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Throughput-Delay Analysis of Mobile Ad-hoc Networks with a Multi-Copy Relaying Strategy

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***Abstract*— Multiuser diversity has been shown to increase the throughput of mobile ad-hoc wireless networks (MANET) 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 find that the average delay and its variance scale like $\Theta(n)$ and $\Theta(n^2)$, respectively, for both the one and multi-copy relay strategies. Furthermore, while for finite n the delay values in the single-copy relaying strategy are not bounded, our multi-copy relay scheme attains bounded delay.

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 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 (MANET), utilizing *multiuser diversity* [9], in which 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. The scheme was shown to increase the capacity of the MANET [1], such that it remains constant as the number of nodes in the MANET increases. However, the delay experienced by packets under this strategy was shown to be large and it can be even 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]. In [1] $\Theta(1)$ [1] source-destination throughput is attained when n tends to infinity. However, the number of nodes in real MANETs is finite and delay is an important performance issue.

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 bounded delays in a MANET when the number of nodes n is fixed. This is far better 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 in [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.

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, improving the reliability of the network [13].

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. By contrast, previous works have only considered the receiver node located at the center of the network [14], [15], [16].

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.

[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.

II. Network Model

The network model we assume is the one introduced by Grossglauser and Tse [1], and consists of a normalized unit area disk containing n mobile nodes. We consider a time-slotted operation to simplify the analysis, and we assume 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 $X_i(t)$. The nodes are assumed to be uniformly distributed on the disk at the beginning, and there is no preferential direction of movement.

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 and the directions of motion are 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. After reaching z the process repeats. This model satisfies the following properties [7]:

- *At any time t, the position of the 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 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, and a time-to-live threshold field as well.

Suppose that at time t a source i has data for a certain destination $d(i)$. 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 can be relayed in sequence at most once.

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

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

where $P_i(t)$ is the transmitting power of node i, $\gamma_{ij}(t)$ 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]

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

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

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

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

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 Eq. (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 multi-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 with 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) and time-to-live (TTL) threshold. 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. All relays delete the packet copies from their queues after the TTL expires for the packet, and the destination of the packet remembers the SN of a packet it receives for a period of time that is much larger than the TTL

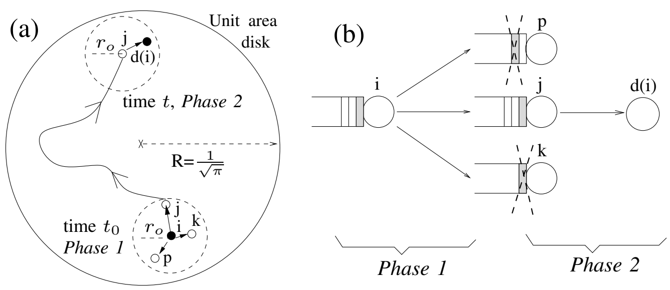

Fig. 1. (a) Three packet copies transmission at *Phase 1*. *Node* j is the first to find the destination, and delivers the packet at *Phase 2*. The movement of all the remaining nodes in the disk is not shown for simplicity. (b) Time-to-live threshold timeout after three packet copies transmission (from (a)).

of the packet to ensure that any handshake for the packet is correct.

Fig. 1(b) depicts the situation in which j finds the destination node $d(i)$ first and delivers the packet before the TTL expires. The other copies are dropped from the queues at p and k, 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 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 [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

Among the total number of nodes n in the network, a fraction of them, n_S, is randomly chosen 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 [1] each sender transmits to its nearest neighbor. However, it may be the case that a sender can have more than one receiver node in the feasible transmission range, and the proposed multi-copy relay strategy takes advantage of this by allowing those additional receiving nodes to also have a copy of the packet. These additional packet copies follow different random routes and can find the destination earlier compared to [1], where only one node receives the packet.

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.

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

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

which is a function of θ and does not depend on n. 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 below. Note that Eq. (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, Mammen, Prabhakar and Shah [11], each cell in our strategy has area $a(n) = \frac{1}{n_S} = \frac{1}{\theta\, n}$. By applying random occupancy theory [17, Chapter 3], the fraction of cells containing L senders and K receivers is obtained by

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

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

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

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

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

Also, the maximum number of nodes in any cell, with high probability (whp)[3], is $O(\frac{log(n)}{log(log(n))})$ [17, Chapter 3]. Thus, whp $K \leq \frac{c\, log(n)}{log(log(n))} << n$ for some constant $c > 0$.

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, in any of these cells, one of the K receiving nodes is at the

[3] With high probability means with probability $\geq 1 - \frac{1}{n}$ [17].

maximum neighborhood distance r_o. 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. We are interested in determining whether feasible communication between the sender and the farthest neighbor[4] (with distance r_o) is still possible, even if the number of interferers grows.

For a packet to be successfully received, Eq. (3) must be satisfied. Hence, 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

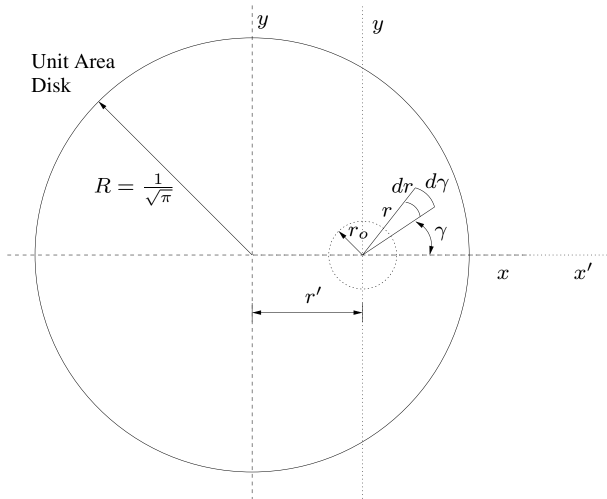

Fig. 2. Snapshot of the unit area disk at a given time t. At this time, the receiver node being analyzed is located at r' from the center while the sender is at distance r_o from the receiver node.

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 $r dr d\gamma$ 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, at the receiver, the following amount of interference[5]

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

For the propagation model we study here, the path loss parameter is modeled to be always greater than two[6] [18, p. 139, Table 4.2], 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 Eq. (10) over all the disk area. Hence,

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

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.,

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

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

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

By substituting this result in Eq. (11) we arrive at

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

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 $\alpha = 4$, Eq. (15) reduces to

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

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

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

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

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

[4]This represents the worst case scenario, because the other $K-1$ neighbors are located either closer or at the same distance r_o to the sender, so they measure either a stronger or the same SIR level.

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

[6]For $\alpha = 2$, we obtain similar results as in [15].

From Eq. (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,

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

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

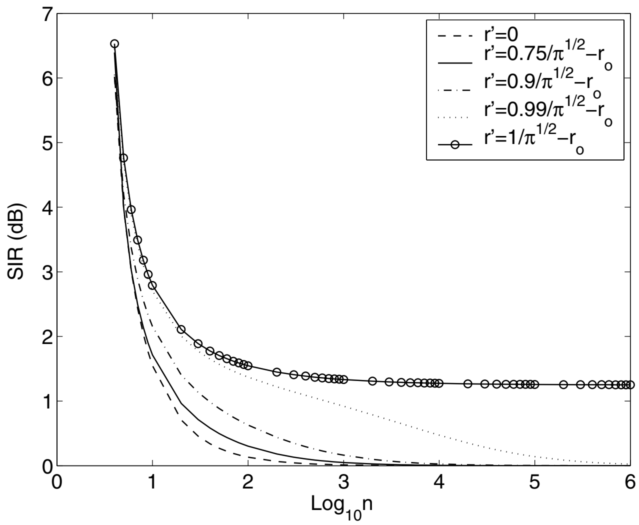

Fig. 3. Signal-to-Interference Ratio curves as a function of n for $\alpha = 4$ and $\theta = \frac{1}{3}$, for the receiver node located at different positions in the network.

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* $0 \le r' < \frac{1}{\sqrt{\pi}} - r_o$, *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 at 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). Fig. 4 shows SIR for $3 \le \alpha \le 6$ and $\theta = \frac{1}{3}$ for the receiver node located at the center and at the boundary of the network for comparison purposes.

Hence, by having the SIR approaching a constant value as n scales to infinity, the network designer can properly devise the receiver (i.e., design modulation, encoding, etc.) such that Eq. (3) 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.

VI. Source-Destination Throughput

We now show that the throughput per source-destination pair with our multi-copy relaying approach remains the *same*

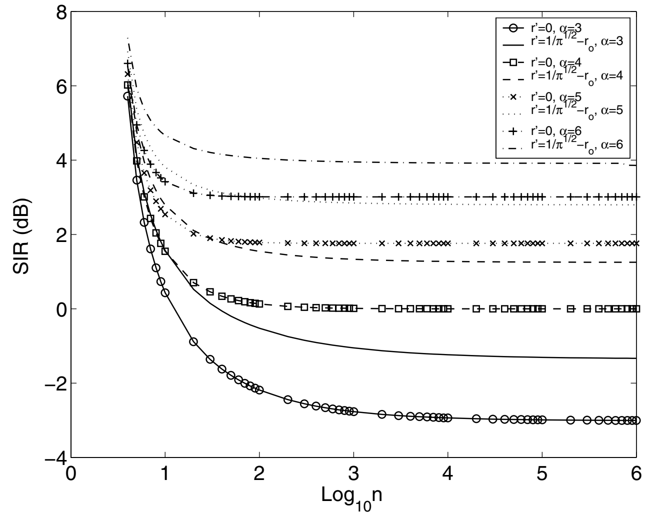

Fig. 4. Signal-to-Interference Ratio curves as a function of n, for $3 \le \alpha \le 6$ and $\theta = \frac{1}{3}$, and the receiver node considered located at the center and at the boundary of the network.

order of magnitude as the original single-copy relaying scheme [1]. We know that the throughput for a one-copy relay is $\Theta(1)$ [1]. In the case of multi-copy forwarding, only one copy is delivered to destination and the others are dropped from the additional relaying nodes after the TTL timeout. Therefore, only one node out of K nodes actually functions as a relay (as in Fig. 1(b)). Accordingly, only one copy of different packets passes successfully through the two-phase process, as shown in Fig. 5. Because node trajectories are iid and the system is in steady-state, the long-term throughput between any two nodes equals the probability that these two nodes are selected by the scheduler as a feasible sender-receiver pair. According to [1] this probability is $\Theta(\frac{1}{n})$. Also, there is one direct route and $n-2$ two-hop routes passing through one relay node for a randomly chosen source-destination pair. Thus, the service rate is $\lambda_j = \Theta(\frac{1}{n})$ through each actual relay node, as well as the direct route. Accordingly, the total throughput per source-destination pair Λ is

$$\Lambda = \sum_{j=1, j\neq i}^{n} \lambda_j = \sum_{j=1, j\neq i}^{n} \Theta\left(\tfrac{1}{n}\right) = \Theta\left(\tfrac{n-1}{n}\right) \overset{n \to \infty}{\longrightarrow} \Theta(1). \quad (20)$$

Since the nodes trajectories are iid and they move according to the *uniform mobility model*, the traffic from each source node is uniformly distributed among all nodes [1]. From Eq. (8), each cell employing multi-copy forwarding has throughput of $\Theta(1) \approx 0.12$. Therefore, the network transport capacity (i.e., the network throughput) is $\Theta(n)$. Consequently, the network throughput of $\Theta(n)$ is uniformly distributed among all source-destination pairs [11]. Thus, 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

$$\begin{aligned}\Lambda = & P\{\text{senders } (L) = 1, \text{ receivers are at least } K\} \\ & \approx \tfrac{1}{\theta}\, e^{-1/\theta} \left(1 - \sum_{k=0}^{K-1} \tfrac{1}{k!} \left(\tfrac{1}{\theta}\right)^k e^{-1/\theta}\right). \quad (21)\end{aligned}$$

Hence, for at least two receivers per cell and $\theta = \frac{1}{3}$, $\Lambda = \frac{1}{\theta} e^{-1/\theta}(1 - e^{-1/\theta} - \frac{1}{\theta} e^{-1/\theta}) \approx 0.12 = \Theta(1)$. Therefore, the multi-copy forwarding strategy attains the same throughput order as in [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 $K \geq 1$, Eqs. (8) and (21) give the same throughput value obtained by Tse and Grossglauser [1], as well as Neely and Modiano [10]. Thus, in the single-copy forwarding strategy [1], although they have $K \geq 1$, their scheme selects only the nearest neighbor from the sender amongst the K receiver nodes.

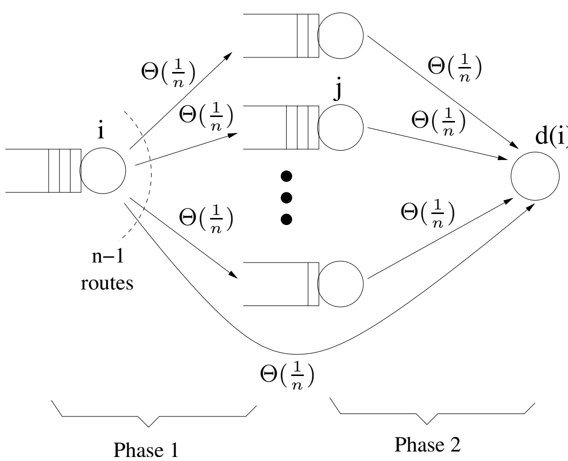

Fig. 5. Two-phase processes for different packets deliveries. Just one copy of each packet is delivered to destination.

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, another answer is obtained because of the random movement of the nodes. K is a small integer much smaller than n whp, as explained in Section IV.

A. Single-Copy Forwarding Case

Because we have node trajectories independent and identically distributed, we focus on the relay node labeled as *node 1*, and without loss of generality assume that *node 1* received a packet from the source during time $t_0 = 0$. Denoted by $P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}$, define it as the probability of relay *node* 1 at position $X_1(s)$ being close enough to the destination node $dest$ given that the time interval length is s, where r_o is the radius distance given by Eq. (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 for 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]

$$\begin{aligned}& E_U\left[P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}\right] = 1 - e^{-\lambda s} \cdot \\ & \qquad \left(1 - \lambda e^{-\lambda \int_0^s h_{X'}(t)dt} \int_0^s e^{\lambda \int_0^t h_{X'}(u)du} h_{X'}(t)dt\right) \\ & = \quad P\{S \leq s\} = F_S(s)\,, \qquad (22)\end{aligned}$$

where $E_U[\cdot]$ means the ensemble average over all possible starting points which 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]

$$\lambda = \tfrac{2\, r_o\, v}{\pi R^2} = \tfrac{2\, r_o\, v}{1} = 2\, r_o\, v\,, \qquad (23)$$

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 Eq. (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

$$\lambda = \tfrac{1}{\Theta(n)}\,. \qquad (24)$$

Now, $h_X(t)$ has to be taken 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 Eq. (22) we have

$$\begin{aligned}& E_U\left[P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}\right] = 1 - e^{-\lambda s} \\ & = \quad P\{S \leq s\} = F_S(s), \qquad (25)\end{aligned}$$

which has the following probability density function:

$$f_S(s) = \frac{\mathrm{d}F_S}{\mathrm{d}s} = \begin{cases} \lambda e^{-\lambda s} & \text{for } 0 \leq s < \infty \\ 0 & \text{otherwise.} \end{cases} \quad (26)$$

Thus, for the *uniform mobility model*, the delay behaves exponentially with mean $\frac{1}{\lambda}$ and variance $\frac{1}{\lambda^2}$. We conclude from Eqs. (24), (25), and (26) that the average packet delivery delay is $\Theta(n)$ and its variance is $\Theta(n^2)$, i.e.,

$$E[S] = \tfrac{1}{\lambda} = \Theta(n) \text{ , and } Var[S] = \tfrac{1}{\lambda^2} = \Theta(n^2). \quad (27)$$

From now on, we change s by d to indicate the delay for single-copy forwarding at *Phase 1* [1]. Accordingly,

$$E_U \left[P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s{=}d\}\right] = 1 - e^{-\lambda d}, \quad (28)$$

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

Also, from Eqs. (25) and (26), we have that, even if the number of total nodes in the network n is finite, *the delay values are not bounded as a consequence of the tail of the exponential distribution*. Thus, the packet delivery time can last to infinity, even though its average value is limited by Eq. (27) 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 $P_D(s)$ 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

$$P_D(s) = P\left\{\bigcup_{i=1}^{K} [|X_i(s) - X_{dest}(s)| \leq r_o \mid s]\right\}. \quad (29)$$

Because of the relay-destination handshake, at most one copy can be delivered, implying that the K relay-destination delivery events are mutually exclusive. Hence,

$$P_D(s) = \sum_{i=1}^{K} P\{|X_i(s) - X_{dest}(s)| \leq r_o \mid s\}. \quad (30)$$

We observe that the K relays are not uniformly spread in the disk right after *Phase 1*, but are close to each other (within r_o), and after that, they need some time (t_{spread}) to be uniformly spread, and this time interval is a function of the speed of the nodes v. However, as we show later, t_{spread} is negligible compared to the maximum delivery delay. Therefore, given that nodes trajectories are iid, we can approximate Eq. (30) by

$$P_D(s) \approx K \cdot P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}. \quad (31)$$

From Eqs. (25) and (31) and changing s by d_K to indicate the delay for K-copies forwarded during *Phase 1*, we have for the *uniform mobility model*,

$$E_U[P_D(s)] = E_U\left[P\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \leq r_o | \, s = d_K]\right\}\right]$$
$$= P\{D_K \leq d_K\} = F_{D_K}(d_K) \approx K\left(1 - e^{-\lambda d_K}\right), \quad (32)$$

for a uniform steady-state distribution resulting from the random motion of the nodes. $F_{D_K}(d_K)$ can be interpreted as the cumulative density function of the delay random variable D_K for K relays copies transmission at *Phase 1*.

From Eq. (32) we see that the maximum value attained by D_K is given when

$$F_{D_K}(d_K^{max}) = 1 \approx K\left(1 - e^{-\lambda d_K^{max}}\right) \Longrightarrow d_K^{max} \approx \tfrac{1}{\lambda} log\left(\tfrac{K}{K-1}\right). \quad (33)$$

Eq. (33) 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 topology uniformly distributed on the disk.

As mentioned above, the exact bounded value must also include the time interval t_{spread} necessary to have all K nodes uniformly spread in the disk after *Phase 1*. Because the nodes move with speed $v = \Theta(\frac{1}{\sqrt{n}})$, then $t_{spread} = \Theta(\sqrt{n})$. Now, from Eqs. (24) and (33), and since $K << n$ whp, we have that $d_K^{max} = \Theta(n)$. Therefore, $t_{spread} << d_K^{max}$. Hence, the approximation used in Eq. (31) is justified!

From Eqs. (24) and (33), 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

$$f_{D_K}(d_K) = \frac{\mathrm{d}F_{D_K}}{\mathrm{d}d_K} \approx \begin{cases} K\lambda e^{-\lambda d_K} & \text{for } 0 \leq d_K \leq d_K^{max} \\ 0 & \text{otherwise.} \end{cases} \quad (34)$$

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

$$E[D_K] = \int_0^{\infty} d_K f_{D_K}(d_K) \mathrm{d}d_K \approx \int_0^{d_K^{max}} d_K K\lambda e^{-\lambda d_K} \mathrm{d}d_K$$
$$\approx \quad \tfrac{1}{\lambda}\left[1 - log\left(\tfrac{K}{K-1}\right)^{K-1}\right], \quad (35)$$

and the delay variance is

$$Var[D_K] = E[D_K^2] - (E[D_K])^2$$
$$\approx \quad \tfrac{1}{\lambda^2}\left\{1 - K(K-1)\left[log\left(\tfrac{K}{K-1}\right)\right]^2\right\}. \quad (36)$$

Since $K << n$ 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 $\Theta(n^2)$. 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.

TABLE I

AVERAGE DELAY AND VARIANCE FOR SINGLE-COPY [1] AND MULTI-COPY ($1 < K << n$) TRANSMISSION OBTAINED FROM EQS. (27), (35), (36), AND RESPECTIVE ASYMPTOTIC DELAY VALUES d_K^{max} FROM EQ. (33) (OR EQ. (41)), 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 $\frac{1}{\lambda^2}$	$\frac{log(4/3)}{\lambda}$

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 only one 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.,

$$P\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \leq r_o \mid s = d_K]\right\} \approx P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s = d\}, \quad (37)$$

and so their ensemble averages are

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

whose solution must be obtained by substituting Eq. (22) (for $s = d_K$ and $s = d$ respectively) on both sides of Eq. (38) 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 Eqs. (28) and (32) in Eq. (38), i.e.,

$$K\left(1 - e^{-\lambda d_K}\right) \approx 1 - e^{-\lambda d}. \quad (39)$$

Solving for d_K we have

$$d_K \approx \frac{1}{\lambda} \, log\left(\frac{K}{K-1+e^{-\lambda d}}\right). \quad (40)$$

This last equation reveals very interesting 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

$$d_K^{max} \approx \lim_{d\to\infty} \frac{1}{\lambda} \, log\left(\frac{K}{K-1+e^{-\lambda d}}\right) = \frac{1}{\lambda} \, log\left(\frac{K}{K-1}\right) \overset{\text{if } K>1}{=} cte. \quad (41)$$

Therefore, if we choose K strictly greater than one, then the delay obtained in the multi-copy relay scheme is bounded for a finite number of nodes n, even when the single-copy relay scheme in [1] incurs infinite delays. This is the same asymptotic value already predicted by Eq. (33). 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 Eq. (41) (or Eq. (33)) for a finite number of nodes n. Note that the time-to-live threshold must be set greater than the worst asymptotic delay ($K = 2$) to allow the packet to be delivered, i.e., $d_2^{max} = \frac{log(2)}{\lambda} < TTL$.

Fig. 6 shows curves for Eq. (40), where λ was taken to be equal to one hundredth. The case of single-copy is also plotted. In all cases, except 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.*

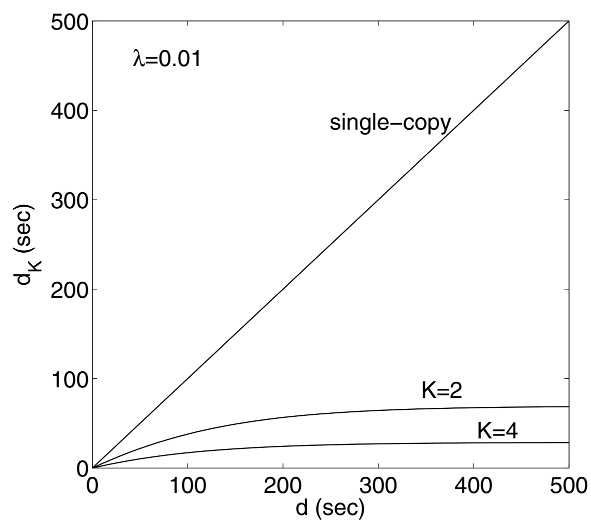

Fig. 6. Relationship between delays d_K and d for single-copy, $K = 2$, and $K = 4$, for a uniform distribution resulting from the random motion of the nodes for the network in steady-state.

Clearly, we can allow the sender itself to keep a copy of the packet it has transmitted, because there is a chance of this sender finding the destination before all other K relays. This results in $K + 1$ nodes looking for the destination, thus reducing the delay compared to using K relays.

D. Simulation Results

To validate our theoretical analysis and approximations, we performed some simulations to compare the behavior of our multi-copy packet forwarding strategy. We used the *BonnMotion* simulator [19], which creates mobility scenarios that can be used to study mobile ad-hoc network characteristics.

We implemented the *random waypoint mobility model* [20], [21] 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 it 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.

In our simulations we implemented the simplified version of the *random waypoint mobility model*, where no pause was used and $v_{min} = v_{max} = v$. Fig. 7 shows the results 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 run 40 random topologies and averaged them as follow. In each run we choose randomly a node with $K = 2$ and $K = 4$ neighbors, respectively, within r_o, and measured the time that each of these K nodes reach 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 by definition d, and d_K is the minimum time among all the K nodes that reach the destination. Figs. 7(a) and (b) shows all pairs of points (d, d_K) obtained in this way for $K = 2$ and $K = 4$, respectively. In each graph we plot a 7^{th} degree polynomial fit for all the points as well as an average obtained by taking the mean of consecutive 90 points. We also plot the theoretical curve (from Eq. (40)) for the steady-state uniform distribution for the same parameters. We see that the averaged 90-points curve follows the polynomial fit and that they both accompany the steady-state uniform distribution predicted by theory as they are related mobility models. We only observe the asymptotic behavior for the experimental curves up to 800 seconds. After that the polynomial fit begins to fall and does not represent the actual asymptotic behavior anymore due to the natural lack of samples at this part of the graph.

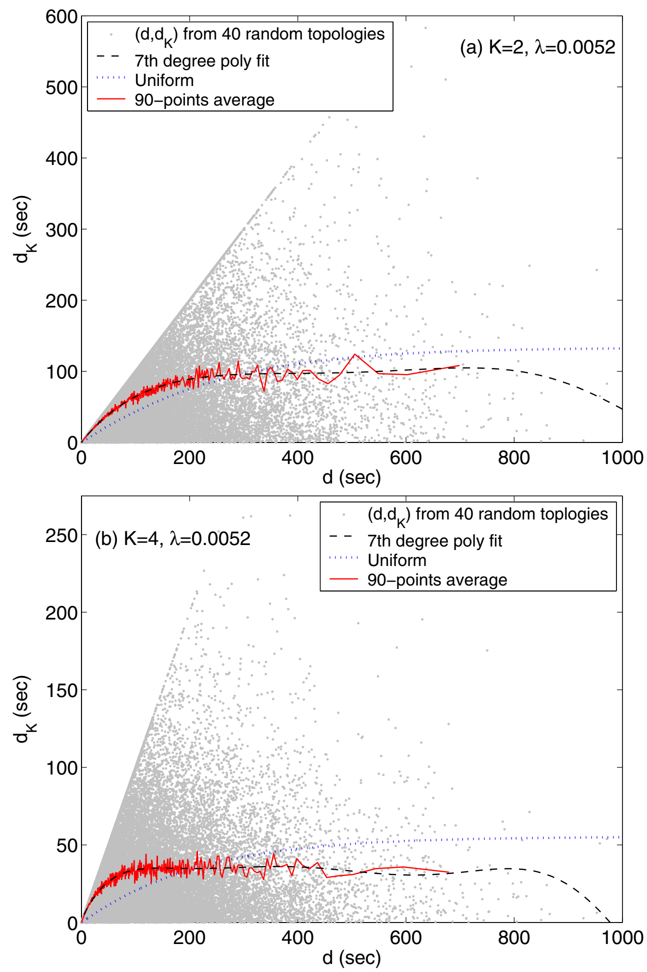

Fig. 7. Simulation results for the *random waypoint mobility model*. Each grey point is a pair (d, d_K) delay measured for 40 random topologies all plotted together. A 7^{th} degree polynomial fit for all the points and a 90 consecutive points average are plotted for (a) $K = 2$ and (b) $K = 4$. The theoretical curve for the steady-state uniform distribution is also plotted.

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. A time-to-live threshold allows the additional nodes carrying the packet copy already delivered to drop it from their queues as soon as the lifetime expires. We also show that our technique does not change the order of the magnitude of the throughput capacity in the MANET compared to the original multiuser diversity scheme by Grossglauser and Tse [1].

We showed that our multi-copy strategy is able to reduce the average delay value by more than 69% of that attained in the single-copy strategy for a fixed 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.

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.

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