Title
TakingFull Advantage of Multiuser Diversity in Mobile Ad-hoc Networks

Journal
IEEE Transactions on Communications, 55(6)

Author
Garcia-Luna-Aceves, J.J.

Publication Date
2007-06-01

Peer reviewed

Taking Full Advantage of Multiuser Diversity in Mobile Ad Hoc Networks

Renato M. de Moraes, *Member, IEEE,* Hamid R. Sadjadpour, *Senior Member, IEEE,* and J.J. Garcia-Luna-Aceves, *Fellow Member, IEEE*

Abstract

Multiuser diversity has been shown to increase the throughput of mobile ad hoc wireless networks (MANETs) when compared to fixed wireless networks. This paper addresses a multiuser diversity strategy that permits one of multiple one-time relays to deliver a packet to its destination. We show that the $\Theta(1)$ throughput of the original single one-time relay strategy is preserved by our multi-copy technique. The reason behind achieving the same asymptotic throughput is the fact that, as we demonstrate in this paper, interference for communicating among closest neighbors is bounded for different channel path losses, even when n goes to infinity. We show that a significant delay reduction is possible by multi-copy relaying when n is finite. Furthermore, we find that the average delay and delay variance for both the one and multi-copy relay strategies scale like $\Theta(n)$ and $\Theta(n^2)$, respectively. We derive an approximation of the delay for multi-copy forwarding scheme and demonstrate that this approximation is very close to simulation results in MANET systems.

Index Terms

Ad hoc network, delay, interference, mobility, multiuser diversity, network capacity, statistics.

I. Introduction

There has been a considerable effort [1], [2], [3] [4], [5], [6], [7] on trying to increase the performance of wireless ad hoc networks since Gupta and Kumar [8] showed that the capacity of a fixed wireless

This work was supported in part by CAPES/Brazil, by the US Army Research Office under grant W911NF-05-1-0246, by the Basking Chair of Computer Engineering, and by UCOP CLC under grant SC-05-33.

R. M. de Moraes is with Department of Computing Systems, University of Pernambuco, Brazil. Email: renato@dsc.upe.br

H. R. Sadjadpour is with Department of Electrical Engineering, University of California at Santa Cruz (UCSC). Email: hamid@soe.ucsc.edu

J.J. Garcia-Luna-Aceves is with Department of Computer Engineering at UCSC and with Palo Alto Research Center, 3333 Coyote Hill Road, Palo Alto, CA 94304, USA. Email: jj@soe.ucsc.edu

network decreases as the number of nodes increases when all the nodes share a common wireless channel. Grossglauser and Tse [1] presented a two-phase packet relaying (forwarding) technique for mobile ad hoc networks (MANETs) based on *multiuser diversity* [9], such that a source node transmits a packet to the nearest neighbor and that relay delivers the packet to the destination when this destination becomes the closest neighbor of the relay. This scheme was shown [1] to attain $\Theta(1)$ [1] source-destination throughput when n tends to infinity. However, the delay experienced by packets under this strategy was shown to be large and it can be infinite for a fixed number of nodes (n) in the system, which has prompted more recent work presenting analysis of capacity and delay tradeoffs [6], [7], [10], [11], [12].

This paper introduces and analyzes an improved two-phase packet forwarding strategy for MANETs that attains the $\Theta(1)$ capacity of the basic scheme by Grossglauser and Tse [1], but provides better delay behavior than the single-copy technique. Our main objective is to decrease the delay incurred by the packet to reach its destination in steady-state[2] while maintaining the capacity of the network at the same order of magnitude from that attained by Grossglauser and Tse [1]. Our basic idea is to give a copy of the packet to multiple one-time relay nodes that are within the transmission range of the sender. By doing so, the time within which a copy of the packet reaches its destination can be decreased. The first one-time relay node that is close enough to the destination delivers the packet.

We find an enormous reduction in delay by having a packet more than one possible random route to the destination. Our approach is analogous to the problem in which Mitzenmacher [13] showed that a small amount of choices can lead to drastically different result in randomized load balancing. More specifically, having just two random choices yields an exponential reduction in maximum loading over having one choice, while each additional choice beyond two decreases the maximum load by just a constant factor. In our case, by multi-copy forwarding a packet and having only the fastest copy being delivered, it is analogous to having the packet taking one of the shortest random path to the destination from multiple random routes (or choices).

An interesting feature of the multi-copy relaying approach is that the additional relaying nodes carrying that same copy of the packet can be used as backups to protect against node failures, which improves the

[1]Here we use the Knuth's notation: (a) $f(n) = O(g(n))$ means there are positive constants c and k, such that $0 \leq f(n) \leq cg(n)$ $\forall$ $n \geq k$. (b) $f(n) = \Theta(g(n))$ means there are positive constants c_1, c_2, and k, such that $0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n)$ $\forall$ $n \geq k$.

[2]That is, after averaging over all possible starting random network topologies so that transient behaviors are removed.

reliability of the network [14].

Another contribution of this paper consists of an analytical model for interference calculation, which permits us to obtain the signal-to-interference ratio (SIR) measured by a receiver node at any point in the network. We show that the receiver SIR tends to a constant if it communicates with close neighbors when the path loss parameter α is greater than two, regardless of the position of the node in the network. These results are consistent with all previous works, except that earlier works have only considered the receiver node located at the center of the network [15], [16], [17].

The remaining of the paper is organized as follows. Section II summarizes the network model used in the past to analyze the capacity of MANETs [1]. Section III explains our multi-copy packet forwarding strategy. Section IV presents the number of feasible receiving nodes around a sender. Section V presents the interference analysis. Section VI shows that the new relaying scheme attains the same capacity order of magnitude as the original two-phase scheme proposed by Grossglauser and Tse [1]. Section VII shows the delay reduction resulting from our forwarding strategy and presents theoretical and simulation results. Section VIII concludes the paper summarizing our main ideas and briefly discusses future work.

II. Network Model

The network model we assume is the one introduced by Grossglauser and Tse [1]. The network consists of a normalized unit area disk containing n mobile nodes and to simplify the analysis, we consider that communication among all nodes are synchronized. The nodes are assumed to be uniformly distributed on the disk at the beginning, and there is no preferential direction of movement. We consider that communication occurs only among those nodes that are close enough, so that interference caused by other nodes is low, allowing reliable communication. The position of node i at time t is indicated by $X_i(t)$.

Nodes are assumed to move according to the *uniform mobility model* [7]. In this model, the nodes are initially uniformly distributed, and move at a constant speed v with the directions of motion being independent and identically distributed (iid) with uniform distribution in the range $[0, 2\pi)$. As time passes, each node chooses a direction uniformly from $[0, 2\pi)$ and moves in that direction at speed v for a distance z, where z is an exponential random variable with mean μ. The process repeats after reaching z. This model satisfies the following properties [7]:

- At any time t, the positions of nodes are independent of each other.
- The steady-state distribution of the mobile nodes is uniform.
- Conditional on the position of a node, the direction of the node movement is uniformly distributed in $[0, 2\pi)$.

At each time step, a scheduler [3] decides which nodes are senders, relays, or destinations, in such a manner that the source-destination association does not change with time. Each node can be a source for one session and a destination for another session. Packets are assumed to have header information for scheduling and identification purposes.

Suppose that source i has data for a certain destination $d(i)$ at time t. Because nodes i and $d(i)$ can have direct communication only $1/n$ of the time on the average, a relay strategy is required to deliver data to $d(i)$ via relay nodes. We assume that each packet is relayed at most once.

At time t, node j is capable of receiving at a given rate of $W\ bits/sec$ from i if [1], [8]

$$\frac{P_i(t)g_{ij}(t)}{N_0+\frac{1}{M}\underbrace{\sum_{k\neq i}P_k(t)g_{kj}(t)}_{I}} = \frac{P_i(t)g_{ij}(t)}{N_0+\frac{1}{M}I} \geq \beta, \tag{1}$$

where $P_i(t)$ is the transmitting power of node i, $g_{ij}(t)$ is the channel path gain from node i to j, β is the signal to noise and interference ratio level necessary for reliable communication, N_0 is the noise power, M is the processing gain of the system, and I is the total interference at node j. The channel path gain is assumed to be a function of the distance only, so that [1], [8]

$$g_{ij}(t) = \frac{1}{|X_i(t)-X_j(t)|^\alpha} = \frac{1}{r_{ij}^\alpha(t)}, \tag{2}$$

where α is the path loss parameter, and $r_{ij}(t)$ is the distance between i and j.

Given that the interference coming from other nodes is generally much greater than the noise power for narrowband communication, the denominator in (1) is dominated by the interference factor. In addition, we assume that no processing gain is used, i.e., $M = 1$, and that $P_i = P\ \forall i$. Then, combining (1) and (2) yields the Signal-to-Interference Ratio (SIR)

$$SIR = \frac{\frac{P}{r_{ij}^\alpha}}{I} = \frac{P}{r_{ij}^\alpha \cdot I} \geq \beta\,. \tag{3}$$

[3]Note that the scheduling can be implemented in a distributed fashion by having each node randomly and independently deciding whether it wants to be a sender or a potential receiver at each time instant [1].

We will determine an equation relating the total interference measured by a receiver communicating with a neighbor node as a function of the number of total nodes n in the network. More precisely, we want to obtain an expression for (3) as a function of n, calculate the asymptotic value of the SIR as n goes to infinity, and verify that communication among close neighbors is still feasible.

III. Multi-Copy One-time Relaying

Grossglauser and Tse [1] consider a single-copy forwarding scheme consisting of two phases. Packet transmissions from sources to relays (or destinations) occur during *Phase 1*, and packet transmissions from relays (or sources) to destinations happen during *Phase 2*. Both phases occur concurrently, but *Phase 2* has absolute priority in all scheduled sender-receiver pairs. We extend this scheme to allow multiple copies, as described below.

A. Packet Forwarding Scheme

We allow more than one relay node to receive a copy of the same packet during *Phase 1*. Thus, the chance that a copy of this packet reaches its destination in a shorter time is increased, compared to using only one relay node as in [1]. Also, if for some reason a relaying node fails to deliver the packet when it is within the transmission range of the destination, the packet can be delivered when another relaying node carrying a copy of the same packet approaches the destination.

In Fig. 1(a), three copies of the same packet are received by adjacent relay nodes j, p, and k during *Phase 1*. All such relays are located within a distance r_o from sender i. At a future time t, in *Phase 2*, node j reaches the destination before the other relays and delivers the packet. Note that relay node j need not be the closest node to the source during *Phase 1*.

B. Enforcing One-Copy Delivery

There are several ways in which the delivery of more than one copy of the same packet to a destination can be prevented. For example, each packet can be assigned a sequence number (SN) [10]. Before a packet is delivered to its destination, a relay-destination handshake can be established to verify that the destination has not received a copy of the same packet and to inform the relay to delete a packet copy that has already been delivered.

Fig. 1(b) depicts the situation in which node j finds the destination node $d(i)$ first and delivers the packet. The other copies are dropped from the queues at p and k at a later time after handshaking with destinations, and only one node out of the three potential relays actually delivers the packet to the destination.

To ascertain if this multi-copy relaying strategy provides any advantages over the single-copy strategy proposed by Grossglauser and Tse [1], we need to answer two questions: a) How many nodes around a sender can successfully receive copies of the same packet? b) What is the delay d_K for the new packet transmission scheme compared to the delay d in the single-copy strategy [1] when the network is in steady-state?

Because we address the network capacity for any embodiment of the multi-copy relaying strategy, we assume in the rest of this paper that the overhead of the relay-destination handshake is negligible.

IV. FEASIBLE NUMBER OF RECEIVERS IN *Phase 1* AND CELL DEFINITION

A fraction of the total number of nodes n in the network, n_S, is chosen randomly by the scheduler as senders, while the remaining nodes, n_R, operate as possible receiving nodes [1]. A sender density parameter θ is defined as $n_S = \theta n$, where $\theta \in$ (0,1), and $n_R = (1-\theta)n$. In the proposed multi-copy relay strategy each sender transmits to all the nodes in the feasible transmission range, these additional packet copies follow different random routes and find the destination earlier compared to the single-copy strategy of Grossglauser and Tse [1].

If the density of nodes in the disk is

$$\rho = \frac{n}{total\ \ area} = \frac{n}{1} = n, \tag{4}$$

then, for a uniform distribution of nodes, the radius for one sender node is given by

$$1 = \theta\rho\pi r_o^2 = \theta n\pi r_o^2 \Longrightarrow r_o = \frac{1}{\sqrt{\theta n\pi}}. \tag{5}$$

Thus, the radius r_o defines a cell (radius range) around a sender.

Assuming a uniform node distribution, the average number of receiving nodes within r_o, called $\overline{K}$, is

$$\overline{K} = n_R\pi r_o^2 = \frac{1}{\theta} - 1, \tag{6}$$

which is a function of θ and does not depend on n. The main idea behind the multi-copy scheme stems from the fact that θ can be smaller than 0.5 and, consequently, there is more than one relay available for many senders for any sender node on average. Grossglauser and Tse [1] showed that the maximum capacity is obtained for $\theta < 0.5$ (for $\alpha \leq 4$), so that we can have $\overline{K} > 1$ and be very close to the maximum capacity, as shown later. Note that (6) provides a benchmark to choose a value for $\overline{K}$ based on θ. However, the actual number of receiving nodes, called K, for each sender node varies.

Referring to the recent work by El Gamal et al. [11], each cell in our strategy has area $a(n) = \frac{1}{n_S} = \frac{1}{\theta n}$. By applying random occupancy theory [18, Chapter 3], the fraction of cells containing L senders and K receivers is obtained by

$$\begin{aligned}
\mathbb{P}\{\text{senders = } L,\ \text{receivers = } K\} &= \mathbb{P}\{\text{senders = } L\}\mathbb{P}\{\text{receivers = } K \mid \text{senders = } L\} \\
&= \begin{pmatrix} n \\ L \end{pmatrix} \Big(\tfrac{1}{n_S}\Big)^{L} \Big(1 - \tfrac{1}{n_S}\Big)^{n-L} \begin{pmatrix} n-L \\ k \end{pmatrix} \Big(\tfrac{1}{n_S}\Big)^{K} \Big(1 - \tfrac{1}{n_S}\Big)^{n-L-K} \\
&= \begin{pmatrix} n \\ L \end{pmatrix} \Big(\tfrac{1}{\theta n}\Big)^{L} \Big(1 - \tfrac{1}{\theta n}\Big)^{n-L} \begin{pmatrix} n-L \\ K \end{pmatrix} \Big(\tfrac{1}{\theta n}\Big)^{K} \Big(1 - \tfrac{1}{\theta n}\Big)^{n-L-K}. \qquad (7)
\end{aligned}$$

Given that we are interested in very large values for n, and using the limit $\big(1 - \frac{1}{x}\big)^{x} \longrightarrow e^{-1}$ as $x \rightarrow \infty$, we have the following result for $n >> L, K$

$$\begin{aligned}
\mathbb{P}\{\text{senders = } L,\ \text{receivers = } K\} &\approx \tfrac{n^L}{L!} \Big(\tfrac{1}{\theta n}\Big)^{L} \Big[\Big(1 - \tfrac{1}{\theta n}\Big)^{\theta n}\Big]^{1/(\theta)} \tfrac{n^K}{K!} \Big(\tfrac{1}{\theta n}\Big)^{K} \Big[\Big(1 - \tfrac{1}{\theta n}\Big)^{\theta n}\Big]^{1/(\theta)} \\
&\approx \tfrac{1}{L!} \Big(\tfrac{1}{\theta}\Big)^{L} e^{-1/\theta} \tfrac{1}{K!} \Big(\tfrac{1}{\theta}\Big)^{K} e^{-1/\theta}. \qquad (8)
\end{aligned}$$

For example, for $L = 1$, $K \geq 2$, and $\theta = \frac{1}{3}$, we have that the fraction of the cells containing one sender and at least two receivers equals $\frac{1}{\theta} e^{-1/\theta} (1 - e^{-1/\theta} - \frac{1}{\theta} e^{-1/\theta}) \approx 0.12$. Therefore, for $K \geq 2$, approximately 12% of the cells can forward packets using multi-copy scheme in *Phase 1*.

In addition, for $\theta = \frac{1}{3}$, we have that the fraction of the cells having one sender and one receiver equals $(\frac{1}{\theta} e^{-1/\theta})^2 \approx 0.02$. In this case, we assume that the scheduler does not select these cells for packet transmission, because the delivery delay incurred can be significantly high, as we show subsequently.

The maximum number of nodes in any cell is $\Theta(\frac{\log(n)}{\log(\log(n^{\theta}))})$ with high probability (whp)[4] [18, Chapter 3]. Thus, whp, $K \leq \frac{c_4 \log(n)}{\log(\log(n^{\theta}))} << n$ for some constant $c_4 > 0$.

[4]With high probability means with probability $\geq 1 - \frac{c_3}{n}$ [18].

The feasibility that all of those K nodes successfully receive the same packet in the presence of interference is the subject of the next section.

V. Interference Analysis

In the previous section, we obtained the fraction of cells that has one sender surrounded by $K \geq 2$ receiving nodes within r_o, assuming a uniform distribution of nodes. Suppose that one of the K receiving nodes is at the maximum neighborhood distance r_o in any of these cells. We want to know how the SIR measured by this receiver behaves as the number of total nodes in the network (and therefore the number of total interferers) goes to infinity.

For a packet to be successfully received, (3) must be satisfied. Consider a receiver at any location in the network during a given time t. Its distance from the center r' is shown in Fig. 2, where $0 \leq r' \leq \frac{1}{\sqrt{\pi}} - r_o$. Let us assume that the sender is at distance r_o from this receiver and transmitting at constant power P, so that the power measured by the receiver P_R is given by

$$P_R = \frac{P}{r_o^{\alpha}}. \tag{9}$$

To obtain the interference at the receiver caused by all transmitting nodes in the disk, let us consider a differential element area $rdrd\gamma$ that is distant r units from the receiver (see Fig. 2). Because the nodes are uniformly distributed in the disk, the transmitting nodes inside this differential element of area generate the following amount of interference[5] at the receiver

$$dI = \frac{P}{r^{\alpha}}\,\theta\,\rho\,r\,dr\,d\gamma = \frac{P}{r^{\alpha-1}}\,\theta\,n\,dr\,d\gamma. \tag{10}$$

A. *The case* $\alpha > 2$

For some propagation models [19, p. 139, Table 4.2], the path loss parameter is modeled to be always greater than two, i.e., $\alpha > 2$. The total interference at the receiver located at distance r' from the center with total of n nodes in the network is obtained by integrating (10) over all the disk area. Hence,

$$I_{r'}(n) = \int_{disk} dI = \int_0^{2\pi}\int_{r_o}^{r_m(r',\gamma)} \frac{P}{r^{\alpha-1}}\theta n dr d\gamma = P\theta n \int_0^{2\pi} \frac{r^{2-\alpha}}{2-\alpha}\bigg|_{r_o}^{r_m(r',\gamma)} d\gamma = \frac{P\theta n}{\alpha-2}\int_0^{2\pi}\left\{\frac{1}{r_o^{\alpha-2}} - \frac{1}{[r_m(r',\gamma)]^{\alpha-2}}\right\} d\gamma. \tag{11}$$

[5]Because the nodes are considered to be uniformly distributed in the disk and n grows to infinity, we approximate the sum in (1) by an integral.

r_m is the maximum radius that r can have and is a function of the location r' and the angle γ. To find this function, we can use the boundary disk curve (or circumference) equation expressed as a function of the x-axis and y-axis shown in Fig. 2, i.e.,

$$x^2 + y^2 = \left(\tfrac{1}{\sqrt{\pi}}\right)^2 . \tag{12}$$

Define $x = x' + r'$, $x' = r_m cos\gamma$, and $y = r_m sin\gamma$, then (12) becomes

$$(r_m cos\gamma + r')^2 + (r_m sin\gamma)^2 = \left(\tfrac{1}{\sqrt{\pi}}\right)^2 \Longrightarrow r_m(r',\gamma) = \sqrt{\tfrac{1}{\pi} - (r' sin\gamma)^2} - r' cos\gamma \, . \tag{13}$$

Substituting this result in (11) we obtain

$$I_{r'}(n) = \tfrac{2\,P\,\theta\,n}{\alpha-2}\left[\tfrac{\pi}{r_o^{\alpha-2}} - f_\alpha(r')\right] , \tag{14}$$

where

$$f_\alpha(r') = \int_0^\pi \frac{d\gamma}{\left[\sqrt{\frac{1}{\pi}-(r' sin\gamma)^2} - r' cos\gamma\right]^{\alpha-2}} \tag{15}$$

is a constant for a given position r'. For the case in which $\alpha = 4$, (15) reduces to

$$f_4(r') = \tfrac{\pi^2}{1-2\pi r'^2+\pi^2 r'^4} \, . \tag{16}$$

We can obtain the SIR using (3), (5), (9), and (14) to arrive at

$$SIR_{r'}(n) = \tfrac{P_R}{I} = \tfrac{\alpha-2}{2}\cdot \frac{1}{\left[1 - \frac{1}{\pi^{\frac{\alpha}{2}}(\theta\,n)^{\frac{\alpha-2}{2}}} f_\alpha(r')\right]} = \tfrac{\alpha-2}{2}\cdot q_{r',\alpha,\theta}(n) \, , \tag{17}$$

where $q_{r',\alpha,\theta}(n) = \left[1 - \frac{1}{\pi^{\frac{\alpha}{2}}(\theta\,n)^{\frac{\alpha-2}{2}}} f_\alpha(r')\right]^{-1}$. Taking the limit as $n \longrightarrow \infty$, we obtain

$$SIR = \lim_{n\to\infty} \tfrac{\alpha-2}{2}\cdot q_{r',\alpha,\theta}(n) = \begin{cases} \tfrac{\alpha-2}{2}\cdot 1 & \text{if } 0 \le r' < \tfrac{1}{\sqrt{\pi}} - r_o \\ \tfrac{\alpha-2}{2}\cdot q_{r',\alpha,\theta}(n\to\infty) & \text{if } r' = \tfrac{1}{\sqrt{\pi}} - r_o \text{ , i.e.,} \\ & \quad \text{the network boundary.} \end{cases} \tag{18}$$

From (17) $q_{r',\alpha,\theta}(n \to \infty) = q_{r',\alpha}(n \to \infty)$ because θ is a scale factor on n and does not change the limit. Thus,

$$q_{r',\alpha,\theta}(n\to\infty) = \begin{cases} 1 & \text{if } 0 \le r' < \tfrac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha > 2 \\ 1.467 & \text{if } r' = \tfrac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 3 \\ 1.333 & \text{if } r' = \tfrac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 4 \\ 1.270 & \text{if } r' = \tfrac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 5 \\ 1.232 & \text{if } r' = \tfrac{1}{\sqrt{\pi}} - r_o \text{ and } \alpha = 6 \, . \end{cases} \tag{19}$$

Fig. 3 shows the SIR as a function of n for $\alpha = 4$, $\theta = \frac{1}{3}$, and for different values of r'.

In addition, Figs. 3, 4, and Eqs. (18) and (19) show that *the SIR remains constant when n grows to infinity and this constant does not depend on r' if $0 \leq r' < \frac{1}{\sqrt{\pi}} - r_o$, i.e., it is the same value for any position of the receiver node inside the disk, whether the position is at the center, close to the boundary, or in the middle region of the radius disk*. Nevertheless, if the receiver node is at the boundary ($r' \frac{1}{\sqrt{\pi}} - r_o$) then the SIR is still a constant when n scales to infinity but it has a greater value (see Figs. 3, and 4). For comparison purposes, Fig. 4 illustrates the SIR for $3 \leq \alpha \leq 6$ and $\theta = \frac{1}{3}$ for the receiver node located at the center and at the boundary of the network.

Hence, by having the SIR approaching a constant value as n grows to infinity, the network designer can properly devise the receiver (i.e., design modulation, encoding, etc.) such that (1) can be satisfied for a given β, allowing reliable (feasible) communication among close neighbors during *Phase 1*, and also during *Phase 2* for those cells that can successfully forward packets.

B. The case $\alpha = 2$

For the free space propagation model [19, p. 107], the path loss parameter is modeled to be equal to two, i.e., $\alpha = 2$. Thus, the total interference at the receiver located at distance r' from the center with total n users in the network is obtained by integrating (10) over all disk area.

$$\begin{aligned} I_{r'}(n) &= \int_{disk} dI = \int_0^{2\pi} \int_{r_o}^{r_m(r',\gamma)} \frac{P}{r}\,\theta\, n\, dr\, d\gamma \\ &= 2P\theta n \int_0^{\pi} \log\left[\frac{r_m(r',\gamma)}{r_o}\right] d\gamma \\ &= 2P\theta n \int_0^{\pi} \log\left[\frac{\sqrt{\frac{1}{\pi} - (r' sin\gamma)^2} - r' cos\gamma}{r_o}\right] d\gamma\,. \end{aligned} \tag{20}$$

For this case, the SIR can readily be obtained by using (3), (5), (9) and (20), so that

$$\begin{aligned} SIR_{r'}(n) &= \frac{P_R}{I} = \frac{\frac{1}{r_o^2}}{2\theta n \int_0^{\pi} \log\left[\frac{\sqrt{\frac{1}{\pi} - (r' sin\gamma)^2} - r' cos\gamma}{r_o}\right] d\gamma} \\ &= \frac{1}{2\theta n r_o^2}\left\{\int_0^{\pi} \log\left[\frac{\sqrt{\frac{1}{\pi} - (r' sin\gamma)^2} - r' cos\gamma}{r_o}\right] d\gamma\right\}^{-1} \\ &= \left\{\frac{2}{\pi}\int_0^{\pi} \log\left[\left(\sqrt{\pi\theta n}\right)\left(\sqrt{\frac{1}{\pi} - (r' sin\gamma)^2} - r' cos\gamma\right)\right] d\gamma\right\}^{-1}. \end{aligned} \tag{21}$$

Fig. 5 shows curves for SIR when $\alpha = 2$ and $\theta = \frac{1}{3}$. Although the limiting SIR tends to zero as n scales to infinity, the decay is not fast. This result is consistent with [16].

VI. Per Source-Destination Throughput

We now show that the throughput per source-destination pair with our multi-copy relaying approach remains the same order of magnitude as the original single-copy relaying scheme, which is $\Theta(1)$ [1]. In the case of multi-copy forwarding, only one copy is delivered to the destination and the other copies are dropped from the additional relaying nodes because the handshake between relay and destination informs the relay that the packet has been delivered. Therefore, only one node out of K nodes actually functions as a relay (as in Fig. 1(b)). Furthermore, El Gamal et al. [11] showed that the exact total throughput per source-destination pair is given by the fraction of cells that successfully forward packets (i.e, the cells that are selected by the scheduler containing feasible sender-receiver pairs). Then, for one sender and at least K receivers per cell, we have as $n \to \infty$

$$\Lambda = \mathbb{P}\{\text{senders } (L) = 1, \text{ receivers are at least } K\} \approx \tfrac{1}{\theta}\, e^{-1/\theta} \left(1 - \sum_{k=0}^{K-1} \tfrac{1}{k!} \left(\tfrac{1}{\theta}\right)^k e^{-1/\theta} \right). \tag{22}$$

Hence, for at least two receivers per cell and $\theta = \frac{1}{3}$, $\Lambda = \frac{1}{\theta} e^{-1/\theta}(1 - e^{-1/\theta} - \frac{1}{\theta} e^{-1/\theta}) \approx 0.12$. Therefore, the multi-copy forwarding strategy attains the same throughput order as in [1], that is, it attains $\Theta(1)$.

Also, for at least one receiver per cell and $\theta = \frac{1}{3}$, $\Lambda = \frac{1}{\theta} e^{-1/\theta}(1 - e^{-1/\theta}) \approx 0.14$. Hence, for the case in which $K \geq 1$, (8) and (22) give the same throughput value obtained by Tse and Grossglauser [1], as well as Neely and Modiano [10]. The single-copy forwarding strategy [1] selects only the nearest neighbor amongst the K potential receiver nodes.

A practical observation worth making here is that the capacity for the case of the single-copy relaying scheme [1] can decrease when the relaying node goes out of service. Our relaying technique is more robust, because other relaying nodes can still be in service carrying other copies and find the destination and deliver it, functioning like backup copies.

VII. Delay Equations

In Sections IV, V and VI, we showed that it is possible to have K feasible receivers that successfully obtain a copy of the same packet around a sender during *Phase 1*. Now we find the relationship between the delay value d obtained for the case of only one copy relaying [1], and the new delay d_K for $K \geq 2$ copies transmitted during *Phase 1* in steady-state behavior. Obviously, we have $d_K \leq d$. A naive guess would be to take $d_K = \frac{d}{K}$. However, a different answer is obtained because of the random movement of the nodes.

A. Single-Copy Forwarding Case

Because we have node trajectories independent and identically distributed, we focus on a given relay node labeled as *node 1*, and without loss of generality assume that *node 1* received a packet from the source during time $t_0 = 0$. Let $\mathbb{P}\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}$ denote the probability that relay *node* 1 at position $X_1(s)$ is close enough to the destination node $dest$ given that the time interval length is s, where r_o is the radius distance given by (5) so that successful delivery is possible. The time interval length s is the delivery-delay random variable. Perevalov and Blum [6] obtained an approximation for the ensemble average with respect to all possible uniformly-distributed starting points, $(X_1(0), X_{dest}(0))$, where they considered the nodes moving on a sphere. We can extend their result to nodes moving in a circle by projecting the sphere surface movement in the sphere equator and thus have trajectories described in a circle and have [6]

$$\begin{aligned} E_U\left[\mathbb{P}\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}\right] &= 1 - e^{-\lambda s}\left(1 - \lambda e^{-\lambda \int_0^s h_{X'}(t)dt} \int_0^s e^{\lambda \int_0^t h_{X'}(u)du} h_{X'}(t)dt\right) \\ &= \mathbb{P}\{S \leq s\} = F_S(s), \end{aligned} \tag{23}$$

where $E_U[\cdot]$ means the ensemble average over all possible starting points that are uniformly distributed on the disk. $F_S(s)$ can be interpreted as the cumulative density function of the delay random variable S. The function $h_X(t)$ is the difference from the uniform distribution, such that $h_X(0) = 0$ and $|h_X(t)| < 1$ for all t, and X' is a point at distance r_o from the destination. The parameter λ is related to the mobility of the nodes in the disk and can be expressed by [6]

$$\lambda = \tfrac{2\,r_o\,v}{\pi R^2} = \tfrac{2\,r_o\,v}{1} = 2\,r_o\,v\,, \tag{24}$$

which results from evaluating the flux of nodes entering a circle of radius r_o during a differential time interval considering the nodes uniformly distributed over the entire disk of unit area and traveling at speed v. From (5), we see that the radius r_o decreases with $\frac{1}{\sqrt{n}}$. To model a real network in which a node would occupy a constant area, if the network grows, the entire area must grow accordingly. Therefore, because in our analysis we maintain the total area fixed, we must scale down the speed of the nodes [11]. Accordingly, the velocity of the nodes also must decrease with $\frac{1}{\sqrt{n}}$. Then

$$\lambda = \frac{1}{\Theta(n)}\,. \tag{25}$$

Now, $h_X(t)$ is considered according to the random motion of the nodes [6]. If we consider the *uniform mobility model* [7], then a steady-state uniform distribution results as the random motion of the nodes in the disk. In such a case, $h_X(t) = 0 \;\forall\; t \geq 0$. Applying this result in (23) we have

$$\begin{aligned} E_U\left[\mathbb{P}\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}\right] &= 1 - e^{-\lambda s} \\ &= \mathbb{P}\{S \leq s\} = F_S(s), \end{aligned} \tag{26}$$

which has the following probability density function (see Fig. 6):

$$f_S(s) = \frac{\mathsf{d}F_S}{\mathsf{d}s} = \begin{cases} \lambda e^{-\lambda s} & \text{for } \; 0 \leq s < \infty \\ 0 & \text{otherwise.} \end{cases} \tag{27}$$

Thus, the delay behaves exponentially with mean $\frac{1}{\lambda}$ and variance $\frac{1}{\lambda^2}$ for the *uniform mobility model*. We conclude from (25), (26), and (27) that the average packet delivery delay is $\Theta(n)$ and its variance is $\Theta(n^2)$, i.e.,

$$E[S] = \frac{1}{\lambda} = \Theta(n)\;, \text{and } \; Var[S] = \frac{1}{\lambda^2} = \Theta(n^2). \tag{28}$$

For the rest of the paper, we change s by d to indicate the delay for single-copy forwarding at *Phase 1* [1]. Accordingly,

$$E_U\left[\mathbb{P}\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s{=}d\}\right]{=}1 - e^{-\lambda d}, \tag{29}$$

for a uniform steady-state distribution resulting from the random motion of the nodes.

Also, from (26) and (27), we have that the delay values are not bounded as a consequence of the tail of the exponential distribution even if the number of total nodes in the network n is finite! Thus, the packet delivery time can be infinitely long for some packets, even though its average value is limited by (28) and n is finite.

B. Multi-Copy Forwarding Case

Now consider that K copies of the same packet were successfully received by adjacent relaying nodes during *Phase 1* (where $1 < K << n$). Let $\mathbb{P}_D(s)$ be the probability of having the first (and only) delivery of the packet at time interval length s. Hence, given that only one-copy delivery is enforced (see Section III-B), and all K relays are looking for the destination, we have that

$$\mathbb{P}_D(s) = \mathbb{P}\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \leq r_o \mid s]\right\}. \tag{30}$$

Using the union bound and considering that $\mathbb{P}_D(s)$ can be at most equal to 1, we obtain

$$\mathbb{P}_D(s) \leq \min\left[\sum_{i=1}^{K}\mathbb{P}\{|X_i(s) - X_{dest}(s)| \leq r_o \mid s\}, 1\right], \tag{31}$$

in which (26) holds for each individual relay i, because all the K nodes have independent and identically distributed movements and therefore, we can use the results in [6] for a single relay. However, when we attempt to compute the probabilities of multiple relays, given that all these nodes start moving from the same area to search for destination (within a circle of radius r_o), their probability distributions are not mutually exclusive. If the time necessary for all these nodes to uniformly spread in the disk is equal to t_{spread}, then in general, $t_{spread} = \Theta(\sqrt{n})$ because each node has a spreed $v = \Theta(\frac{1}{\sqrt{n}})$. However, as we will show subsequently that the maximum delay $d_K^{max} = \Theta(n)$ given that $K << n$ whp. Therefore, $t_{spread} << d_K^{max}$ for large values of n, and consequently we can approximate all K probabilities using (26). This approximation for (31) results in

$$\mathbb{P}_D(s) \leq \min\left[K \cdot \mathbb{P}\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}, 1\right]. \tag{32}$$

Furthermore, (32) describes two cases. The first case is when $\mathbb{P}_D(s)$ is less than 1, and the second case is when the union bound is greater than 1. Obviously, we can derive a meaningful relationship between d_K and d only for the first case and that is the basis of our remaining analysis. From (26) and (32) and changing s by d_K [6] to indicate the delay for K-copies forwarded during *Phase 1*, we have for the *uniform mobility model*,

$$\begin{aligned} E_U[\mathbb{P}_D(s)] &= E_U\left[\mathbb{P}\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \leq r_o | \, s = d_K]\right\}\right] \\ &= \mathbb{P}\{D_K \leq d_K\} = F_{D_K}(d_K) \approx K\left(1 - e^{-\lambda d_K}\right), \end{aligned} \tag{33}$$

[6]To be more accurate, we should use $\tilde{d}_K$ instead of d_K for the rest of the paper, because of the approximation. In order to make the paper easy to read, we will continue to use the same notation for simplicity.

for a uniform steady-state distribution resulting from the random motion of the nodes. The exact computation of $\mathbb{P}_D(s)$ for d_K is a tedious task, instead, we assume that the upper bound probability can be achieved while this is simply an approximation. We make this assumption to find an approximate relationship between d_K and d and then by using computer simulation for MANETs given in Section VII-D, we show that this approximation follows the asymptotic behavior of d_K reasonably well. $F_{D_K}(d_K)$ can be interpreted as the cumulative density function of the delay random variable D_K for K copies being transmitted during *Phase 1*.

We see From (33) that the maximum value attained by D_K is given when

$$F_{D_K}(d_K^{max}) = 1 \approx K\left(1 - e^{-\lambda d_K^{max}}\right) \Longrightarrow d_K^{max} \approx \tfrac{1}{\lambda}\log\left(\tfrac{K}{K-1}\right). \tag{34}$$

This result reveals that, *for a finite* n, the new delay obtained by multi-copy forwarding is bounded by d_K^{max} after ensemble averaging over all possible starting points that are uniformly distributed on the disk. On the other hand, our analysis of the relationship between d_K and d is based on the fact that $d_K < d_K^{max}$, otherwise, the cumulative density function is equal to one.

From (25) and (34), and because $K << n$ whp, d_K^{max} grows to infinity and no bounded delay is guaranteed if n scales to infinity.

The probability density function for D_K is (see Fig. 6)

$$f_{D_K}(d_K) = \tfrac{\mathsf{d}F_{D_K}}{\mathsf{d}d_K} \approx \begin{cases} K\lambda e^{-\lambda d_K} & \text{for } \ 0 \leq d_K \leq d_K^{max} \\ 0 & \text{otherwise.} \end{cases} \tag{35}$$

Hence, in the multi-copy forwarding scheme the tail of the exponential delay distribution is cut off, and the average delay for K-copies forwarding is then given by

$$\begin{aligned} E[D_K] = \int_0^{\infty} d_K f_{D_K}(d_K)\mathsf{d}d_K \ &\approx \ \int_0^{d_K^{max}} d_K K\lambda e^{-\lambda d_K}\mathsf{d}d_K \\ &\approx \ \tfrac{1}{\lambda}\left[1 - \log\left(\tfrac{K}{K-1}\right)^{K-1}\right], \end{aligned} \tag{36}$$

and the delay variance is

$$Var[D_K] = E[D_K^2] - (E[D_K])^2 \approx \tfrac{1}{\lambda^2}\left\{1 - K(K-1)\left[\log\left(\tfrac{K}{K-1}\right)\right]^2\right\}. \tag{37}$$

Because $K << n$ whp, we conclude that the average delay and variance for any K are fractions of $\frac{1}{\lambda}$ and $\frac{1}{\lambda^2}$, respectively, and they also scale like $\Theta(n)$ and $\Theta(n^2)$. Note that d_K and λ scale to infinity and zero like n and $\frac{1}{n}$, respectively. Thus, λd_K which appears in (34) and (35) is not a function of n. Nevertheless, the number of nodes does not scale to infinity in real MANETs, and for a fixed n we can obtain significant average and variance delay reductions for small values of K compared to the single-copy relay scheme, as it is shown in Table I. For example, if $K = 2$ a reduction of more than 69% over the average delay is obtained (i.e., for single-copy Mean= $\frac{1}{\lambda}$, for multi-copy ($K = 2$) Mean= $\frac{0.307}{\lambda}$). Observe also that the mean and variance values decrease when K increases, i.e., the dispersion from the mean delay is significantly diminished.

C. Relationship between Delays

We showed that the throughput of our multi-copy scheme is the same order as the one-copy scheme [1]. Indeed, we showed that $\Lambda \approx 0.14$ for single-copy and $\Lambda \approx 0.12$ for multi-copy ($K > 1$), for $\theta = \frac{1}{3}$. This capacity is proportional to the probability of a packet reaching the destination. Hence, because <u>only one</u> copy of the packet is actually delivered to the destination for single-copy or multi-copy, their total probabilities can be approximated at their respective delivery time, i.e.,

$$\mathbb{P}\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \leq r_o \mid s = d_K]\right\} \approx \mathbb{P}\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s = d\}, \tag{38}$$

and so their ensemble averages are

$$E_U\left[\mathbb{P}\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \leq r_o \mid s = d_K]\right\}\right] \approx E_U\left[\mathbb{P}\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s = d\}\right], \tag{39}$$

whose solution must be obtained by substituting (23) (for $s = d_K$ and $s = d$ respectively) on both sides of (39) and solving for d_K for the particular model of random motion of nodes. For a steady-state uniform distribution for the motion of the nodes, a simplified solution is obtained by substituting (29) and (33) in (39), i.e.,

$$K\left(1 - e^{-\lambda d_K}\right) \;\approx\; 1 - e^{-\lambda d}. \tag{40}$$

Solving for d_K we have

$$d_K \approx \tfrac{1}{\lambda}\,\log\left(\tfrac{K}{K-1+e^{-\lambda d}}\right). \tag{41}$$

This last equation reveals some properties for the strategy of transmitting multiple copies of a packet during *Phase 1*. If $K = 1$, then obviously $d_K = d$. If we let $d \to \infty$, n be finite, and because $K << n$, then we have

$$d_K^{max} \approx \lim_{d\to\infty} \frac{1}{\lambda} \log\left(\frac{K}{K-1+e^{-\lambda d}}\right) = \frac{1}{\lambda} \log\left(\frac{K}{K-1}\right) \stackrel{\text{if } K>1}{=} c_5. \quad (42)$$

This is the same asymptotic value already predicted by (34). The last column of Table I shows values of this asymptotic delay for the single-copy and multi-copy ($2 \leq K \leq 4$) cases, expressed as a function of the mobility parameter λ, obtained from (42) (or (34)) for a finite number of nodes n.

Fig. 7 shows curves for (41), where λ was taken to be equal to 0.0052. The case of single-copy ($K = 1$) is also plotted. Except for the case of single-copy, the delay d_K tends to a constant value as d increases. *Hence, for a finite n, the multi-copy relay scheme can reduce a delay of hours in the single-copy relay scheme to a few minutes or even a few seconds, depending on the network parameter values*. Fig. 7 also shows that, having a packet two random routes to reach its destination, produces an exponential reduction in delay compared to having only one random route, whereas having three (or more) random routes leads only to incremental improvements from having two random routes [13].

D. Simulation Results

Equation (32) and all the results derived from it simply approximate the behavior of the delay d_K. In order to demonstrate if this approximation and the associated results are justified, we have simulated a MANET with 1000 nodes. Our simulations compare the behavior of our multi-copy packet forwarding strategy with the single-relay strategy. We used the *BonnMotion* simulator [20], which creates mobility scenarios that can be used to study MANET characteristics.

We implemented the *random waypoint mobility model* [21], [22] for the random motion of the nodes (as it resembles the *uniform mobility model* [7]). In this model, nodes are initially randomly distributed in the network area. A node begins its movement by remaining in a certain position for some fixed time, called *pause time* distributed according to some random variable, and when the pause time expires the node chooses a random destination point in the network area and begins to move toward that point with a constant speed uniformly distributed over $[v_{min}, v_{max}]$, where v_{min} and v_{max} stands for minimum and maximum velocity, respectively. Upon arrival at the destination, the node pauses again according to the pause-time random variable and the process repeats. Nodes move independently of each other.

We implemented the simplified version of the *random waypoint mobility model*, where no pause was used and $v_{min} = v_{max} = v$ in our simulations. Fig. 7 shows the averaged pairs of points (d, d_K) obtained for $K = 2$ and $K = 4$ for 1000 seconds of simulations for $n = 1000$ nodes, $v = 0.13\, m/s$, $r_o = 0.02\, m$, and a unit area disk as the simulation area, which results $\lambda = 0.0052$. To obtain a solution close to the steady-state behavior, we ran 40 random topologies and averaged them as follows. In each run we choose randomly a node with $K = 2$ and $K = 4$ neighbors within r_o, respectively, and measured the time that each of these K nodes reached each of the other $n - K$ nodes in the disk (i.e., except the sender and its other $K - 1$ neighbors) considering each of them as a destination. The delay of the sender's nearest node reaching each destination is d by definition, and d_K is the minimum time among all the K nodes that reach the destination. We see that the averaged random waypoint mobility curves follow the steady-state uniform distribution predicted by the theory. Note that they do not match exactly each other, because they are slightly different mobility models and our delay analysis for multi-copy forwarding scheme is only an approximation.

VIII. Conclusions

We have analyzed delay issues for two packet forwarding strategies, namely, the single-copy two-phase scheme advocated by Grossglauser and Tse [1], and a multi-copy two-phase forwarding technique. We found that in both schemes the average delay and variance scale like $\Theta(n)$ and $\Theta(n^2)$ for n total nodes in a mobile wireless ad hoc network. In the case of multi-copy relaying, *multiuser diversity* is preserved by allowing one-time relaying of packets and by delivering only the copy of the packet carried by the node that first reaches the destination close enough so that it successfully delivers the packet. The handshake phase with the destination lasts a negligible amount of time and prevents the delivery of multiple copies of the same packet to the destination, and it allows the additional nodes carrying the packet copy already delivered to drop it from their queues. We also show that our technique does not change the order of the magnitude of the throughput in the MANET compared to the original multiuser diversity scheme by Grossglauser and Tse [1].

We showed that our multi-copy strategy can reduce the average delay value by more than 69% of that attained in the single-copy strategy for a finite number n of total nodes in the network. The multi-copy technique also has an advantage of presenting bounded delay for a finite n, after ensemble averaging with regard to all possible starting uniform distribution of the nodes in the disk. Theoretical and simulations results were presented. This paper did not report exact delay analysis for the new scheme due to the complicated behavior of probabilities related to multi-copy forwarding, however, as it can be seen from the simulations, the approximation for delay analysis is consistent with simulation results. Since the multi-copy forwarding scheme can reduce the delay significantly in MANETs, it is important to analyze the behavior of the delay exactly. Our analysis did not provide such solution and future work can concentrate on computing exact equation for the delay.

Lastly, we have analyzed the interference effects for a large number of nodes n in the network. We showed that the signal-to-interference ratio for a receiver node communicating with a close neighbor tends to a constant as n scales to infinity, when the path loss parameter α is greater than two, regardless of the position of the receiver node in the network. Therefore, communication is feasible for close neighbors when the number of interferers scale to infinity. For the receiver nodes at the boundary of the network, we showed that, as expected, they experience less interference than those inside.

IX. Acknowledgments

We would like to thank the thoughtful comments provided by the anonymous reviewers.

References

[1] M. Grossglauser and D. Tse, “Mobility increases the capacity of wireless ad-hoc networks,” in *Proc. of IEEE Infocom*, Anchorage, Alaska, March 2001.

[2] S. Yi, Y. Pei, and S. Kalyanaraman, “On the capacity improvement of ad hoc wireless networks using directional antennas,” in *Proc. of ACM MobiHoc*, Annapolis, Maryland, June 2003.

[3] C. Peraki and S. D. Servetto, “On the maximum stable throughput problem in random networks with directional antennas,” in *Proc. of ACM MobiHoc*, Annapolis, Maryland, June 2003.

[4] B. Liu, Z. Liu, and D. Towsley, “On the capacity of hybrid wireless networks,” in *Proc. of IEEE Infocom*, San Francisco, California, March 2003.

[5] W. Yuen, R. Yates, and S.-C. Mau, “Exploiting data diversity and multiuser diversity in noncooperative mobile infostation networks,” in *Proc. of IEEE Infocom*, San Francisco, California, March 2003.

[6] E. Perevalov and R. Blum, “Delay limited capacity of ad hoc networks: asymptotically optimal transmission and relaying strategy,” in *Proc. of IEEE Infocom*, San Francisco, California, March 2003. “Delay-limited throughput of ad hoc networks,” *IEEE Transactions on Communications*, vol. 52, no. 11, pp. 1957–1968, November 2004.

[7] N. Bansal and Z. Liu, "Capacity, delay and mobility in wireless ad-hoc networks," in *Proc. of IEEE Infocom*, San Francisco, California, March 2003.

[8] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, March 2000.

[9] R. Knopp and P. A. Humblet, "Information capacity and power control in single-cell multiuser communications," in *Proc. of IEEE ICC*, Seattle, Washington, June 1995.

[10] M. J. Neely and E. Modiano, "Improving delay in ad-hoc mobile networks via redundant packet transfers," in *Proc. of Conference on Information Sciences and Systems*, Baltimore, Maryland, March 2003.

[11] A. E. Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Throughput-delay trade-off in wireless networks," in *Proc. of IEEE Infocom*, Hong Kong, March 2004.

[12] S. Toumpis and A. J. Goldsmith, "Large wireless networks under fading, mobility, and delay constraints," in *Proc. of IEEE Infocom*, Hong Kong, March 2004.

[13] M. Mitzenmacher, "The power of two choices in randomized load balancing," *IEEE Transactions on Parallel and Distributed Systems*, vol. 12, no. 10, pp. 1094–1104, October 2001.

[14] D. Nain, N. Petigara, and H. Balakrishnan, "Integrated routing and storage for messaging applications in mobile ad hoc networks," in *Proc. of WiOpt*, Antipolis, France, March 2003.

[15] C. T. Lau and C. Leung, "Capture models for mobile packet radio networks," *IEEE Transactions on Communications*, vol. 40, no. 5, pp. 917–925, May 1992.

[16] T. J. Shepard, "A channel access scheme for large dense packet radio networks," in *Proc. of ACM SigComm*, San Francisco, California, August 1996.

[17] B. Hajek, A. Krishna, and R. O. LaMaire, "On the capture probability for a large number of stations," *IEEE Transactions on Communications*, vol. 45, no. 2, pp. 254–260, February 1997.

[18] R. Motwani and P. Raghavan, *Randomized Algorithms*. Cambridge Univ. Press, 1995.

[19] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Prentice Hall, 2002.

[20] C. de Waal and M. Gerharz, "Bonnmotion: A mobility scenario generation and analysis tool," http://www.cs.uni-bonn.de/IV/BonnMotion/, 2003.

[21] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research," *Wireless Communication & Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications*, vol. 2, no. 5, pp. 483–502, 2002.

[22] C. Bettstetter, H. Hartenstein, and X. Pérez-Costa, "Stochastic properties of the random waypoint mobility model: epoch length, direction distribution, and cell change rate," in *Proc. of MSWiM*, Atlanta, Georgia, September 2002.

TABLE I

AVERAGE DELAY AND VARIANCE FOR SINGLE-COPY [1] AND MULTI-COPY ($1 < K << n$) TRANSMISSION OBTAINED FROM (28), (36), (37), AND RESPECTIVE ASYMPTOTIC DELAY VALUES d_K^{max} FROM (34) (OR (42)), FOR FINITE n.

Copies	**Mean**	**Variance**	d_K^{max}
Single-copy	$\frac{1}{\lambda}$	$\frac{1}{\lambda^2}$	∞
$K = 2$	$0.307\ \frac{1}{\lambda}$	$0.039\ \frac{1}{\lambda^2}$	$\frac{\log(2)}{\lambda}$
$K = 3$	$0.189\ \frac{1}{\lambda}$	$0.014\ \frac{1}{\lambda^2}$	$\frac{\log(3/2)}{\lambda}$
$K = 4$	$0.137\ \frac{1}{\lambda}$	$0.007\ \frac{1}{\lambda^2}$	$\frac{\log(4/3)}{\lambda}$

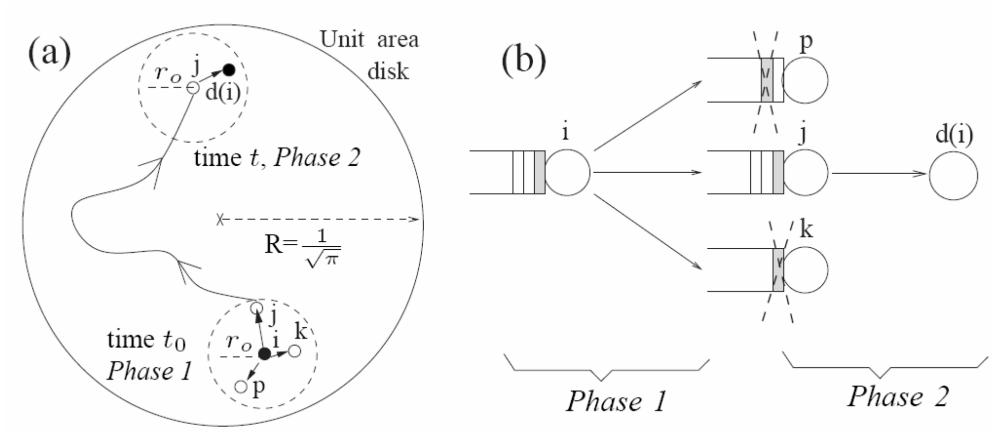

Fig. 1. (a) Three packet copies transmission at *Phase 1*. *Node* j is the first to find the destination, and delivers the packet at *Phase 2*. The movement of all the remaining nodes in the disk is not shown for simplicity. (b) The other copies are deleted later after p and k nodes handshake with destination $d(i)$.

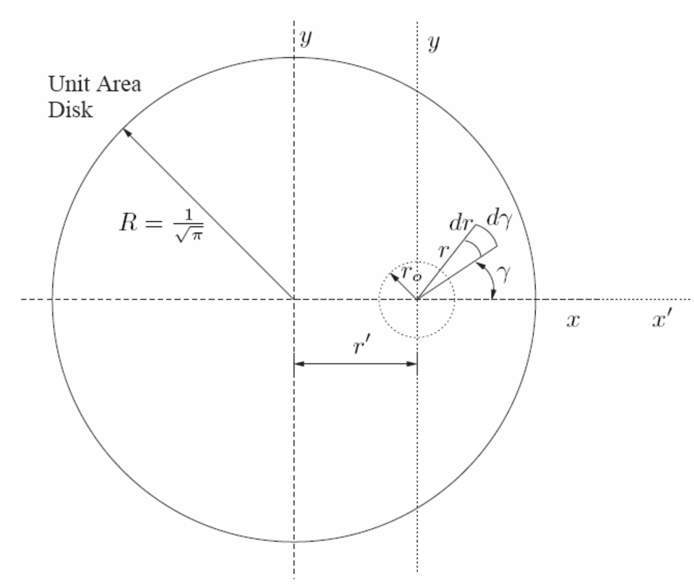

Fig. 2. Snapshot of the unit area disk at a given time t. At this time, the receiver node being analyzed is located at r' from the center while the sender is at distance r_o from the receiver node.

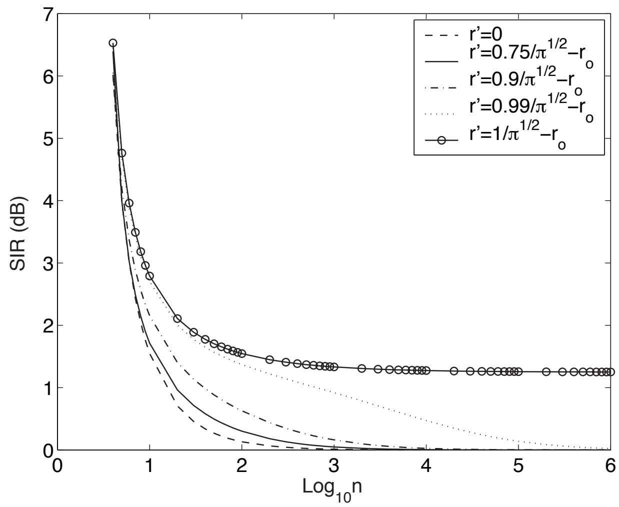

Fig. 3. Signal-to-Interference Ratio curves as a function of n for $\alpha = 4$ and $\theta = \frac{1}{3}$, for the receiver node located at different positions in the network.

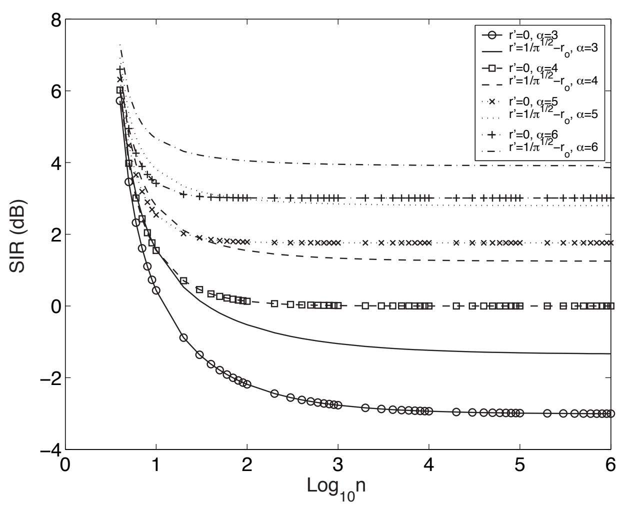

Fig. 4. Signal-to-Interference Ratio curves as a function of n, for $3 \leq \alpha \leq 6$ and $\theta = \frac{1}{3}$, and the receiver node considered located at the center and at the boundary of the network.

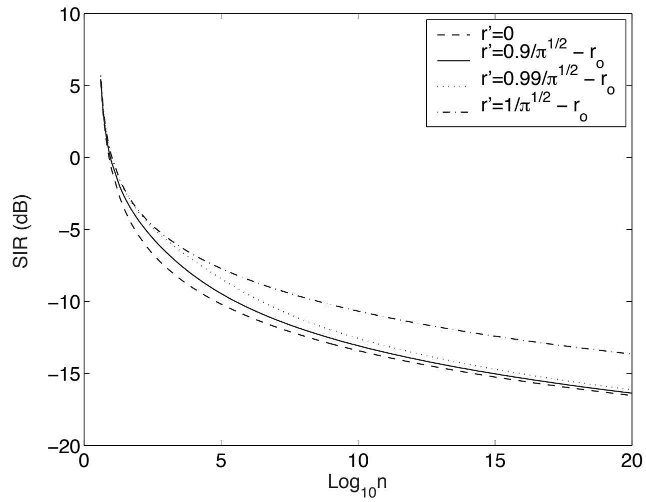

Fig. 5. Signal-to-Interference Ratio curves as a function of n for $\alpha = 2$ and $\theta = \frac{1}{3}$, for the receiver node located at different positions in the network cell.

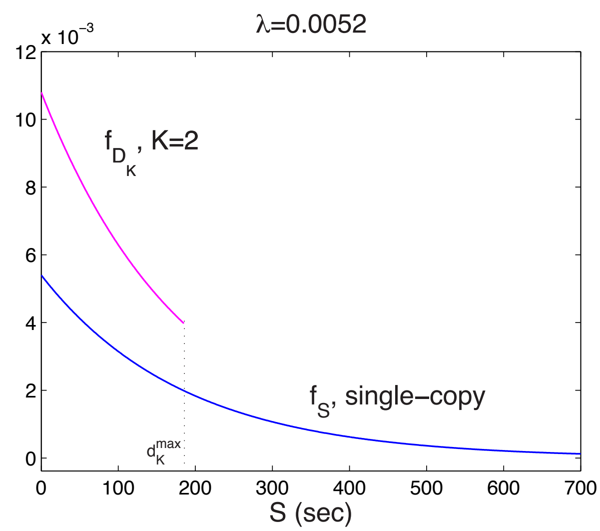

Fig. 6. Delay probability density functions for single-copy and $K = 2$, when $\lambda = 0.0052$, for the network in steady-state.

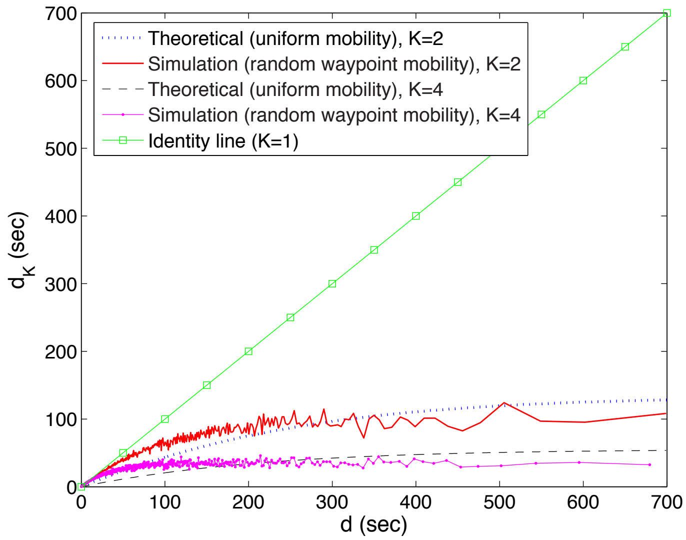

Fig. 7. Theoretical and simulation results for the *uniform mobility model* and *random waypoint mobility model*, respectively, for $K = 2$ and $K = 4$, with $\lambda = 0.0052$. For simulations, the delay measured is averaged over 40 random topologies.