Making Ad Hoc Networks Scale Using Mobility and Multi-Copy Forwarding

Renato M. de Moraes, Hamid R. Sadjadpour
Department of Electrical Engineering
University of California at Santa Cruz
Santa Cruz, CA 95064, USA
Email: {renato,hamid}@soe.ucsc.edu

J.J. Garcia-Luna-Aceves
Department of Computer Engineering
University of California at Santa Cruz
Santa Cruz, CA 95064, USA
Email: jj@soe.ucsc.edu

***Abstract*— Multiuser diversity has been shown to increase the throughput of mobile ad hoc wireless networks (MANET) when compared to fixed networks. We present a different multiuser diversity strategy for packet relaying, which permits more than one-copy (multi-copies) of a packet being received by relay nodes, thus allowing to decrease the delay on such networks for a fixed number of total users n. We show that the $\Theta(1)$ throughput is preserved by our multi-copy technique when n goes to infinity. In addition, we find that the average delay and variance scale like $\Theta(n)$ and $\Theta(n^2)$ respectively for both one-copy and multi-copies techniques. We also show that for a fixed n and by multi-copy forwarding, a maximum bounded delay value can be guaranteed.**

I. Introduction

In recent past years, there has been a considerable effort [1], [2], [3] on trying to increase the performance of wireless ad hoc networks since Gupta and Kumar [4] showed that the capacity of a fixed wireless network decreases as the number of nodes increases. Grossglauser and Tse [1] presented a two-phase packet forwarding technique for mobile ad hoc networks (MANET), utilizing *multiuser diversity*, 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 [1] to increase the capacity of the MANET, such that it remains constant as the number of users in the MANET increases. The delay experienced by packets under this strategy was shown to be large and even infinite for a fixed number of users (n), which has prompted more recent work presenting capacity and delay tradeoffs analysis [2], [3], [5], [6]. Although $\Theta(1)$ source-destination throughput is attained when n tends to infinity [1], the number of users 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 delay when the number of users 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[1] 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.

The remaining of the paper is organized as follows. Section II introduces the network model and explains our relaying strategy. Section III presents the fraction of cells that successfully forward packets. Section IV 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 V shows the delay reduction resulting from our forwarding strategy and presents theoretical and simulation results. Section VI concludes the paper summarizing the main ideas presented.

II. Model

The modeling problem we address is that of a MANET where n mobile nodes move in a unit circular area (or disk). We consider a time-slotted operation of the system to simplify the analysis, and we assume that the communication occurs among those nodes that are close enough, so that interference caused by other nodes is low, allowing reliable communication. The model is basically the same as the one introduced by Grossglauser and Tse [1], who consider a packet to be delivered from sender to destination via one-time relaying.

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. The trajectories for different users are independent and identically distributed (iid). Nodes are assumed to move according to the *uniform mobility model* [3], in which the steady-state distribution for the mobile nodes is uniform. At each time step, a scheduler decides which nodes are senders, relays, or destinations, in such a manner that the association pair, source-destination, 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 to a certain destination $d(i)$. Since nodes i and $d(i)$ have a direct transmission only $1/n$ fraction of time on the average, a relay strategy

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

is required to deliver data $d(i)$ via relay nodes. We assume that each packet can be relayed in sequence at most once. So a packet passes two phases (see Figs. 1 and 2): The packet is transmitted from the source to a relay node during *Phase 1* (time slot t_0), and it is delivered to its destination by the relay node during *Phase 2* (time slot t). Direct transmission from source to destination is also allowed. Both phases occur concurrently, but *Phase 2* has absolute priority in all scheduled sender-receiver pairs.

At time t, node j is capable of receiving at a given rate of $W\ bits/sec$ from i if [1], [4]

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

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 (SNIR) level necessary for reliable communication, N_0 is the noise power, and M is the processing gain of the system. The channel path gain is assumed to be a function of the distance only, so that $\gamma_{ij}(t) = 1/|X_i(t) - X_j(t)|^\alpha = 1/r_{ij}^\alpha(t)$ [1], [4], where α is the path loss parameter, and $r_{ij}(t)$ is the distance between i and j.

A. Multi-Copy Forwarding Scheme

We introduce a new packet delivery scheme to reduce the delay by allowing more than one copy of the same packet being received during *Phase 1*, i.e., more than one relay node receives the same copy of the packet. 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]. 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 first the destination and delivers the packet. Note that relay node j is not the closest node to source during *Phase 1* while it reaches the destination first.

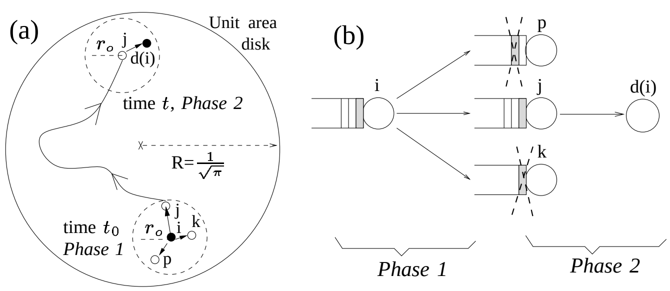

Fig. 1. (a) Three packet copies transmission at *Phase 1*. *Node* j is the first to find the destination, and delivers the packet at *Phase 2*. The movement of all the remaining nodes in the disk are not shown for simplicity. (b) Time-to-live threshold timeout after three packet copies transmission (from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

B. Enforcing Single-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 handshake can be established between relay and destination to verify that the destination has not received a copy of the same packet. 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. 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 larger than the TTL 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.

III. Receivers at *Phase 1* and Cell Definition

Among the total number of nodes n, a fraction of them, n_S, are randomly chosen by the scheduler as senders, while the remaining nodes, n_R, function like 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 we can take advantage of that. We allow those additional receiving nodes to also have a copy of the packet. These additional packet copies can find the destination earlier compared to [1], where only one (the sender's nearest) node receives the packet.

If the density of nodes in the disk is $\rho = \frac{n}{total\ area} = n$, then, for a uniform distribution of nodes, the radius for one sender node is given by

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

Thus, the radius r_o defines a cell (radius range) around a sender. The number of receiving nodes, called K, around each sender node varies.

Referring to the recent work by El Gamal et al. [6], each cell in our strategy has area $a(n) = \frac{1}{n_S} = \frac{1}{\theta n}$. By applying random occupancy theory [7], the fraction of cells containing L senders and K receivers is obtained by

$$P\{\text{senders} = L,\ \text{receivers} = K\} \approx \frac{1}{L!}\left(\frac{1}{\theta}\right)^L e^{-1/\theta}\frac{1}{K!}\left(\frac{1}{\theta}\right)^K e^{-1/\theta}. \tag{3}$$

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*.

IV. Source-Destination Throughput

We now show that the throughput per source-destination pair with our packet forwarding approach remains the same order of magnitude as in [1]. We know that the throughput for a one-copy relay is $\Theta(1)$ [1]. In the case of multi-copy transmission, only one copy is delivered to destination and the others are dropped from the additional relaying nodes. Thus, 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 through the two-phase processes, as shown in Fig. 2. Because the 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, for a randomly chosen source-destination pair there is one direct route and $n-2$ two-hop routes passing through one relay node. Thus, the service rate through each actual relay node, as well as the direct route, is $\lambda_j = \Theta(\frac{1}{n})$. So the total per source-destination pair throughput Λ is

$$\Lambda = \sum_{j=1, j\neq i}^{n} \lambda_j = \Theta\left(\tfrac{n-1}{n}\right) \overset{n\to\infty}{\longrightarrow} \quad \Theta(1) \quad \square \tag{4}$$

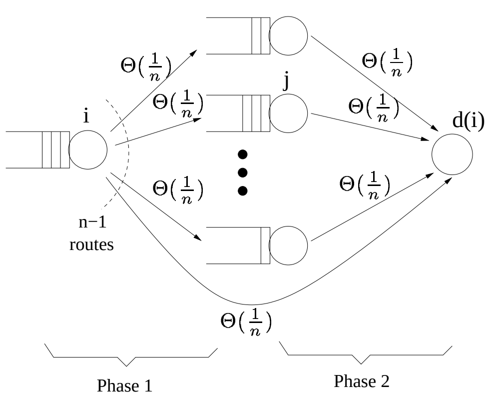

Fig. 2. Two-phase processes for different packet deliveries. Just one copy of each packet is delivered to destination.

V. Delay Equations

In the Section III, 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. 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. Clearly, $K << n$ since the distribution of nodes is assumed to be uniform and we might expect only a small number of nodes within r_o from the sender.

A. Single-Copy Forwarding Case

Assume that *node 1* received a packet from the source during time $t_0 = 0$. $P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}$ is denoted 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 (2) so that successful delivery is possible. The time interval length s is the delivery-delay random variable. Perevalov and Blum [2] 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 extend their result for nodes moving in a disk by projecting the sphere surface movement in the sphere equator and thus have trajectories described in the disk and have [2]

$$\begin{aligned} E_U\left[P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}\right] &= 1 - e^{-\lambda s} \cdot \\ &\left(1 - \lambda e^{-\lambda \int_0^s h_{X'}(t)dt} \int_0^s e^{\lambda \int_0^t h_{X'}(u)du} h_{X'}(t)dt\right) \\ = \quad P\{S \leq s\} = F_S(s)\,, \end{aligned} \tag{5}$$

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 [2]

$$\lambda = \tfrac{2\, r_o\, v}{\pi R^2} = \tfrac{2\, r_o\, v}{1} = 2\, r_o\, v\,. \tag{6}$$

From (2), the radius r_o decreases with $\frac{1}{\sqrt{n}}$. It can be also shown [6] that v must decrease with $\frac{1}{\sqrt{n}}$. Then

$$\lambda = \tfrac{1}{\Theta(n)}\,. \tag{7}$$

Now, $h_X(t)$ has to be taken according to the random motion of the nodes [2]. If we consider the *uniform mobility model* [3], then $h_X(t) = 0\ \forall\ t \geq 0$. Applying this result in (5) we have

$$E_U\left[P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s\}\right] = 1 - e^{-\lambda s} = F_S(s), \tag{8}$$

which has the following probability density function:

$$f_S(s) = \tfrac{\mathsf{d}F_S}{\mathsf{d}s} = \begin{cases} \lambda e^{-\lambda s} & \text{for } 0 \leq s < \infty \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

Thus, for the *uniform mobility model* the delay behaves exponentially with mean $\frac{1}{\lambda}$ and variance $\frac{1}{\lambda^2}$. We conclude from (7), (8), and (9) that the average packet delay is $\Theta(n)$ and its variance is $\Theta(n^2)$, i.e.,

$$E[S] = \tfrac{1}{\lambda} = \Theta(n), \text{ and } Var[S] = \tfrac{1}{\lambda^2} = \Theta(n^2). \tag{10}$$

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

$$E_U\left[P\{|X_1(s) - X_{dest}(s)| \leq r_o \mid s{=}d\}\right]{=}1 - e^{-\lambda d}, \tag{11}$$

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

Also, from (8) and (9), the delay value can last to infinity as a consequence of the tail of the exponential distribution even if the number of total nodes in the network 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 II-B), and all K relays are looking for the destination, we have that

$$P_D(s) = P\left\{\bigcup_{i=1}^{K} [|X_i(s) - X_{dest}(s)| \leq r_o \mid s]\right\}. \tag{12}$$

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,

$$P_D(s) = \sum_{i=1}^{K} P\{|X_i(s) - X_{dest}(s)| \le r_o \mid s\}. \tag{13}$$

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 node trajectories are iid, we can approximate (13) by

$$P_D(s) \approx K \cdot P\{|X_1(s) - X_{dest}(s)| \le r_o \mid s\}. \tag{14}$$

From (8) and (14) and changing s by d_K to indicate the delay for K-copies forwarded during *Phase 1*, we have for the *uniform mobility model*,

$$\begin{aligned} E_U[P_D(s)] &= E_U\left[P\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \le r_o \mid s = d_K]\right\}\right] \\ &= P\{D_K \le d_K\} = F_{D_K}(d_K) \approx K\left(1 - e^{-\lambda d_K}\right), \end{aligned} \tag{15}$$

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 (15), the maximum value attained by D_K is

$$F_{D_K}(d_K^{max}) = 1 \approx K\left(1 - e^{-\lambda d_K^{max}}\right) \Longrightarrow d_K^{max} \approx \tfrac{1}{\lambda} log\left(\tfrac{K}{K-1}\right). \tag{16}$$

Eq. (16) 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 (7) and (16), and since $K << n$, we have that $d_K^{max} = \Theta(n)$. Therefore, $t_{spread} << d_K^{max}$.

Also, from (7) and (16), since $K << n$, 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

$$f_{D_K}(d_K) = \frac{\mathrm{d}F_{D_K}}{\mathrm{d}d_K} \approx \begin{cases} K\lambda e^{-\lambda d_K} & \text{for } 0 \le d_K \le d_K^{max} \\ 0 & \text{otherwise.} \end{cases} \tag{17}$$

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

$$E[D_K] = \int_0^\infty d_K f_{D_K}(d_K)\mathrm{d}d_K \approx \frac{1}{\lambda}\left[1 - log\left(\frac{K}{K-1}\right)^{K-1}\right], \tag{18}$$

and the delay variance is

$$Var[D_K] \approx \frac{1}{\lambda^2}\left\{1 - K(K-1)\left[log\left(\frac{K}{K-1}\right)\right]^2\right\}. \tag{19}$$

Since $K << n$, 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. 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= $\frac{0.307}{\lambda}$). We also observe that the mean and variance values decrease when K increases.

C. Relationship between Delays

We showed that the throughput of our multi-copy scheme is the same order as the one-copy scheme [1]. 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.,

$$\begin{aligned} &P\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \le r_o | s = d_K]\right\} \\ &\qquad \approx P\{|X_1(s) - X_{dest}(s)| \le r_o | s = d\}, \end{aligned} \tag{20}$$

and so their ensemble averages are

$$\begin{aligned} &E_U\left[P\left\{\bigcup_{i=1}^{K}[|X_i(s) - X_{dest}(s)| \le r_o | s = d_K]\right\}\right] \\ &\qquad \approx E_U\left[P\{|X_1(s) - X_{dest}(s)| \le r_o | s = d\}\right], \end{aligned} \tag{21}$$

whose solution must be obtained by substituting (5) (for $s = d_K$ and $s = d$ respectively) on both sides of (21) 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 (11) and (15) in (21) and solving for d_K we have

$$d_K \approx \frac{1}{\lambda} log\left(\frac{K}{K-1+e^{-\lambda d}}\right). \tag{22}$$

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

$$d_K^{max} \approx \lim_{d\to\infty} \frac{1}{\lambda} log\left(\frac{K}{K-1+e^{-\lambda d}}\right) = \frac{1}{\lambda} log\left(\frac{K}{K-1}\right) \overset{\text{if } K>1}{=} cte. \tag{23}$$

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 (16). 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. 3 shows curves for (22), 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.*

D. Simulation Results

To validate our theoretical analysis and approximations, we performed some simulations using the *BonnMotion* simulator [8], which creates mobility scenarios that can be used to study mobile ad hoc network characteristics.

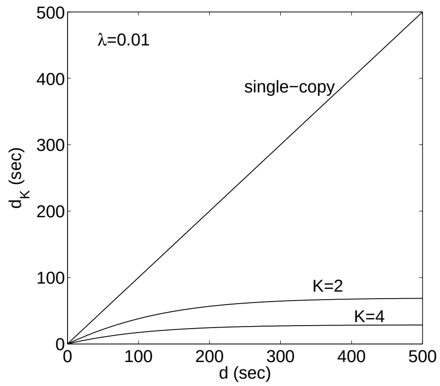

Fig. 3. Relationship between delays d_K and d for single-copy, $K = 2$, and $K = 4$, for a uniform distribution resulting from the random motion of the nodes for the network in steady-state.

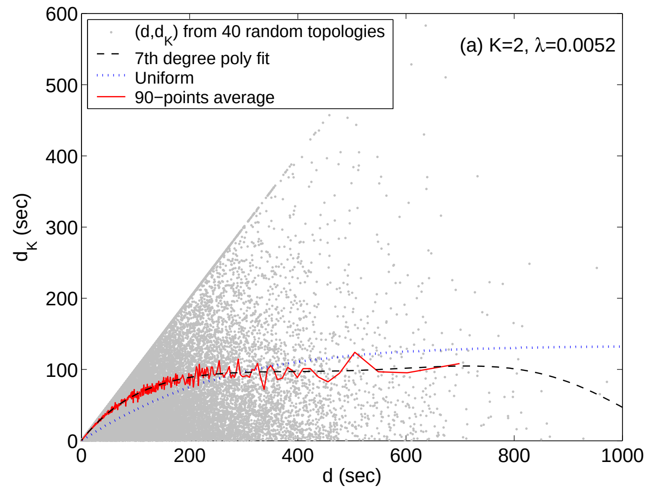

Fig. 4. Simulation results for the *random waypoint mobility model*. Each grey point is a pair (d, d_K) delay measured for 40 random topologies all plotted together. A 7^{th} degree polynomial fit for all the points and a 90 consecutive points average are plotted for $K = 2$. The theoretical curve for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

In our simulations we implemented the simplified version of the *random waypoint mobility model* [9] for the random motion of the nodes, where no pause was used and $v_{min} = v_{max} = v$ (as it resembles the *uniform mobility model* [3]). Fig. 4 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 $K = 2$ neighbors, 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. Fig. 4 shows all pairs of points (d, d_K) obtained in this way for $K = 2$. In addition, 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 (22)) 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.

VI. Conclusions

We have analyzed delay issues for two packet forwarding strategies, namely, the one-copy two-phase scheme advocated by Grossglauser and Tse [1], and a multi-copy two-phase technique. We found that in both schemes the average delay and variance scale like $\Theta(n)$ and $\Theta(n^2)$ for n total users in a mobile wireless ad hoc network. In the case of multi-copies transmission the *multiuser diversity* strategy 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. We assumed that packets are endowed with header information containing packet number and time-to-live threshold fields. The handshake phase with the destination lasts a negligible amount of time and prevents the multiple delivery of the same packet. The 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, while a bounded delay can be guaranteed for finite n.

Acknowledgment

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