strictly increasing or decreasing function of  $x$  within the range where  $\text{pdf}(X, x) > 0$ .

The density function of  $Y$ ,  $\text{pdf}(Y, d)$ , can then be derived as follows.

$$\begin{aligned} \text{pdf}(X_A - X_B, d) &= \text{pdf}(Y_A - Y_B, d) = \iint \text{pdf}(X_A, x) \cdot \text{pdf}(X_B, y) \cdot \delta((x - y) - d) dx dy = \\ &= \begin{cases} \int_0^{k-d} \frac{1}{k} \cdot \frac{1}{k} dx - k \leq d \leq 0 \\ \int_d^k \frac{1}{k} \cdot \frac{1}{k} dx & 0 < d \leq k \\ 0 & \text{otherwise} \end{cases} = \\ &= \begin{cases} 1/k + d/k^2 & -k \leq d \leq 0 \\ 1/k - d/k^2 & 0 < d \leq k \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

$$\text{pdf}(|X_A - X_B|, d) = \begin{cases} 2/k - 2d/k^2 & 0 \leq d \leq k \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{aligned} \text{pdf}((X_A - X_B)^2, d) &= \text{pdf}(|X_A - X_B|^2, d) = \text{pdf}(|X_A - X_B|, \sqrt{d}) \cdot \left| \frac{1}{2\sqrt{d}} \right| \\ &= \begin{cases} \frac{1}{k\sqrt{d}} - \frac{1}{k^2} & 0 \leq d \leq k^2 \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

$$\begin{aligned} \text{pdf}((X_A - X_B)^2 + (Y_A - Y_B)^2, d) &= \iint \text{pdf}((X_A - X_B)^2, x) \cdot \text{pdf}((Y_A - Y_B)^2, y) \cdot \delta((x + y) - d) dx dy = \\ &= \begin{cases} \int_0^d \left( \frac{1}{k\sqrt{x}} - \frac{1}{k^2} \right) \left( \frac{1}{k\sqrt{d-x}} - \frac{1}{k^2} \right) dx & 0 \leq d \leq k^2 \\ \int_{d-k^2}^{k^2} \left( \frac{1}{k\sqrt{x}} - \frac{1}{k^2} \right) \left( \frac{1}{k\sqrt{d-x}} - \frac{1}{k^2} \right) dx & k^2 < d < 2k^2 \\ 0 & \text{otherwise} \end{cases} = \\ &= \begin{cases} \left[ \frac{2}{k^2} \tan^{-1} \left( \frac{\sqrt{x}}{\sqrt{d-x}} \right) + \frac{2\sqrt{d-x}}{k^3} - \frac{2\sqrt{x}}{k^3} + \frac{x}{k^4} \right]_0^d & 0 \leq d \leq k^2 \\ \left[ \frac{2}{k^2} \tan^{-1} \left( \frac{\sqrt{x}}{\sqrt{d-x}} \right) + \frac{2\sqrt{d-x}}{k^3} - \frac{2\sqrt{x}}{k^3} + \frac{x}{k^4} \right]_{d-k^2}^{k^2} & k^2 < d < 2k^2 \\ 0 & \text{otherwise} \end{cases} = \\ &= \begin{cases} \frac{\pi}{k^2} - \frac{4\sqrt{d}}{k^3} + \frac{d}{k^4} & 0 \leq d \leq k^2 \\ \frac{2}{k^2} \tan^{-1} \left( \frac{2k^2 - d}{2k\sqrt{d-k^2}} \right) - \frac{2}{k^2} + \frac{4\sqrt{d-k^2}}{k^3} - \frac{d}{k^4} & k^2 < d < 2k^2 \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

$$\begin{aligned} \text{pdf}(Y, d) &= \text{pdf}((X_A - X_B)^2 + (Y_A - Y_B)^2, d^2) \cdot |2d| \\ &= \begin{cases} 2d \cdot \left( \frac{\pi}{k^2} - \frac{4d}{k^3} + \frac{d^2}{k^4} \right) & 0 \leq d \leq k \\ 2d \cdot \left( \frac{2}{k^2} \tan^{-1} \left( \frac{2k^2 - d^2}{2k\sqrt{d^2 - k^2}} \right) - \frac{2}{k^2} + \frac{4\sqrt{d^2 - k^2}}{k^3} - \frac{d^2}{k^4} \right) & k < d < \sqrt{2}k \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

#### Author details

<sup>1</sup>Saab Aeronautics, Linköping, Sweden <sup>2</sup>Department of Computer and Information Science, Linköping University, Linköping, Sweden <sup>3</sup>Department of Science and Technology, Linköping University, Linköping, Sweden

#### Competing interests

The authors declare that they have no competing interests.

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