Performance Modeling of Opportunistic Networks

Jerzy Martyna

Institute of Computer Science, Jagiellonian University,
ul. Prof. S. Lojasiewicza 6, 30-348 Cracow, Poland

Abstract. The influence of node mobility in Mobile Ad hoc NETworks (MANETs) has significant implications for system performance. A class of MANETs characterised by a sparse density of nodes coupled with a relatively short range of radio communication, results in a network topology that is disconnected most of the time.This wireless mobile ad hoc network is called an "opportunistic network" or "delay-tolerant" network. This paper presents some models in which the rate of information propagation within the opportunistic network is considered. Furthermore, a characterisation of the multicast time in the opportunistic network is developed.

Keywords: opportunistic networks, mobility models, performance evaluation.

1 Introduction

Opportunistic networking is a new paradigm in wireless mobile ad hoc networks. These networks are an evolution of MANETs, where mobile nodes communicate with each other even if a route connecting them does not exist. The nodes that are spread access the environment form the actual network, and they are not required to possess information about the network topology. The routes between nodes are dynamically created, and any nodes can be opportunistically used as a next hop if they can bring the message closer to the destination [1–3]. The opportunistic networks are often considered as a class of Delay-Tolerant Networks (DTNs), where communication opportunities are intermittent and an end-to-end path between the source and the destination may never exist [4].

The opportunistic networks are typically used in an environment that is tolerant of long delays and high error rates. These networks naturally arise in many contexts, including battlefield communication networks, animal tag based sensor networks [5], emergency response networks. Examples of such networks also include deep-space interplanetary networks [6], networks of mobile robots [7] and vehicular ad hoc networks [8].

There are many works devoted to the subject of mobility modeling. Some popular mobility models belong the Random Waypoint [9], and the Random Direction model [10]. However, two important parameters, namely hitting and meeting times, under such models is not available. These parameters have been analysed for Random Walk mobility model [11]. Recently, these models have been extensively analysed and simulated [12, 13].

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Several opportunistic network performance analysis have been recently introduced in the literature. For instance, in by R. Groenevelt et al. [14], the message delay in mobile ad hoc networks is studied. A framework for routing performance analysis in DTN with application to non-cooperative networks has been presented by G. Resta and P. Santi [15]. Performance modelling of epidemic routing has been carried out by X. Zhang et al. [16]. In these papers, the authors have assumed the inter-contact times between any pair of nodes in the opportunistic network. For instance, in network performance models in [17–19], the simple geometric, random-walk mobility models have been used. On the other hand, these models have been derived based on much simpler mobility models. Recently, the impact of mobility in information spreading has been studied by A. Clementi et al. [20]. Theoretical performance bounds on broadcast time in opportunistic networks as the size n of the network grows are derived by L. Becchetti et al. [21].

In this paper, we present for the first time new results aimed at characterising opportunistic network performance. More specifically, we present two possible network models based on epidemic routing and two-hop multicopy routing. Both models concern pairwise inter-contact between nodes in the network. Additionally, we present a realistic model with inter-contact time between nodes, namely the Home-MEG model. Next, we introduce an upper-bound on the multicast time for the network with n nodes and the the k-ary multicast tree. As our results below demonstrate, our bound suggests a different performance measure than that predicted by the previous studies based on on various mobility models.

The paper is organized as follows. First, we describe the pairwise inter-contact patterns between nodes models of opportunistic networks in Sect. 2. In Section 3, we present the Home-MEG model of opportunistic network. In Section 4, we introduce new performance measures for the opportunistic networks such as the upper multicast time and the lower multicast time. Section 5 concludes the paper.

2 Opportunistic Network with Pairwise Inter-contact Patterns between Nodes

In this section, we present a performance analysis of the opportunistic network with pairwise inter-contact patterns between nodes.

Let be an opportunistic network composed of n nodes. We assume that a randomly selected source, node S, wants to deliver a message, M, to a randomly selected destination node $D (D \neq S)$. In order to characterize performance in this opportunistic network, the following assumption is made: each message is delivered to its destination within a certain time TTL (Time to Live) since its generation. Three different routing protocols are used in the analysis: (1) epidemic routing, and (2) two-hops routing.

Ad (1). In the epidemic routing, described as a.o. by A. Vahdat et al. [22], source node S delivers a copy of message M to all nodes it encounters.

If the two nodes meet, they exchange message copies with each other until the message is delivered to the destination node.

Ad (2). Two-hops routing was introduced by M. Grossglauser et al. [23] and further studied in several articles (see: [12, 14]). In this routing scheme, the source node generates up to L copies of the message and delivers $L-1$ (encountered new nodes). Any node holding a message or a copy of the message can send it only to the destination node. These nodes cannot send the message further.

Next, the following assumptions are made:

(a) Pairwise contacts are instantaneous, but sufficiently long as to entirely transfer the message M between nodes.
(b) The nodes move according to an arbitrary mobility model with exponentially distributed meeting time, with rate $\frac{1}{\mu}$ between arbitrary node pairs. The meeting time of a mobility model is defined as the time that has elapsed between a random time and the first "meeting" of an arbitrary node pair. It was formally proved for some mobility models, i.e. random walks [24]; and such mobility models as a random waypoint, random direction, etc. [12].
(c) The transmission range is equal to r. This means that any communicating pair of nodes communicating at the same time can do so without interference.

2.1 Epidemic Routing

In the following pare, we consider the performance of epidemic routing. Our focus will be on the *expected delivery delay*, which is formally defined by Groenevelt et al. [14].

Definition 1. *Let T_D be the random variable corresponding to the time elapsing between the time instant at which message M is generated at node S and the time at which the message M is first delivered to node D. The expected value of random variable T_D and is denoted $E[T_D]$.*

Under the assumption of exponential pairwise distribution of inter-contact times in the epidemic routing, the expected delivery delay with epidemic routing is as follows:

Theorem 1. *[14] The expected delivery delay with epidemic routing and exponentially distributed pairwise inter-contact times with parameter λ is given by:*

$$E_{\exp}\left[T_D^{\text{epi}}\right] = \frac{1}{\lambda(n-1)}\left(\log n + 0.57721 + O\left(\frac{1}{n}\right)\right) \qquad (1)$$

where n is size of network.

The asymptotic behaviour of $E_{\exp}[T_D^{\text{epi}}]$ requires the investigation of the influence of n. Thus, for large n is satisfied:

$$\lim_{n\to} E_{\text{exp}}\left[T_D^{\text{epi}}\right] = \lim_{n\to\infty} \frac{\log n}{n} = 0 \ . \tag{2}$$

When the bundle size is smaller than the link size, bundles may perform up to $\lfloor \frac{1}{\alpha} \rfloor$ hops during one time step. Thus, the expected delivery time is as follows:

Theorem 2. *The expected delivery delay with epidemic routing and inter-contact times obeying the parameter* $\alpha(0 < \alpha < 1)$ *grows unboundedly with* n*, that is:*

$$\lim_{n\to\infty} E_{\text{exp}}[T_D^{\text{epi}}] = +\infty \ . \tag{3}$$

In other hand, the expected delivery time of epidemic routing in network with a boundle size smaller then the link size grows unboundedly.

2.2 Two-Hops Routing

Here, we give an overview of two main theories on two-hops routing. The first was derived by Groenevelt et al. [14] and states that an expected delivery delay with two-hops routing under the Assumption is distributed in inter-contact time.

Theorem 3. *The expected delivery delay with two-hops routing and exponentially distributed pairwise inter-contact times with parameter* λ *is equal to*

$$E_{\text{exp}}\left[T_D^{2h}\right] = \frac{1}{\lambda}\left(\sqrt{\frac{\pi}{2(n-1)}} + O\left(\frac{1}{n}\right)\right) \ . \tag{4}$$

The above theorem implies the following asymptotic trend for $E_{\text{exp}}\left[T_D^{2h}\right]$, that is

$$\lim_{n\to\infty} E_{\text{exp}}\left[T_D^{2h}\right] = \lim_{n\to\infty} \frac{1}{\sqrt{n}} - 0 \ . \tag{5}$$

In particular, when the source node S delivering the copy of the message to the first node meets relay node R, and then node R is in charge of delivering message M to the destination node D, then multi-copy version of two-hops routing is faster than its single-copy counterpart in delivering a message to its destination. The expected routing delay for two-hops routing can be considered as an upper bound to the expected routing delay under the multicopy twohops routing is presented in the following theorem.

Theorem 4. *The expected delivery delay with single-copy two-hops routing and inter-contact times with truncated Pareto distribution of parameters* γ*, 1,* b*, with* $0 < \gamma < 2$*,* $1 < b$*, is equal to*

$$E_{\text{Pareto}}\left[T_D^{s2h}\right] = \frac{1}{E_{\text{Pareto}}[T_{u,v}](1-b^{-\gamma})}\left(\frac{b^{2-\gamma}-1}{2-\gamma} - \frac{b^2-1}{2b^\gamma}\right) \tag{6}$$

where $E_{\text{Pareto}}\left[T_{u,v}\right]$ *is the expected inter-contact time with truncated Pareto distribution and is defined as follows:*

$$E_{\text{Pareto}}\left[T_{u,v}\right] = \begin{cases} \left[\ln \frac{b}{1-b^{-1}}\right] & \text{if} \quad \gamma = 1 \\ \frac{\gamma}{\gamma-1}\left(\frac{1-b^{1-\gamma}}{1-b^{-\gamma}}\right) & \text{otherwise} \end{cases} . \tag{7}$$

This theorem implies the assumption

$$\lim_{n\to\infty} E_{\text{Pareto}}\left[T_D^{s2h}\right] \leq \lim_{n\to\infty} E_{\text{Pareto}}\left[T_D^{s2h}\right] = c \tag{8}$$

where $c > 0$.

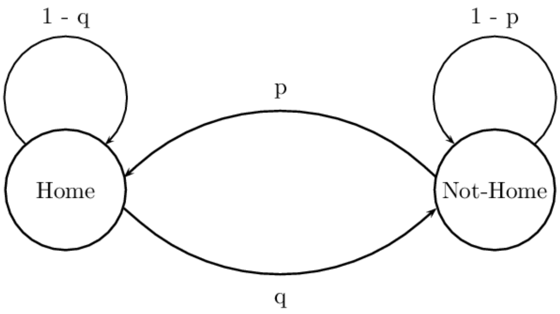

Fig. 1. The Home-MEG model

3 Opportunistic Network with the Inter-contact Time between Nodes

In this section the contacts between nodes in the opportunistic network is modeled. This approach allows us to produce simpler models of contact patterns amenable for use in performance analysis between network nodes.

3.1 The Home-MEG Model

A simple pairwise contact model for opportunistic networks, called the Home-MEG (Markovian Evolving Graph), has been introduced by L. Becchetti et al. [25]. This model is used to model the occurrence and/or disappearance of wireless links between pairs of nodes. Thus, Home-MEG is a discrete-time model, according to which the existence of the link between u and v can change state at time $t, t+1$, etc. The state transition diagram of the Home-MEG model is given in Fig. 1. We can thus interpret the state transition in Fig. 1 diagram as follows: the pair of arbitrary nodes, u and v, can be in one of two states: the *Home* state, corresponding to the situation in which both nodes u and v are at one of their home locations; and the *Non-Home* state, corresponding to the complementary situation in which one of the nodes (or both) are not in a home location. The *Home* state is based on the well-known observation made by T. Karagiannis et al. [26]

that pairs of individuals in the network tend to repeatly meet in a few locations, known as "home" (or "meeting") location.

In accordance with the observation made by T. Karagiannis et al., in the Home-MEG model the probability of establishing an instaneous communication opportunity (e.g., a contract between u and v) at time t depends on the state of the pair: it is α with $0 < \alpha < 1$ where the pair is in state *Home*, and it is β with $0 < \beta \leq \alpha$ when the pair is in the *Non-Home* state.Two further parameters of the model are the probability q of making a transition from *Home* to *Non-Home* state, and the probability p of making a transition from *Non-Home* to *Home* state. Finally, the Home-MEG model is fully characterised by four parameters: the state transition probabilities p and q, and the contract opportunity probabilities α and β.

The Home-MEG model was introduced to model *communication opportunities* or *contacts u and v*, where a communication opportunity is intended as an instantaneous event during which an arbitrary large of message can be exchanged. The stationary probabilities can be derived as follows. Let IC be the random variable corresponding to the number of time steps elapsing between two consecutive contacts. The stationary probabilities p_H and p_{NH} of finding the pair of nodes in the *Home* state and the *Non-Home* state respectively are given by:

$$p_H = \frac{p}{p+q} \quad \text{and} \quad p_{NH} = 1 - p_H \ . \tag{9}$$

The probability of finding the prior state *Home* (*Non-Home*), conditioned on the event that a contact occurs can be computed by the use of the Bayes' theorem

$$P(H \mid Contact) = \frac{P(Contact \mid H) \cdot P(H)}{P(Contact)} = \frac{\alpha \cdot p}{p \cdot \alpha + q \cdot \beta} \tag{10}$$

$$P(NH \mid Contact) = \frac{\beta \cdot q}{p \cdot \alpha + q \cdot \beta} \tag{11}$$

For any $k \geq 1$ the probability that $P(IC = k)$ is recursively defined as follows:

$$P(IC = k)P(H \mid Contact)P_{kH} + P(NH \mid Contact)P_{kN} \tag{12}$$

where

$$P_{1H} = (1-q)\alpha + \beta, \quad P_{1N} = (1-p)\beta + p\alpha \tag{13}$$

$$P_{iH} = q(1-\beta)P_{(i-1)N} + (1-q)(1-\alpha)P_{(i-1)H} \tag{14}$$

$$P_{iN} = (1-p)(1-\beta)P_{(i-1)N} + p(1-\alpha)P_{(i-1)H}, \quad i = 2, \ldots, k \ . \tag{15}$$

Various aspects of the Home-MEG model validation have been studied in the past few years.

The obtained results [25] proved that the Home-MEG model is able to accurately reproduce pairwise contact patterns observed in real-world traces. The Home-MEG model can be modeled by use of a four-states Markov chain. In the states HC and NC (where -C is modeling the existence), we say the edge exists and the nodes u and v are in *Home* and *Non-Home* states respectively. In the HD and ND (where -D is modeling non-existence) states, we say that the edge does not exist. The Markov chain over such state space is given in Table 1.

Table 1. The transition matrix of the Markov chain used to model existence/non-existence of a pairwise wireless link in the Home-MEG model

	HC	HD	NC	ND
HC	$(1-q)\alpha$	$(1-q)(1-\alpha)$	$q\beta$	$q(1-\beta)$
HD	$(1-q)\alpha$	$(1-q)(1-\alpha)$	$q\beta$	$q(1-\beta)$
NC	$p\alpha$	$p(1-\alpha)$	$(1-p)\beta$	$(1-p)(1-\beta)$
ND	$p\alpha$	$p(1-\alpha)$	$(1-p)\beta$	$(1-p)(1-\beta)$

The Markov chain used to model existence/non-existence of a pairwise link in the Home-MEG model is ergodic (irreducible and aperiodic). To reproduce the pairwise contact patterns in a network with n nodes is sufficient to generate $n(n-1)/2$ identical and independent copies of the above Markov chain (one for each possible paiwise link) in the network.

3.2 The Broadcast Time in the Opportunistic Networks with the Home-MEG Model

An upper bound on the broadcasting time for the network with n nodes defined by dynamic graphs obtained when for any pair of nodes $u, v \in V$ is determined by the above Markov chain is proved by Becchetti [25] in the following theorem.

Theorem 5. *Assume the dynamic graph $G = (V, E_T)$ is defined according to the Home-MEG model of parameters (q, p, α, β) as described above, that the initial edge set E_0 is randomly chosen according to the stationary distribution of the underlying Markov chain, and that*

$$\left\lceil \frac{\Lambda}{n} \right\rceil \leq \min \left\{ \frac{1}{\alpha}, \frac{1}{4 \cdot p} \right\} \tag{16}$$

where Λ is defined as follows

$$\Lambda = \frac{4(q+p)}{q \cdot \alpha} \ . \tag{17}$$

Then the upper bound on the broadcasting is given by

$$B(G) = O\left(\frac{\log n}{\log\left(1 + \frac{1}{\Lambda}\right)} \right) \ . \tag{18}$$

It is easy to see that for the values $q \ll p, \quad \alpha \gg \beta,$ and $q + p \ll 1$ is satisfied a special case of the above theorem.

Theorem 6. *Under the same assumption for Theorem 3 let p, q, α, β be defined as follows:*

$$q = \frac{1}{n^{1+\epsilon}}, \quad p = \frac{1}{n}, \quad \alpha = \frac{1}{n^{1-\epsilon}}, \quad \beta = \frac{1}{n^2} \tag{19}$$

the broadcasting time in the dynamic graph is given by $O(\log n)$ with high probability.

4 Multicast Time in Opportunistic Networks under Exponential Inter-contact Times

In order to evaluate the inter-contact time of multicast, we concentrate on a one-to-many communication where a source node sends a different message to m, uniformly distributed destinations from the source to each destination. The multicast economises on the number of links travelled: the message is only copied at each branch point of the multicast tree to m destinations. Let us note that $H_n(m)$ is the number of links in the shortest path tree (SPT) to m uniformly chosen nodes. We define the multicast gain $g_n(m) = E[H_n(m)]$ as the average number of hops in the SPT rooted at a source to m randomly chosen distinct destinations. Thus, $g_n(m) \leq f_n(m)$, where $f_n(m) = m \cdot E[H_n]$ is the average number of hops to a uniform location in the graph with n nodes.

We now assume that the multicast delivers packets along the shortest path from a source to each of the m destination. We also assumed that the m multicast group member nodes are uniformly chosen out of the total number of nodes n. Next, we will give a following theorem.

Theorem 7. *For any connected graph with n nodes the number of m, the destinations are given by*

$$m \leq g_n(m) \leq \frac{n \cdot m}{m+1} \ . \tag{20}$$

For the multicast tree, we can consider the k-ary tree of depth D with the source at the root of the tree and m receivers at randomly chosen nodes. We recall that the depth D is equal to the number of hops from the root to a node at the leaves. In a k-ary tree the total number of nodes is given by

$$n = 1 + k + k^2 + \cdots + k^D = \frac{k^{D+1} - 1}{k - 1} \ . \tag{21}$$

Thus, we can formulate the following theorem.

Theorem 8. *For the k-ary multicast tree the gain is given by*

$$g_{n,k(m)} = N - 1 - \sum_{j=0}^{D-1} k^{D-j} \frac{\binom{N-1-\frac{k^{j+1}-1}{k-1}}{m}}{\binom{N-1}{m}} \tag{22}$$

which indicates the average number of hops in this multicast tree.

Thus, we can give the boundaries on the multicast time for the network with n nodes and the k-ary multicast tree of depth D. The following theorem quantifies the multicast time.

Theorem 9. *An upper bound on the multicastt time for the opportunistic network with n nodes and the k-ary multicast tree of depth D is given by*

$$B_M^{(u)}(G) = g_{n,k(m)} \frac{\log n}{\log\left(1 + \frac{n}{\Lambda}\right)} \tag{23}$$

where $g_{n,k(m)}$ is given by Equation (22), Λ is approximately by Equation (17).

The lower bound is attained in a star topology, where $k = n - 1$, $D = 1$, and the average hopcount is $E[H_n] = \frac{n}{2}$. Thus, in a k-ary tree the average hopcount, $E[H_n] = g_n(1)$, and is given by

$$E[H_n] = N - 1 - \sum_{j=0}^{D-1} k^{D-j} \frac{N - 1 - \frac{k^{j+1}-1}{k-1}}{N-1} \quad . \tag{24}$$

For large n, we can obtain

$$E[H_n] = \log_k n + \log_k \left(1 - \frac{1}{k}\right) - \frac{1}{k-1} + \frac{\log_k(n)}{n} \quad . \tag{25}$$

Theorem 10. *A lower bound on the multicast time for the opportunistic network with n nodes and the k-ary multicast tree of depth D is as follows:*

$$B_M^{(l)}(G) = E[H_n] \frac{\log n}{\log\left(1 + \frac{n}{\Lambda}\right)} \tag{26}$$

where $E[H_n]$ is given by Equation (25), Λ is approximated by Equation (17).

5 Simulation Results

In this section we compare the analytical bounds with the simulation results.

We have performed a set of simulations, in which n ($1 \leq n \leq 2000$) nodes are initially distributed uniformly at random in a square area of 5 km side. Nodes have a transmission range of 250 m, and move according to the random waypoint (RWP) mobility model with no pause time and fixed speed v. A random selected node generates the messages directed towards a randomly selected destinations. We performed a large set of such experiments for each parameter setting.

The results of this experimental estimation of the average number of hops in shortest path tree (SPT) to m uniformly chosen nodes as the destination nodes is depicted in Fig. 2. As shown in Fig. 2, $g_n(m)$ is monotonously decreasing in k. In other words, we observe that the deeper D (or the smaller value of k), the more overlap is possible.

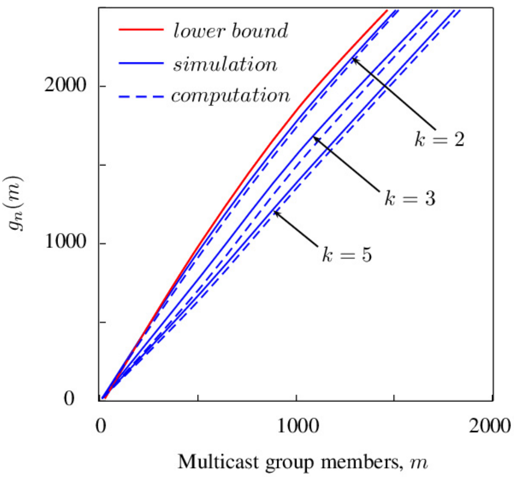

Fig. 2. The multicast gain $g_n(m)$ obtained for the k-arry tree with three values of k

6 Conclusions

In this paper, we have analysed the encounter statistics for modelling contacts in opportunistic networks. Instead of employing an unrealistic mobility model or mobility models that are derived from the user's mobility traces: temporal connectivity models that are developed from stochastic behaviour on human seems to be promising. We have explained the definitions and specific performance indices of interest to opportunistic networks, such as the delivery delay or the multicast time in these networks. Our delay analysis has many applications. For example, it can be used to predict the storage requirement at any nodes that prevents data loss due to buffer overflow.

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