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Delay and resource analysis in MANETs in presence of throwboxes

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Abstract

This paper addresses the delay analysis and resource consumption in mobile ad hoc networks (MANETs) equipped with throwboxes. Throwboxes are stationary, wireless devices that act as relays, and that are deployed to increase the connectivity between mobile nodes. Our objective is to quantify the impact of adding throwboxes on the performance of two routing protocols, namely the Multicopy Two-hop Routing protocol and the Epidemic Routing protocol, in the cases where the throwboxes are fully disconnected or mesh connected. To this end, we use a Markovian model where the successive meeting times between any pair of mobile nodes (resp. any mobile node and any throwbox) are represented by a Poisson process with intensity λ (resp. μ). We derive closed-form expressions for the distribution of the delivery delay of a packet and for the distribution of the total number of copies of a packet that are generated, the latter metric reflecting the overhead induced by the routing protocol. These results are then compared to simulation results. Through a mean-field approach we also provide asymptotic results when the number of nodes (mobile nodes and/or throwboxes) is large.

Keywords: MANET; Throwbox; Delay analysis; Mobility model; Markov models

1. Introduction

In sparse Mobile Ad Hoc Networks (MANETs) most of the time a node has no neighbor[2] and traditional store-and-forward routing protocols, which require the existence of a connected path between a packet source and a packet destination, do not achieve good performance (throughput, delay). The store-carry-and-forward paradigm has been proposed as an alternative to the store-and-forward paradigm [21]. Store-carry-and-forward protocols aim at increasing the number of contact opportunities between a packet and its destination, by using intermediary nodes (i.e. all nodes but the packet source and the packet destination) as relay nodes. The protocol in this class which yields the highest throughput and the lowest delay is the Epidemic Routing (ER) protocol, but it does so at the cost of increasing the energy and resource consumption. In the ER protocol every node acts as a relay for the other nodes [22].

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[2] Two nodes are neighbors if there are within transmission range of one another.

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Another well-known routing protocol in this class is the two-hop relay protocol introduced in [9], where at most one-hop relay is allowed.

Relaying opportunities can be further increased by adding throwboxes, as proposed in [24]. A throwbox is a stationary device which acts as a relay between nodes passing by it at different times. The throwboxes may either be fully disconnected or mesh connected. The latter situation provides yet additional packet forwarding opportunities.

In the last years fundamental results have been obtained in the field of wireless communications, including MANETs. Gupta and Kumar [10] and Grossglauser and Tse [9] have investigated the capacity in fixed wireless networks and in mobile ad hoc networks, respectively, and established some key results. In [10] it is shown that the per-node throughput capacity decreases approximately like $1/\sqrt{n}$, with n the number of nodes by unit area. It is shown in [9] that one can take advantage of node mobility, and use relaying, to reach a constant per-node throughput capacity, but at the expense of unbounded delays. In [19] Sharma et al. relate the nature of the delay-capacity trade-off to the nature of the node mobility pattern. In particular, they introduce the notion of critical delay, below which node mobility cannot be used to improve the capacity. Below, we mention some works which are related to ours (nonexhaustive list). Small and Haas in [20] provides a model, based on ODEs, to evaluate the performance of MANETs imbedded in an infostation network architecture. They consider the case where the ER protocol is used to relay data from the mobile nodes to the infostations. An infostation can be seen as a wireless access port to the Internet or to some private networks [7].

In [8], Groenevelt et al. introduce the so-called Multicopy Two-hop Relay protocol (MTR), a variant of the two-hop relay protocol [9]. In MTR the source forwards a copy of the packet to all (relay) nodes that it encounters; relay nodes are only allowed to forward packets to their destination. By modeling the successive meeting times between any pair of mobile nodes by Poisson processes, Groenevelt et al. characterize the distributions of the packet delivery delay and of the number of copies generated before a packet is delivered to its destination. This work is extended in [2] by Al Hanbali et al. by imposing lifetime constraints. Building on [8], Zhang et al. in [23] extend the work in [20] by studying variations of the ER protocol, including probabilistic routing (see [14]) and recovery infection schemes.

In [24] Zhao et al. investigate the capacity enhancement of using throwboxes in Disruption Tolerant Networks (DTNs). Using a linear programming approach, they find the maximum total rate (λ) such that the network can sustain a rate of λb_{ij} between nodes i and j for all i and j, where $[b_{ij}]$ is the traffic matrix. In a follow-up of this work, Banerjee et al. in [3] report experimental results collected on the UmassDieselNet testbed (a 40 bus DTN) showing that the use of a single throwbox improves the packet delivery by 37% and reduces the message delivery latency by more than 10%.

In this paper, we address the delivery delay of a single packet and the resource consumption generated until its delivery, in a MANET with throwboxes. This is done for both the MTR protocol and the ER protocol and for either fully disconnected or mesh connected throwboxes. Inspired by [8], we model contact opportunities between nodes (mobile nodes and throwboxes) by independent Poisson processes, and we develop a Markov analysis.

The rest of the paper is organized as follows: in Section 2 we study the successive meeting times between a mobile node and a throwbox. We show that the Poisson assumption is accurate for sparse MANETs and for two standard mobility models (the random way point and the random direction models). We also provide an approximation formula for the intensity of this Poisson process. In Section 3, we introduce Markov models to characterize the packet delivery delay and the resource consumption, both for the MTR protocol 3.1 and for the ER protocol 3.2. The asymptotic behaviour of the MTR protocol is addressed in Section 4, as the number of mobile nodes and/or the number of throwboxes become large. Our results are validated through simulations in Section 5 and concluding remarks are given in Section 6.

2. Characterizing the inter-meeting time distribution

Two nodes may only communicate when they are within each other's transmission range. When at least one of the nodes is mobile, this event occurs in a random way at certain points in time, called *meeting times*. The time that elapses between two consecutive meeting times is called the *inter-meeting time*. In [8], it was shown through extensive simulations that one may accurately model the successive meeting times by a Poisson process when both nodes move according to the same mobility pattern in a square of size $L \times L$, as long as the communication radius r is "small" with respect to L. The simulations in [8] were performed for $r = 50$ m, $r = 100$ m, $r = 250$ m and $L = 4$ km, and for three mobility patterns: the random waypoint (RWP) without pause, the random direction (RD) model with reflection or

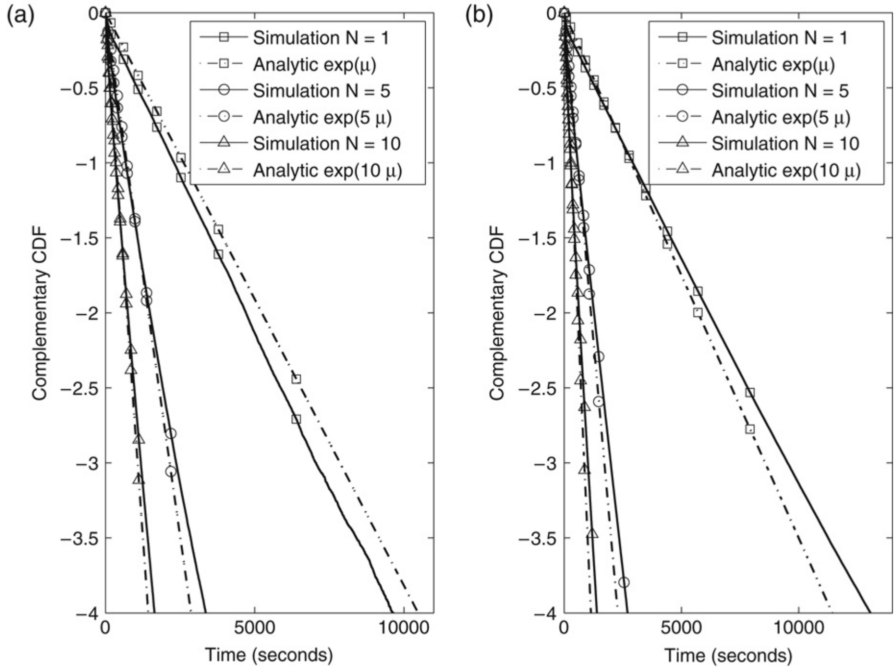

Fig. 1. Tail distribution of intermeeting times between N throwboxes and a mobile node moving according to RWP model (a) and RD model with reflection (b).

with wraparound, and the random walker. Approximation formulas for the intensity of the Poisson process are given in [8, Lemma 4] for both the RWP and the RD mobility models.

The aim of this section is to investigate the statistical nature of the consecutive meeting times between a mobile node and N throwboxes located in a square $\mathcal{A}$ of size $L \times L$. Similar to [8] we have first proceeded through simulations. The simulation scenario is as follows: there are N throwboxes and one mobile node. The mobile node moves according to either the RWP [5] without pause (with uniform speed in $[V_{\min} = 2\ \text{m/s}, V_{\max} = 12\ \text{m/s}]$) or the RD model with reflection at the boundaries [4] (with exponentially distributed travel times with mean 200 s, and uniform speed in $[V_{\min} = 2\ \text{m/s}, V_{\max} = 12\ \text{m/s}]$). All nodes have the same constant transmission range $r = 100$ m, and $L = 2$ km.

Let τ_N be the stationary intermeeting time between the mobile node and a throwbox. This time is defined as the time that elapses between two consecutive instants when the mobile node meets a throwbox. Fig. 1 plots, on a linear-log scale, the complementary cumulative distribution function (CCDF) of τ_N for $N \in \{1, 5, 10\}$, in the case where the throwboxes are placed in the area $\mathcal{A}$ independently of each other according to the uniform distribution, for both the RWP (Fig. 1(a)) and the RD (Fig. 1(b)) models. For each $N \in \{1, 5, 10\}$, at least 100,000 meeting times have been simulated. For each $N \in \{1, 5, 10\}$, we observe that τ_N is well-approximated by an exponential random variable (rv), with parameter μ_N. By estimating the slope μ_N associated with each mapping $t \to \log P(\tau_N > t)$ for $N = 1, 5, 10$, we have also observed that $\mu_N \approx \mu_1 N$, thereby showing that τ_N is well approximated by the minimum of N independent exponential rvs with common parameter $\mu := \mu_1$.

We have also conducted a statistical analysis using the classical autocorrelation function (ACF) method to test the mutual independence of inter-meeting times between a mobile and a throwbox. Recall that for a discrete time series $x = (x_1, \ldots, x_n)$ of length n, an estimate of the ACF of x (denoted by $\hat{R}$) is

$$\hat{R}(k) = \frac{1}{(n-k)\sigma^2} \sum_{i=1}^{n-k} (x_{i+k} - \bar{x})(x_i - \bar{x}), \quad k = 1, \ldots, n-1,$$

where $\bar{x} = (1/n) \sum_{i=1}^{n} x_i$ and $\sigma^2 = (1/(n-1)) \sum_{i=1}^{n} (x_i - \bar{x})^2$ denote the empirical mean and the empirical variance, respectively, of x.

Fig. 2 displays the autocorrelation function of the intermeeting times over a range of 10 lags (i.e. $k = 1, 2, \ldots, 10$) when the mobile moves according to the random waypoint model (left) or to the random direction model (right). For

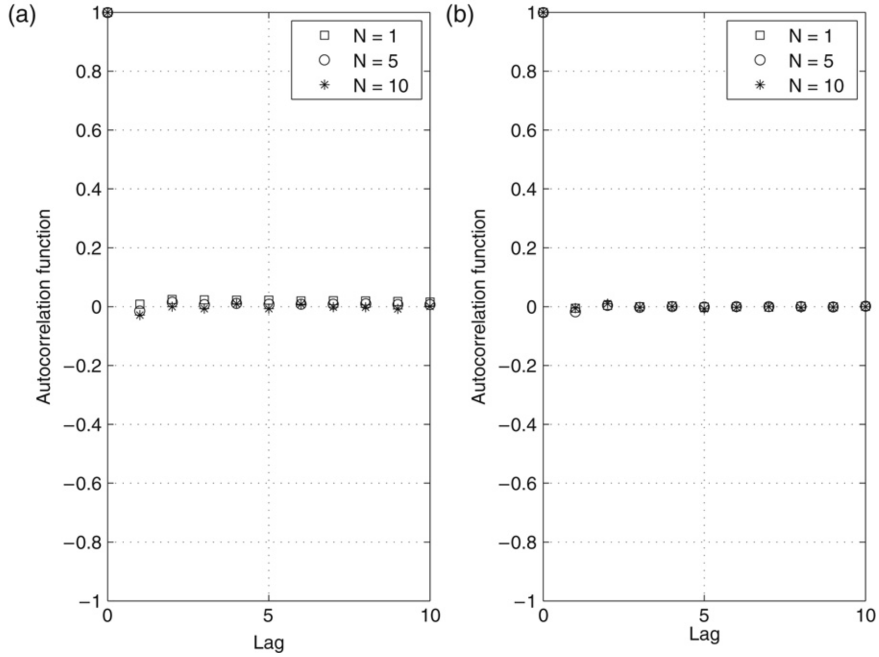

Fig. 2. Autocorrelation function of intermeeting times over 10 lags between N throwboxes and a mobile node moving according to the RWP model (a) and the RD model with reflection (b).

either mobility model, we observe that at each lag the autocorrelation is very close to zero, thereby justifying the assumption that intermeeting times are mutually independent.

We conclude from the above that the consecutive meeting times between a mobile node and a throwbox can be represented by a Poisson process, with rate $N\mu$.

It is also worth pointing out that the same result holds if nodes are placed in $\mathcal{A}$ according to the stationary distribution of the RWP [12,13], but of course we will get a different value of μ. These results are not reported in this paper due to space limitation.

In the Appendix section we derive an approximation formula for μ which holds (in particular) for the RWP and the RD models. Recall that μ is defined as the intensity at which the mobile node meets a single throwbox (i.e. $N = 1$). We have found (see Appendix)

$$\mu \approx \frac{2r}{\mathbf{E}[V_c^{-1}]} \int_{\mathcal{A}} f(x, y) g(x, y) \mathrm{d}x \mathrm{d}y, \tag{1}$$

where $f(\cdot,\cdot)$ is the density of the stationary location of the mobile node, $g(\cdot,\cdot)$ is the density of the location of the throwbox, and V_c is the speed of the mobile node when it meets the throwbox.

Consider our simulation scenario where each throwbox is “thrown over the area $\mathcal{A}$” according to the uniform distribution. Then, $g(x, y) = 1/L^2$ and $\mu \approx \frac{2r}{L^2\mathbf{E}[V_c^{-1}]}$ from (1). In Fig. 1 we have also plotted, for each $N \in \{1, 5, 10\}$, the mapping $t \to -\mu_N t$ (referred to as “Analytical $\exp(N\mu)$”) with $\mathbf{E}[V_c^{-1}] = (\log(V_{\max})-\log(V_{\min}))/(V_{\max}-V_{\min})$ when the mobile node moves according to the RWP model (Fig. 1(a)) and with $\mathbf{E}[V_c^{-1}] \approx 2/(V_{\max} + V_{\min})$ when the mobile node moves according to the RD model (Fig. 1(b)). The justification of these values for $\mathbf{E}[V_c^{-1}]$ can be found in Appendix. Observe from Fig. 1 that for each N the approximation formula for μ gives accurate results.

3. Markovian analysis

In this section we introduce and analyse simple stochastic models which will allow us to quantify the impact on the performance (packet delivery delay, resource consumption, etc.) of adding throwboxes in MANETs and of using them as additional relay nodes. Throughout the focus is on the transmission of a *single packet* between a source node and a destination node, both nodes being mobile nodes. We assume that the transmission time of the packet (or one of its copies, see below) between two nodes is instantaneous and successful. This setting typically corresponds to a situation where the network is sparse.

There are $N + 1$ identical mobile nodes, one source, one destination and $N - 1$ potential relay nodes, and M identical throwboxes, which can also be used as relay nodes, all located in a two-dimensional area, say a square $\mathcal{A}$. The mobile nodes are assumed to move independently of each other, according to the same mobility model.

Motivated by the results in [8] for mobile nodes and by our findings in Section 2 for a mobile node and several throwboxes, we assume that the intermeeting times between any pair of mobile nodes form a renewal sequence of rvs with a common exponential distribution with parameter λ, and that the intermeeting times between any pair composed of a mobile node and of a throwbox form a renewal sequence of rvs with a common exponential distribution with parameter μ. All these renewal sequences are assumed to be mutually independent.

Two different routing protocols are considered: the Multicopy Two-hop Relay (MTR) protocol and the Epidemic Routing (ER) protocol. Both protocols are defined in Section 1. Recall that in MTR when the source meets either a mobile node different from the destination node or a throwbox, it sends a copy of the packet to it; a mobile node or a throwbox that carries a copy of the packet are only allowed to forward it to the destination when they meet. ER behaves the same as MTR except that a relay node (a mobile node or a throwbox) that carries a copy of the packet is allowed to generate another copy and to forward it to a node (different from the destination) that does not already carry a copy. In both MTR and ER, when the source meets the destination, it forwards the packet to it (no relay node used).

Let T_{MTR} (resp. T_{ER}) be the first time where the packet or one of its copies, whichever event occurs first, reaches the destination under the MTR (resp. ER) protocol. Let G_{MTR} (resp. G_{ER}) be the number of copies generated until time T_{MTR} (resp. T_{ER}) under MTR (resp. ER) (we assume that the source is ready to transmit the packet at time $t = 0$ and that no copy has been generated yet).

For each protocol, we investigate the case where throwboxes are fully disconnected or mesh connected. The later case models situations when throwboxes are linked to each others (e.g. via wired lines or wireless links). In this case, a throwbox that receives a copy of the packet will forward it to all other throwboxes instantaneously.

The following notation will be used throughput this section. Let $B(t) \in \{0, 1, 2, \ldots, M\}$ (resp. $R(t) \in \{1, 2, \ldots, N\}$) be the number of throwboxes (resp. mobile nodes including the source) that carry a copy of the packet. We define the stochastic process $I(t) = (R(t), B(t))$ for $0 \le t < T_{\mathrm{MTR}}$ (resp. $0 \le t < T_{\mathrm{ER}}$) and $I(t) = a$ for $t \ge T_{\mathrm{MTR}}$ (resp. $t \ge T_{\mathrm{ER}}$). $I(t) = a$ indicates that the packet has been delivered to the destination at time t. Throughout this section we will assume $I(0) = (1, 0)$. Our modelling assumptions imply that, for both the MTR and the ER protocols, the process $\mathbf{I} = \{I(t),\ t \ge 0\}$ is an absorbing continuous-time Markov chain, with transient states $\mathcal{E} = \{1, 2, \ldots, N\} \times \{0, 1, \ldots, M\}$ and with one absorbing state $\{a\}$.

3.1. MTR protocol

We first consider the situation where throwboxes are fully disconnected. Let us first determine the probability distribution of the delivery delay T_{MTR}. We use the same approach as in [1]. Let D_{sd} be the time for the source to encounter the destination, D^r_n be the time for the mobile relay node n to deliver a copy of the packet to the destination, and D^t_m be the time for a throwbox m to deliver a copy of the packet to the destination. Thanks to our modelling assumptions we see that D_{sd} is distributed according to an exponential rv with rate λ, D^r_n is distributed as the sum of two independent exponential rvs each with the same parameter λ, and D^t_m is distributed as the sum of two independent exponential rvs with the same parameter μ. Clearly

$$T_{\mathrm{MTR}} \stackrel{st}{=} \min(D_{sd}, D^r_1, \ldots, D^r_{N-1}, D^t_1, \ldots, D^t_M).$$

These rvs being all mutually independent, we have that

$$P(T_{\mathrm{MTR}} > t) = P(D_{sd} > t) \prod_{n=1}^{N-1} P(D^r_n > t) \prod_{m=1}^{M} P(D^t_m > t),$$

so that

$$P(T_{\mathrm{MTR}} > t) = \mathrm{e}^{-(\lambda N + \mu M)t} (\lambda t + 1)^{(N-1)} (\mu t + 1)^M. \tag{2}$$

From (2) we can compute the expected delivery delay under MTR, given by

$$\mathbf{E}[T_{\mathrm{MTR}}] = \frac{1}{\alpha} \sum_{n=0}^{N-1} \sum_{m=0}^{M} \binom{N-1}{n} \binom{M}{m} (n+m)! \left(\frac{\lambda}{\alpha}\right)^n \left(\frac{\mu}{\alpha}\right)^m, \tag{3}$$

where $\alpha := N\lambda + M\mu$. Asymptotic results for $\mathbf{E}[T_{\mathrm{MTR}}]$ when N and M are large will be obtained in Section 4.

Let us now turn our attention to the probability distribution of G_{MTR}, the number of copies generated by the MTR protocol until the delivery of the packet to the destination. Define $P_a(n, m)$ as the probability that the last state visited by the Markov chain $\mathbf{I}$ before absorption in state $\{a\}$ is (n, m) given that $I(0) = (1, 0)$. The probability of the event $\{G_{\mathrm{MTR}} = k\}$ is equal to the sum of the probabilities $P_a(n, m)$ for which $n + m = k$ with $1 \le n \le N$ and $0 \le m \le M$, that is,

$$P(G_{\mathrm{MTR}} = k) = \sum_{n=\max(1,k-M)}^{\min(k,N)} P_a(n, k-n), \quad k = 1, 2, \ldots, N + M. \tag{4}$$

It remains to find $P_a(n, m)$. The Markov chain $\mathbf{I}$ stays for an exponential amount of time with rate α in state $(i, j) \in \mathcal{E}$ after which it jumps into state $(i + 1, j)$ with probability $\lambda(N - i)/\alpha$, it jumps in state $(i, j + 1)$ with probability $\mu(M - j)/\alpha$ and it is absorbed with probability $(\lambda i + \mu j)/\alpha$. By writing down the probabilities of the different paths joining state $(1, 0)$ to state (n, m) (there are $\binom{n+m-1}{n-1}$ such paths) we see that they are all as likely to occur, so that (Hint: take the path $(1, 0) \to (N - 1, 0) \to (N - 1, 1) \to (N, M)$)

$$\begin{aligned} P_a(n, m) &= \binom{n+m-1}{n-1} \frac{n\lambda + m\mu}{\alpha} \prod_{i=1}^{n-1} \frac{(N-i)\lambda}{\alpha} \prod_{j=0}^{m-1} \frac{(M-j)\mu}{\alpha} \\ &= \frac{\lambda^{n-1}\mu^m (n\lambda + m\mu)}{\alpha^{n+m}} (n+m-1)! \binom{N-1}{n-1} \binom{M}{m}. \end{aligned} \tag{5}$$

The expected number of copies generated until the delivery of the packet, $\mathbf{E}[G_{\mathrm{MTR}}]$, may be obtained from (4) and (5). There exists an alternative way of computing $\mathbf{E}[G_{\mathrm{MTR}}]$, which is based on the observation that T_{MTR} is the sum of G_{MTR} independent, identical, exponential rvs with parameter α (each of them corresponds to the sojourn time of the Markov chain $\mathbf{I}$ in a state). Hence, by Wald's formula we obtain that $\mathbf{E}[T_{\mathrm{MTR}}] = \mathbf{E}[G_{\mathrm{MTR}}]/\alpha$, that is $\mathbf{E}[G_{\mathrm{MTR}}] = \alpha\mathbf{E}[T_{\mathrm{MTR}}]$, where $\mathbf{E}[T_{\mathrm{MTR}}]$ is given in (3).

We conclude this section by briefly discussing the situation where all throwboxes are fully connected. In this setting, when a copy of the packet is transmitted to a throwbox (which does not already carry a copy) then all the other throwboxes receive this copy instantaneously. The analysis of this case therefore appears to be a particular instance of the case where the throwboxes are all disconnected, and is obtained by letting $M = 1$ and then by replacing μ by $M\mu$ in the above analysis.

3.2. Epidemic routing protocol

Similar to the analysis in Section 3.1 we first consider the case where all throwboxes are disconnected. Let $\mathbf{Q}_{\mathrm{ER}} = [q_{\mathrm{ER}}(\cdot, \cdot)]$ denote the infinitesimal generator of the Markov chain $\mathbf{I}$ under the ER protocol. For sake of clarity, we will discard the subscript ER in $\mathbf{Q}_{\mathrm{ER}}$ and in $q_{\mathrm{ER}}(\cdot, \cdot)$ from now on.

Because of the involved structure of the infinitesimal generator $\mathbf{Q}$, a direct approach like in Section 3.1 will not be possible to determine the probability distributions of T_{ER} and G_{ER}. We will instead rely on the theory of absorbing Markov chains to identify these calculations.

The generator $\mathbf{Q}$ can be written as

$$\mathbf{Q} = \left(\begin{array}{c|c} \mathbf{M} & \mathbf{R} \\ \hline \mathbf{0} & 0 \end{array}\right), \tag{6}$$

where $\mathbf{M} = [q(\mathbf{u}, \mathbf{v})]_{\mathbf{u}\in\mathcal{E},\mathbf{v}\in\mathcal{E}}$, $\mathbf{R} = (q((1, 0), a), \ldots, q((N, M), a))^{\mathrm{T}}$, and $\mathbf{0}$ is the row vector of dimension $N \times (M + 1)$ whose all components are equal to 0. The entries of the matrix $\mathbf{M}$ and of the vector $\mathbf{R}$ are arranged in lexicographical order.

The entries of the matrix $\mathbf{M}$ are given by

$$q((n,m),(n+1,m)) = (N-n)\beta(n,m), \quad n = 1,\ldots,N-1,\ m = 0,\ldots,M$$
$$q((n,m),(n,m+1)) = n(M-m)\mu, \quad n = 1,\ldots,N,\ m = 0,\ldots,M-1$$
$$q((n,m),(n,m)) = -((N-n+1)\beta(n,m) + n(M-m)\mu), \quad n = 1,\ldots,N,\ m = 0,\ldots,M,$$

while the entries of the vector $\mathbf{R}$ are

$$q((n,m),a) = \beta(n,m), \quad n = 1,\ldots,N,\ m = 0,\ldots,M$$

with $\beta(m,n) := n\lambda + m\mu$.

From the theory of absorbing Markov chains, we find that the probability distribution of the delivery delay T_{ER} is given by (see Lemma 2.2.2 [16])

$$P(T_{\text{ER}} < x) = 1 - \mathbf{b}\,\mathrm{e}^{\mathbf{M}x}\,\mathbf{e}, \tag{7}$$

where $\mathbf{b}$ is a row vector of dimension $N \times (M+1)$ with the first entry equal to one and the remaining ones equal to zero, and $\mathbf{e}$ is a column vector of dimension $N \times (M+1)$ with all entries equal to one.

In particular, the k-th order moment of T_{ER} is equal to

$$\mathbf{E}[T_{\text{ER}}^k] = (-1)^k k! \sum_{j=1}^{N\times(M+1)} m_k^*(1,j), \tag{8}$$

where $m_k^*(i,j)$ is the (i,j)-entry of the matrix $(\mathbf{M}^{-1})^k$. Define $m^*(i,j) = m_1^*(i,j)$ for all entries (i,j).

The inverse of the matrix $\mathbf{M}$, which enters the calculation of the moments of T_{ER}, can be obtained in closed-form, as shown below. It is easily seen that $\mathbf{M}$ is an upper block bi-diagonal matrix with the $M+1$ square matrices $\mathbf{A}_m := [q((i,m),(j,m))]_{\{1\le i,j\le N\}}$, $m = 0,1,\ldots,M$, on the diagonal, and with the M square matrices $\mathbf{B}_m := [q((i,m),(j,m+1))]_{\{1\le i,j\le N\}}$, $m = 0,1,\ldots,M-1$, on the upper diagonal. The matrices $\mathbf{A}_m$, $m = 0,1,\ldots,M$, are upper bi-diagonal matrices with strictly negative diagonal entries, so that they are all invertible. The matrices $\mathbf{B}_m$, $m = 0,1,\ldots,M$, are all diagonal matrices. It can be checked that

$$\mathbf{M}^{-1} = \begin{pmatrix} \mathbf{A}_0^{-1} & \mathbf{U}_{0,1} & & \cdots & & \mathbf{U}_{0,M} \\ & \ddots & \ddots & & & \\ & & \mathbf{A}_m^{-1} & \mathbf{U}_{m,m+1} & \cdots & \mathbf{U}_{m,M} \\ & & & \ddots & \ddots & \\ & & & & & \mathbf{A}_M^{-1} \end{pmatrix}$$

where $\mathbf{U}_{m,l} = (-1)^{l-m}(\prod_{j=m}^{l-1}\mathbf{A}_j^{-1}\mathbf{B}_j)\mathbf{A}_l^{-1}$ for $0 \le m \le M-1$ and $m+1 \le l \le M$.

It remains to find $\mathbf{A}_m^{-1}$ in closed-form in order to derive $\mathbf{M}^{-1}$ in closed-form. Let $a_m^*(i,j)$ denote the (i,j)-entry of $\mathbf{A}_m^{-1}$. Since $\mathbf{A}_m$, $m = 0,1,\ldots,M$, is an upper-bidiagonal square matrix, we find that

$$a_m^*(i,j) = \begin{cases} \dfrac{1}{q((i,m),(i,m))}, & i = j \\ \dfrac{(-1)^{j-i}}{q((j,m),(j,m))} \displaystyle\prod_{k=i}^{j-1} \dfrac{q((k,m),(k+1,m))}{q((k,m),(k,m))}, & j \ge i+1 \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

We now derive the distribution of G_{ER}, the number of copies generated by the protocol ER until the delivery of the packet to the destination. Similar to the MTR protocol, each transition in the Markov chain $\mathbf{I}$ corresponds to a packet transmission. Starting from the state $(1,0)$, the largest path length is equal to $N+M$, therefore $P(G_{\text{ER}}) > (N+M) = 0$. For $1 \le k < N+M$, $P(G_{\text{ER}} = k)$ is the probability that the last state visited before the absorption is one of the states (n,m) for which $n+m = k$. Therefore, it remains to find the probability $P_a(n,m)$ that the absorption occurs in state (n, m). By splitting the absorption state a into $N \times (M + 1)$ independent absorption states $\{a_1, \ldots, a_{N\times(M+1)}\}$, one can show that (see [6, Lemma 1.c] for a similar approach)

$$P_a(n, m) = -m^*(1, n + mN)q((n, m), a), \tag{10}$$

for $n \in \{1, \ldots, N\}$ and $m \in \{0, \ldots, M\}$. Hence,

$$P(G_{\mathrm{ER}} = k) = \sum_{n=\max(1,k-M)}^{\min(k,N)} P_a(n, k - n) = - \sum_{n=\max(1,k-M)}^{\min(k,N)} m^*(1, n + (k - n)N)q((n, k - n), a). \tag{11}$$

In direct analogy with the MTR protocol (see end of Section 3.1) the performance of the ER protocol in the case where all throwboxes are connected can be obtained from the results in Section 3.2 by substituting M by 1 and μ by μM.

4. Asymptotics for the MTR protocol

We conduct an asymptotic analysis of the expected delivery delay and of the expected number of copies generated under the MTR protocol as the number of mobile nodes and/or the number of throwboxes are large. Since such an analysis cannot easily be done by using the formulas obtained for $\mathbf{E}[T_{\mathrm{MTR}}]$ and $\mathbf{E}[G_{\mathrm{MTR}}]$ in Section 3.1, we will follow a different approach.

We will use a mean-field approach [11]. In the context of MANETs, this approach was recently used in [20,23] to study the ER protocol. In these papers, the authors model the packet relaying in a MANET by ordinary differential equations (ODEs) by making an analogy with the infection of disease in a biological environment.

We still consider the stochastic model introduced at the beginning of Section 3: $N+1$ mobile nodes, M throwboxes, and the successive meeting times between a mobile node and a throwbox (resp. between two mobile nodes) form a Poisson process with intensity μ (resp. λ), all these Poisson processes being mutually independent. Until otherwise mentioned, we will only focus on the MTR protocol.

We first address the case where the throwboxes are fully disconnected.

Let $Y(t)$ (resp. $X(t)$) denote the expected number of throwboxes (resp. expected number of mobile nodes including the source) that hold a copy of the packet at time t or, equivalently, that have been infected at time t to reinforce the analogy with the spreading of an epidemy. When MTR is enforced, the rate at which mobile nodes are infected at time t is equal to λ, the intensity at which mobile nodes meet, multiplied by $N - X(t)$, the number of mobile nodes yet to be infected at time t. Similarly, the infection rate of throwboxes at time t is equal to μ, the intensity at which the source meets a throwbox, multiplied by $M - Y(t)$, the number of throwboxes yet to be infected at time t.

This gives rise to the following set of ODEs:

$$\dot{X}(t) = \lambda(N - X(t)) \tag{12}$$

$$\dot{Y}(t) = \mu(M - Y(t)) \tag{13}$$

for $t > 0$. Solving these ODEs with the initial conditions $X(0) = 1$ and $Y(0) = 0$ (these conditions reflect the assumption that at time $t = 0$ only the source carries the packet), yields

$$X(t) = N - (N - 1)\mathrm{e}^{-\lambda t}, \qquad Y(t) = M - M\mathrm{e}^{-\mu t}, \quad t \geq 0.$$

Let $F_{\mathrm{MTR}}(t)$ denote the cumulative distribution function of the delivery delay T_{MTR} at instant t, i.e. $F_{\mathrm{MTR}}(t) = P(T_{\mathrm{MTR}} < t)$, with $F_{\mathrm{MTR}}(0) = 0$. In a small time interval of length h, the probability that a node, whether it is fixed or mobile, infects the destination is equal to $(\lambda X(t) + \mu Y(t))h$. Hence, similar to [20], we have

$$\dot{F}_{\mathrm{MTR}}(t) = (\lambda X(t) + \mu Y(t))(1 - F_{\mathrm{MTR}}(t)), \quad t > 0. \tag{14}$$

Solving for (14) with the initial condition $F_{\mathrm{MTR}}(0) = 0$ gives

$$F_{\mathrm{MTR}}(t) = 1 - \mathrm{e}^{-\int_0^t (\lambda X(u)+\mu Y(u))\mathrm{d}u}, \quad t \geq 0. \tag{15}$$

From (15) we find that the expected delivery delay is given by

$$\mathbf{E}[T_{\mathrm{MTR}}] = \int_0^\infty \mathrm{e}^{-\int_0^t (\lambda X(u)+\mu Y(u))\mathrm{d}u} \mathrm{d}t.$$

Observe that when either N or M is large enough, then $\mathrm{e}^{-\int_0^t (\lambda X(u)+\mu Y(u))\mathrm{d}u}$ is extremely small except near $t = 0$, where the main contribution to the above integral comes from. Therefore, by expanding the function $-\int_0^t (\lambda X(u) + \mu Y(u))\mathrm{d}u$ in Taylor series in the vicinity of $t = 0$ to the order three, the average delivery delay can be approximated by

$$\begin{aligned}\mathbf{E}[T_{\mathrm{MTR}}] &\approx \int_0^\infty \mathrm{e}^{\frac{-(\lambda^2(N-1)+\mu^2 M)t^2}{2}} \mathrm{e}^{\frac{(\lambda^3(N-1)+\mu^3 M)t^3}{6}} \mathrm{d}t \\ &\approx \sqrt{\frac{\pi}{2(\lambda^2(N-1)+\mu^2 M)}} + \frac{\lambda^3(N-1)+\mu^3 M}{3(\lambda^2(N-1)+\mu^2 M)^2}\end{aligned} \tag{16}$$

when either N or M is large.

If $M = o(N)$ (i.e. $\lim_{N\to\infty} \frac{M}{N} \to 0$) then, as expected, we retrieve the asymptotic expression for the expected delivery delay reported in [8,23], that is,

$$\mathbf{E}[T_{\mathrm{MTR}}] \approx \frac{1}{\lambda}\left(\sqrt{\frac{\pi}{2N}} + \frac{1}{3\lambda N}\right) = O\left(\frac{1}{\sqrt{N}}\right). \tag{17}$$

In this case, the introduction of throwboxes only marginally improves the performance of the MTR protocol. On the other hand, if $N = o(M)$ (i.e. $\lim_{M\to\infty} \frac{N}{M} \to 0$) then

$$\mathbf{E}[T_{\mathrm{MTR}}] \approx \frac{1}{\mu}\left(\sqrt{\frac{\pi}{2M}} + \frac{1}{3M}\right) = O\left(\frac{1}{\sqrt{M}}\right). \tag{18}$$

Also of interest is the case where N and M grow to infinity in the same proportion, that is typically $N = \theta M$ with $\theta > 0$. From (16) we see that in this case

$$\mathbf{E}[T_{\mathrm{MTR}}] \approx \frac{\lambda^3\theta + \mu^3}{3\,(\lambda^2\theta + \mu^2)^2}\,\frac{\theta}{N} = O\left(\frac{1}{N}\right). \tag{19}$$

Let us briefly consider the expected number of copies generated until the delivery of the packet to the destination. Clearly, it is given by $\int_0^\infty (X(t) + Y(t))\mathrm{d}F_{\mathrm{MTR}}(t)$, which yields (same formula as the one established at the end of Section 3.1)

$$\mathbf{E}[G_{\mathrm{MTR}}] = (\lambda N + \mu M)\mathbf{E}[T_{\mathrm{MTR}}]. \tag{20}$$

From (20) and the asymptotic formulas derived earlier for $\mathbf{E}[T_{\mathrm{MTR}}]$ as N and/or M are large, we can derive asymptotics for $\mathbf{E}[G_{\mathrm{MTR}}]$ as N and/or M are large.

When the throwboxes are fully connected, the same analysis yields (Hint: see comments at the end of Sections 3.1 and 3.2) (the superscript "c" stands for "connected")

$$\mathbf{E}[T^c_{\mathrm{MTR}}] \approx \sqrt{\frac{\pi}{2(\lambda^2(N-1)+\mu^2 M^2)}} + \frac{\lambda^3(N-1)+\mu^3 M^3}{3(\lambda^2(N-1)+\mu^2 M^2)^2}. \tag{21}$$

In this case, the "cut-off value" occurs when M is of the order of $\sqrt{N}$ as opposed to M being of the order of N as in the case where the throwboxes are all disconnected.

The same analysis can be done for the ER protocol. The corresponding ODEs are

$$\dot{X}(t) = \lambda X(t)(N - X(t)) + \mu Y(t)(N - X(t)) \tag{22}$$

$$\dot{Y}(t) = \mu X(t)(M - Y(t)) \tag{23}$$

$$\dot{F}_{\mathrm{ER}}(t) = (\lambda X(t) + \mu Y(t))(1 - F_{\mathrm{ER}}(t)). \tag{24}$$

Unfortunately, we were not able to find an explicit solution to these differential equations.

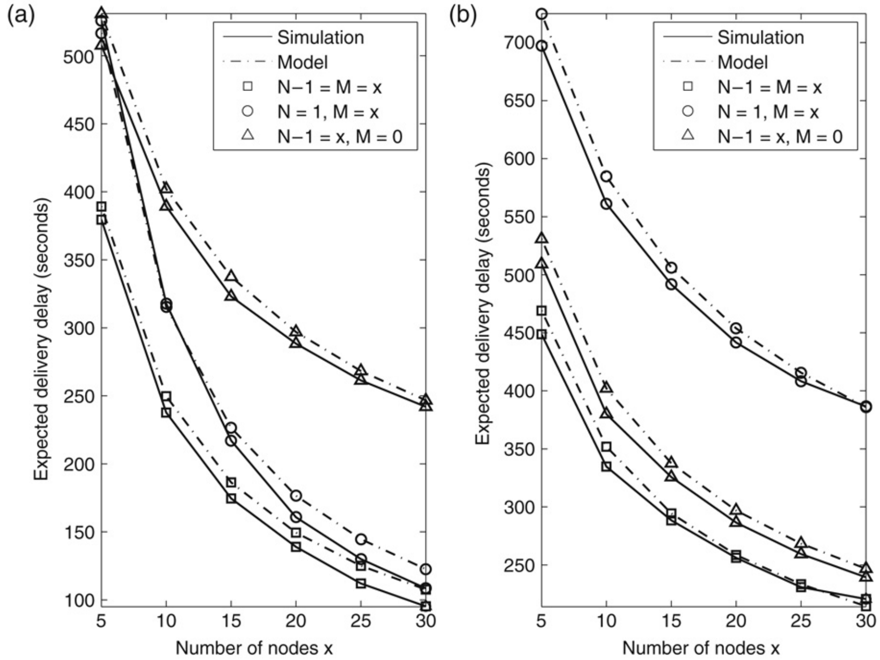

Fig. 3. $\mathbf{E}[T_{\mathrm{MTR}}]$: (a) Throwboxes are connected, (b) Throwboxes are disconnected.

5. Simulation results

To validate our analytical models and results, we have conducted extensive simulations for the various schemes that have been considered throughout the paper (RWP/RD mobility models, MTR/ER protocols, fully connected/disconnected throwboxes). Due to space limitations, we only present results obtained for the random waypoint mobility model. However, we point out that the results obtained under the random direction mobility model are as accurate as the results obtained for the RWP model.

The mobility of the nodes has been simulated by using the code available at [17]. This code avoids the various pitfalls associated with the simulation of the RWP model. Throughput our simulations the speed is held constant and is equal to 10 m/s, and nodes do not pause at the end of a movement. Each node is assigned a constant and fixed transmission range $r = 100$ m. The transmission of a packet between two nodes is assumed to occur instantaneously when the nodes are located at a distance less than or equal to r of one another.

The intensity μ (resp. λ) of the meeting times between a mobile node and a throwbox (resp. two mobile nodes) are taken from Section 2 (resp. from [8]).

In the next section we address the validation of our model, and investigate the impact on the performance of the presence of uniformly distributed throwboxes. Then, for both the MTR and the ER protocols, we investigate the effect on their performance induced by two different throwbox deployment scenarios.

5.1. Validation

To validate our models, we have considered small networks, where throwboxes are *uniformly distributed* in a square area of size 2×2 km^2.

Figs. 3 and 4 compare the expected delivery delay obtained through simulations (solid lines) to those obtained by the Markov model (dashdot lines), under both the MTR and the ER protocols, when throwboxes are either fully connected or fully disconnected. Three sets of networks have been considered in which the first one is composed of an equal number of mobile nodes and throwboxes, the second one is composed only by throwboxes with the mobile source and the mobile destination, and the third one is composed only by mobile nodes (no throwbox). For the different considered cases, we observe that our model is able to accurately predict the expected delivery delay with a small relative error when the number of nodes becomes large (this is a consequence of the fact that as the number of

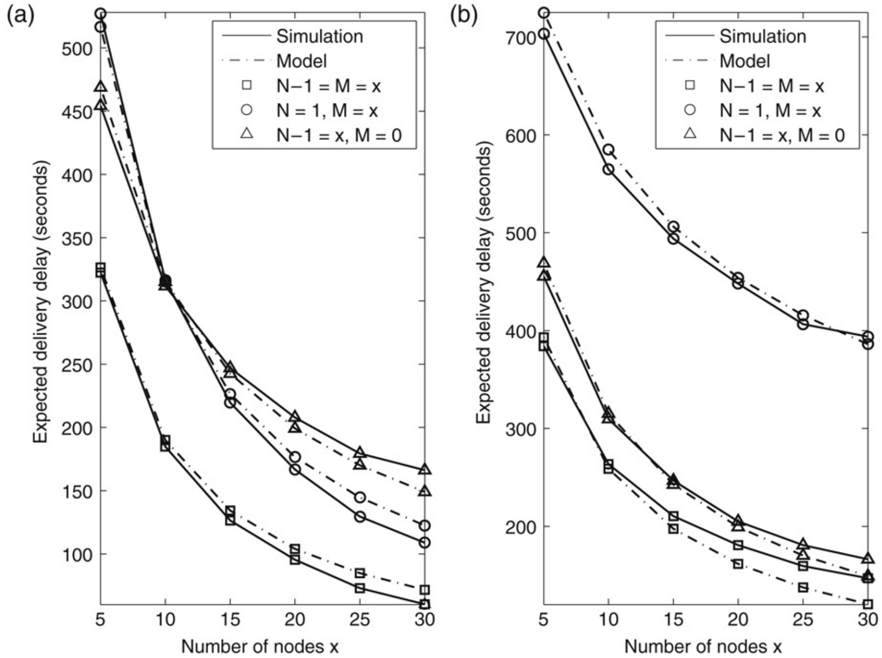

Fig. 4. $\mathbf{E}[T_{\mathrm{ER}}]$: (a) Throwboxes are connected, (b) Throwboxes are disconnected.

nodes increases then the intermeeting times are no longer mutually independent). We also observe that when relaying is performed according to the MTR protocol and throwboxes are connected, the expected delivery delays in networks where $N = M$ and where there are no relay nodes are very close whenever $\sqrt{N} \ll M$. This observation is in agreement with the asymptotic results obtained in Section 4.

Results for the expected number of copies generated until the packet delivery are reported in Figs. 5 and 6. Here too there is a good fit between the analytical model and the simulations, across all scenarios that have been considered.

For either relay protocol, we can also assess the impact of having throwboxes on the expected delivery delay by distinguishing the cases where $M > 0$ from the case where $M = 0$ in Figs. 3 and 4.

5.2. *Impact of different throwbox deployments*

The aim of this section is to compare, for the performance of both MTR and the ER protocols, the impact of two different deployments of the throwboxes. We consider a large network of size $10 \times 10\ \mathrm{km}^2$ with an equal and varying number of mobile relay nodes and throwboxes. Fig. 7 plots the expected delivery delay under both the MTR and the ER protocols for two different distributions of throwboxes: the uniform distribution and the stationary distribution of the RWP model [12]. Since the nodes are moving according to the RWP model, it is not too surprising to observe that the best performance is obtained when the throwboxes are deployed according to the stationary distribution of this mobility model. Note also the excellent agreement between the analytical results and the simulation results.

6. Conclusion

In this paper, we have developed Markovian models to analyse the impact on the performance of MANETs (delivery delay, resource consumption) of adding throwboxes. These models are based on the assumptions that (1) the successive meeting times between any pair of mobile nodes (resp. between a mobile node and a throwbox) from a Poisson process, and (2) that these Poisson processes are mutually independent. We have considered two different store-carry-and-forward protocols, the multicopy two-hop routing protocol and the epidemic routing protocol. Both the situations where the throwboxes are fully disconnected and mesh connected have been studied. Our results have been validated through simulations when nodes are moving either according to the random waypoint model or to the

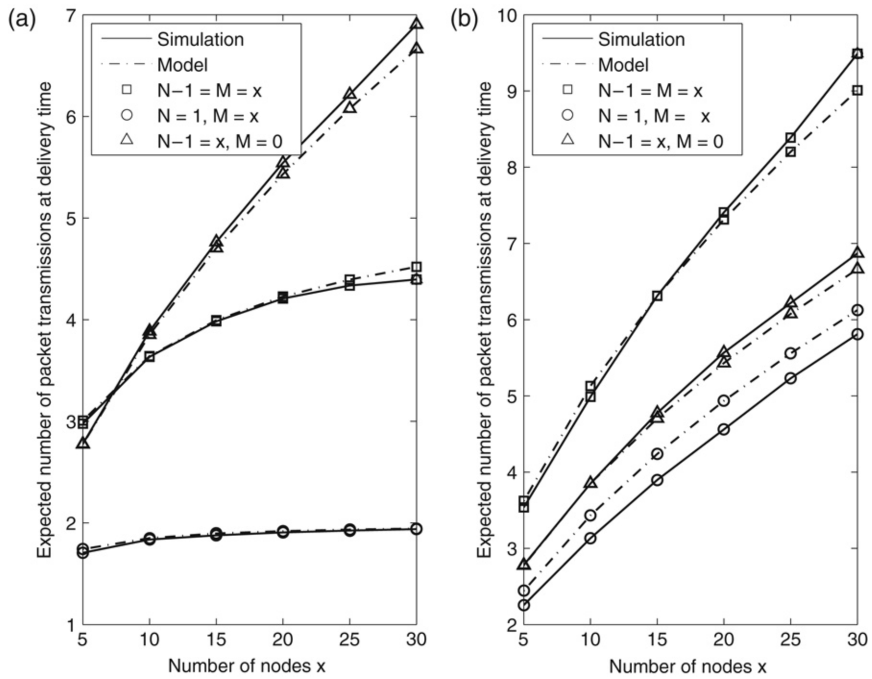

Fig. 5. $\mathbf{E}[G_{\mathrm{MTR}}]$: (a) Throwboxes are connected, (b) Throwboxes are disconnected.

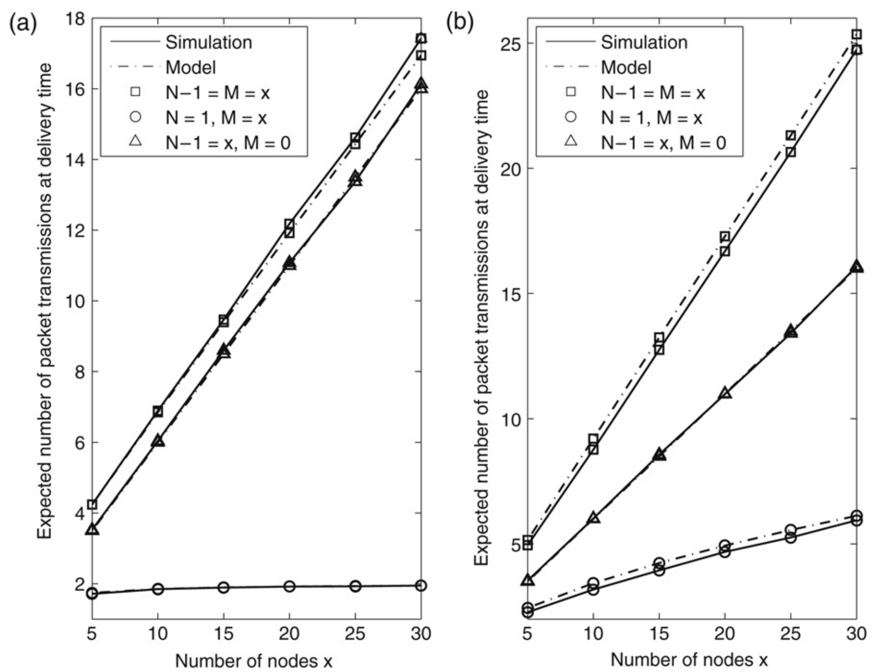

Fig. 6. $\mathbf{E}[G_{\mathrm{ER}}]$: (a) Throwboxes are connected, (b) Throwboxes are disconnected.

random direction model. In all cases, we have found excellent matches between the results predicted by the analytical models and the simulations.

Future extensions include the introduction of multiple (flows of) packets, of limited storage capabilities, of power saving mechanisms at the mobile nodes and/or at the throwboxes, and of packet lifetime constraints.

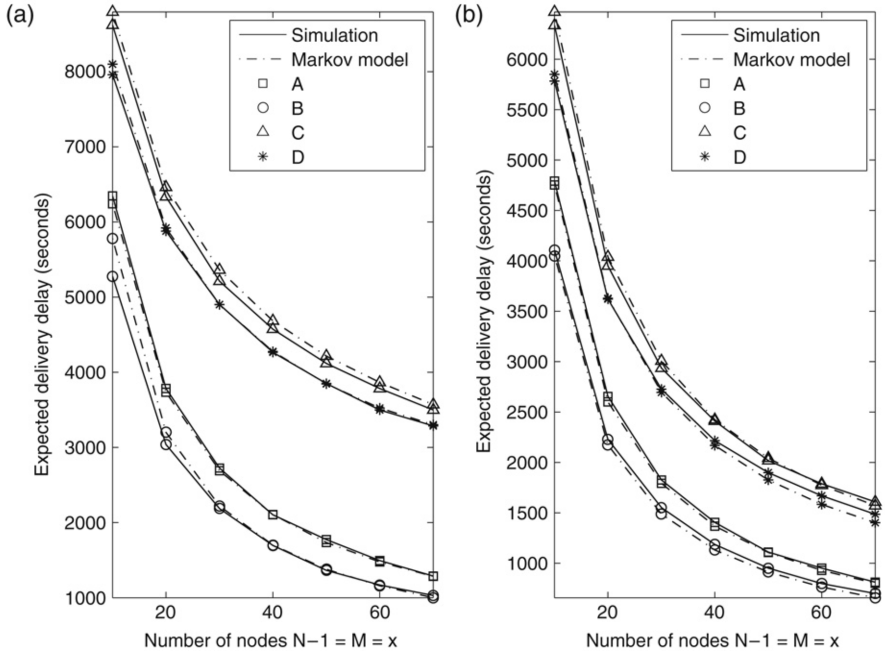

Fig. 7. $\mathbf{E}[T_{\mathrm{MTR}}]$ (a) and $\mathbf{E}[T_{\mathrm{ER}}]$ (b): (A) Throwboxes are connected and uniformly distributed, (B) Throwboxes are connected and stationary distributed, (C) Throwboxes are disconnected and uniformly distributed, (D) Throwboxes are disconnected and stationary distributed.

Appendix. Approximation formula for the intensity of the inter-meeting time

We have seen in Section 2 that the stationary inter-meeting time distribution between a single mobile node (**M**) and a single throwbox (**B**) is well-approximated by an exponential distribution when the transmission range r is small compared to L. In this appendix, we derive an approximation formula for the intensity μ of this exponential distribution.

Let π_c be the stationary probability that **M** lies within the communication range of **B**. If we denote by $f(\cdot,\cdot)$ the density of the stationary location of the mobile node, then

$$\pi_c = \int_{\mathcal{K}} f(x, y)\mathrm{d}x\mathrm{d}y,$$

where K is the area covered by **B**. Conditioned on the location (x, y) of **B**, if $r \ll L$ then we may approximate π_c by

$$\pi_c \approx \pi r^2 f(x, y).$$

We define the (stationary) contact time C as the time that elapses between a meeting time, say t, of **M** and **B** and the first time after time t when they are no longer within transmission range of one another. By an argument from renewal theory (recall that we work under the assumption that successive meeting times between **M** and **B** form a Poisson process with rate μ) we have that $\pi_c = \mathbf{E}[C]/\mathbf{E}[\tau] = \mu\,\mathbf{E}[C]$. From the above we conclude that

$$\mu \approx \frac{\pi r^2 f(x, y)}{\mathbf{E}[C]}$$

conditioned on the location (x, y) of **B**. It remains to evaluate $\mathbf{E}[C]$. To do so, we assume that **M** does not change direction when it crosses $\mathcal{K}$, the coverage area of **B**. Therefore, if σ denotes the length of the trip of **M** when it crosses the area $\mathcal{K}$ and V_c denotes its (constant) speed, we have that $C = \sigma/V_c$.

When **M** crosses the coverage area **K** of **B**, the intersection of length σ can be seen as a random line intercepting a convex area, so that $\mathbf{E}[\sigma] = \pi F/P = \pi r/2$, where F and P are respectively the area and the perimeter of $\mathcal{K}$ [18] (note that in this calculation we have implicitly assumed that $\mathcal{K} \cap \mathcal{A} = \mathcal{K}$, which is justified if $r \ll L$). If we further assume that

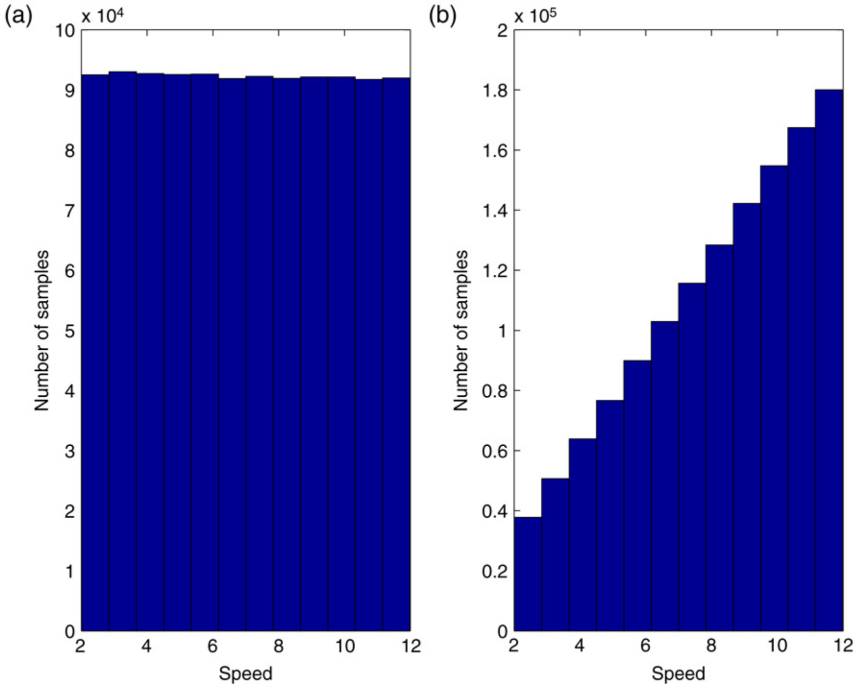

Fig. 8. Histogram of speeds sampled at meeting times for the RWP model (a), and the RD model with reflection (b).

(H): the speed V_c of the mobile at a meeting time is independent of σ

an assumption which holds for both the RWP and the RD models, we conclude from the above that $\mathbf{E}[C] = \mathbf{E}[\sigma]\,\mathbf{E}[V_c^{-1}] = \pi r \mathbf{E}[V_c^{-1}]/2$, so that

$$\mu \approx \frac{2rf(x, y)}{\mathbf{E}[V_c^{-1}]}$$

conditioned on the location (x, y) of **B**. By removing the conditioning on the location of **B**, we finally find

$$\mu \approx \frac{2r}{\mathbf{E}[V_c^{-1}]} \int_{\mathcal{A}} f(x, y) g(x, y) \mathrm{d}x \mathrm{d}y,$$

with $g(\cdot, \cdot)$ the density of the throwbox location.

It remains to find $\mathbf{E}[V_c^{-1}]$ for both the RWP and the RD models. For the RWP, the speed is uniformly distributed in $[V_{\min}, V_{\max}]$ at meeting times, which follows from the definition of this mobility pattern (see Fig. 8(a) for simulation results). This implies that $\mathbf{E}[V_c^{-1}] = (\log(V_{\max}) - \log(V_{\min}))/(V_{\max} - V_{\min})$. In the case of the RD model, the event of **M** crossing the coverage area $\mathcal{K}$ of **B** clearly depends on the numerical value of the speed, since there will be more opportunities for higher speeds than for lower speeds. This is confirmed by the simulation results in Fig. 8(b). We deduce from the latter figure that the density probability of the speed, $f_{V_c}(x)$, sampled at meeting times is approximately a linear function (i.e. $f_{V_c}(x) = ax$, with a a normalizing constant). This yields $\mathbf{E}[V_c^{-1}] \approx 2/(V_{\max} + V_{\min})$ for the RD model with reflection, where we have used the result that in this setting nodes are uniformly distributed over the area [15].

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