End-to-End Delay in Mobile Ad Hoc Networks with Generalized Transmission Range and Limited Packet Redundancy

---

Citation:

Jiajia Liu, Xiaohong jiang, Hiroki Nishiyama, Nei Kato, and Xuemin (Sherman) Shen, "End-to-End Delay in Mobile Ad Hoc Networks with Generalized Transmission Range and Limited Packet Redundancy," IEEE Wireless Communications and Networking Conference (WCNC 2012), Paris, France, pp. 1731-1736, Apr. 2012.

URL:

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6214063

End-to-End Delay in Mobile Ad Hoc Networks with Generalized Transmission Range and Limited Packet Redundancy

Jiajia Liu*§, Xiaohong Jiang†, Hiroki Nishiyama*, Nei Kato* and Xuemin (Sherman) Shen‡
*Graduate School of Information Sciences, Tohoku University, Japan
†School of Systems Information Science, Future University Hakodate, Japan
‡Department of Electrical and Computer Engineering, University of Waterloo, Canada
§Email: liu-jia@it.ecei.tohoku.ac.jp

Abstract—**One of the challenging roadblocks stunting the development and commercialization of mobile ad hoc networks (MANETs), is the lack of a thorough understanding of the fundamental performance limits in MANETs. Distinguished from available works which mainly focused on deriving order sense scaling laws of the delay performance in MANETs and usually assumed a localized transmission range, this paper examines the MANET packet delay from a much more detailed perspective. Specifically, we assume for each node a general transmission power control such that the transmission range can be flexibly adapted and adopt a generalized two-hop relay with limited packet redundancy for packet routing. For a tagged traffic flow in the MANET, we first develop a theoretical framework based on two correlated FIFO queues to fully characterize the complicated packet delivery process. Then for any feasible traffic input rate there, we derive closed-form expressions for the corresponding expected end-to-end packet delay. Extensive simulations are further conducted to validate our theoretical results.**

I. Introduction

The mobile ad hoc network (MANET) is a kind of self-autonomous wireless network, which consists of pure mobile nodes communicating with each other via wireless links without any infrastructure support or centralized administration. As it is highly robust to single point of failure and can be rapidly deployed and reconfigured, the MANET has drawn a lot of interests from both the academia and industry with many promising applications, such as the daily information exchange, disaster relief, military troop communication, etc, and thus becomes an indispensable component among the next generation networks [1].

However, the lack of a thorough understanding of the fundamental performance limits in MANETs, such as the packet delay, throughput capacity, etc, remains a challenging roadblock stunting the wide applications of such networks. Such a basic understanding should provide insight to improve network design and performance optimization, and thus serve as an instruction guideline for the engineering of future MANETs, just like the Shannon capacity has done for the engineering of point-to-point and multiuser channels.

So far, extensive order sense scaling laws have been reported for the delay performance in MANETs under various mobility models, like the $\Theta(n \log n)$ delay under both the random walk model [2] and the restricted mobility model [3], the $O(n)$ delay under the independent and identically distributed (i.i.d.) mobility model [4], and the $\Theta(n^{1/2}/v(n))$ delay under the Brownian motion model where $v(n)$ is the node mobility velocity [5]. Later, Lin *et al.* [6] also considered the Brownian model and showed that the delay there is $\Omega(\log n/\sigma_n^2)$ where σ_n^2 is the variance parameter of the Brownian model. More recently, Sharma *et al.* [7] examined the packet delay in a $n^\beta \times n^\beta$ cell-partitioned network, and showed that the two-hop delay is $\Theta(n)$ for $0 \leq \beta < 1/2$ and $\Theta(n \log n)$ for $\beta = 1/2$ under a family of discrete random direction models, while the delay becomes $\Theta(n)$ for $\beta < 1/2$ and $\Theta(n \log n)$ for $\beta = 1/2$ when a family of hybrid random walk models are considered.

Although these order sense results are helpful for understanding the growth rate of delay performance in a MANET as the network size n tends towards a particular value or infinity, they tell little about the actual end-to-end packet delay there. It is also noticed that all the above delay results are derived under the classic two-hop relay [8] or its variants and assume for each node a localized transmission range, i.e., $r = \Theta(1/\sqrt{n})$. In this paper, we study the MANET packet delay from a much more detailed perspective. Specifically, each node adopts a general transmission power control such that the transmission range can be flexibly adapted and follows a generalized two-hop relay with limited packet redundancy for packet routing.

The main contributions of this paper are summarized as follows.

- We develop a theoretical framework based on two correlated FIFO queues to fully characterize the complicated packet delivery process of a tagged traffic flow in the challenging MANET.
- For any feasible traffic input rate, we derive closed-form expressions for the corresponding expected end-to-end packet delay under any given setting of transmission range and packet redundancy limit.
- Extensive simulations are conducted to validate the new theoretical framework, which indicates that our theoretical framework can efficiently capture the expected end-to-end packet delay behaviors in the considered MANET.

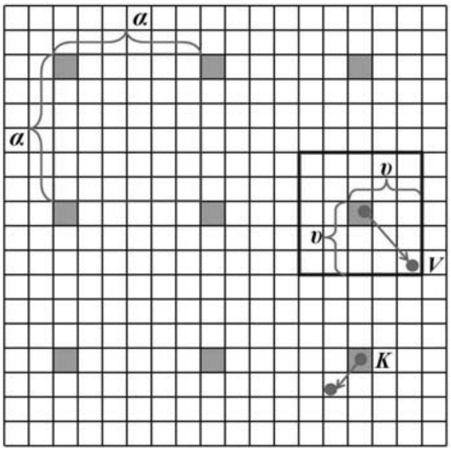


Fig. 1. Illustration of a transmission-group with $\alpha = 6$ where all the shaded cells belong to the same transmission-group. The distribution of all the remaining nodes in the unit torus is not shown for simplicity.

The remainder of this paper is outlined as follows. Section II introduces the system assumptions, a transmission-group based MAC scheme and the routing scheme adopted in this paper. In Section III, we develop a theoretical framework and derive closed-form expressions for the expected end-to-end packet delay. We provide numerical results and model validation in Section IV, and finally conclude the paper in Section V.

II. MAC Scheme And Routing Scheme

A. System Assumptions

Similar to [5], in this paper, we consider a time slotted system and assume the network as a two-dimensional unit torus with n nodes moving independently inside. The network is further evenly divided into $m \times m$ cells and nodes move among these cells according to the ideal i.i.d. mobility model [4]. At the beginning of each time slot, each node randomly and independently selects a destination cell from these m^2 cells and stays in it for a whole time slot. We consider a limited channel bandwidth scenario where the total number of bits that can be successfully transmitted during a time slot is limited and normalized to one packet here.

We consider the permutation traffic pattern widely adopted in previous studies [9], where each node has a locally generated traffic flow and we assume it is a Poisson stream with average rate λ (packets/slot). Similar to the [10], we consider a general node transmission range in this paper, where each node is assumed to employ a power level so as to cover a set of cells with horizontal and vertical distances of no more than $\upsilon - 1$ cells away from its current cell, $1 \le \upsilon \le \lfloor \frac{m+1}{2} \rfloor$. The protocol interference model with guarding factor Δ is adopted here to account for the interference among simultaneous transmissions [11].

B. A Transmission-group Based MAC Scheme

Similar to [12], we consider a transmission-group based MAC scheme.

Definition 1: A *transmission-group* is defined as a subset of cells, where any two of them have a vertical and horizontal distance of some multiple of α cells away and all the cells there could transmit simultaneously without interfering with each other.

In order to support as many simultaneous transmissions as possible, α should be set as small as possible. As shown in Fig. 1, suppose during some time slot node V is scheduled to receive a packet from some transmitting node, while the node K in another active cell of the same transmission-group is transmitting to other node. According to the interference mode [11], in order to ensure the successful reception at V, we only need to ensure that the transmission of K will not interfere with the reception at V.

Suppose V is at a relative distance of (x, y) cells away from its transmitter, where x and y denote the horizontal distance and vertical distance, respectively, $x, y \in [-\upsilon+1, \upsilon-1]$. Using a derivation similar to [13], the parameter α can be determined as

$$\alpha = \min\{\upsilon + \lceil \sqrt{2(\Delta+1)^2\upsilon^2 - (\upsilon-1)^2} \rceil, m\} \quad (1)$$

C. Routing Scheme

We consider a generalization of the classic two-hop routing scheme with f-cast (2HR-f) [4], $1 \le f \le n-2$, where each packet waiting at the source is replicated to at most f distinct relay nodes and should be received in sequence order at the destination. Without loss of generality, we focus on a tagged flow and denote its source and destination by node S and node D, respectively.

Under the 2HR-f routing scheme, each locally generated packet P is labeled with a *sequence number* $SN(P)$ by the source node S, and the destination node D also maintains a *request number* $RN(D)$ such that each packet is accepted in their sequence order. Every time a node is selected as the transmitter in an active cell, it will conduct the "source-to-destination" transmission if its destination node is inside the one-hop transmission range; otherwise, it will first randomly select a node from all its one-hop neighbors as the receiver, then conduct the "source-to-relay" transmission or "relay-to-destination" transmission with equal probability [14].

III. Expected End-to-end Packet Delay in MANETs

A. A General Theoretical Framework

Lemma 1: For a given time slot and a tagged flow, we denote by p_1 and p_2 the probability that node S conducts a source-to-destination transmission and the probability that node S conducts a source-to-relay or relay-to-destination transmission, respectively. Then we have

$$p_1 = \frac{1}{\alpha^2}\Big\{\frac{t - \frac{m^2}{n}}{n-1} - \Big(\frac{m^2-1}{m^2}\Big)^{n-1}\frac{(t-1)n+1-m^2}{n(n-1)}\Big\} \quad (2)$$

$$p_2 = \frac{1}{\alpha^2}\Big\{\frac{m^2-t}{n-1}\Big(1-\Big(\frac{m^2-1}{m^2}\Big)^{n-1}\Big) - \Big(\frac{m^2-t}{m^2}\Big)^{n-1}\Big\} \quad (3)$$

where $t = (2\upsilon-1)^2$.

Proof: The basic probability p_1 can be determined as

$$p_1 = \frac{1}{\alpha^2}\Bigg\{\sum_{j=0}^{n-2}\binom{n-2}{j}\Big(\frac{1}{m^2}\Big)^j\Big(\frac{m^2-1}{m^2}\Big)^{n-2-j}\frac{1}{(j+2)m^2} + \sum_{j=0}^{n-2}\binom{n-2}{j}\Big(\frac{1}{m^2}\Big)^j\Big(\frac{m^2-1}{m^2}\Big)^{n-2-j}\frac{4\upsilon^2-4\upsilon}{(j+1)m^2}\Bigg\} \quad (4)$$

Similarly, the basic probability p_2 can be determined as

$$p_2 = \frac{m^2-(2\upsilon-1)^2}{m^2\alpha^2}\Bigg\{\sum_{j=1}^{n-2}\binom{n-2}{j}\Big(\frac{1}{m^2}\Big)^j\Big(\frac{m^2-1}{m^2}\Big)^{n-2-j}\frac{1}{j+1} + \sum_{j=1}^{n-2}\binom{n-2}{j}\Big(\frac{4\upsilon^2-4\upsilon}{m^2}\Big)^j\Big(\frac{m^2-(2\upsilon-1)^2}{m^2}\Big)^{n-2-j}\Bigg\} \quad (5)$$

After applying some basic algebraic operations, (2) and (3) follow from (4) and (5), respectively. ■

Lemma 2: For a tagged flow, suppose that the source node S is delivering copies for some packet P in the current time slot, the destination node D is also requesting for the P, i.e., $SN(P) = RN(D)$, and there are already j $(1 \leq j \leq f+1)$ copies of P in the network (including the original one at the S). For the next time slot, we use $P_r(j)$ to denote the probability that node D will receive the P, use $P_d(j)$ to denote the probability that node S will successfully deliver out a copy of P to some new relay (if $j \leq f$). Then we have

$$P_r(j) = p_1 + \frac{j-1}{2(n-2)}p_2 \quad (6)$$

$$P_d(j) = \frac{n-j-1}{2(n-2)}p_2 \quad (7)$$

Proof: Given that there are already j copies of packet P inside the network, we know that the source node S has distributed $j-1$ replicas of the packet to $j-1$ distinct relay nodes. In the next time slot, the destination node D will either directly receive P from node S or receive P from some relay, say node R. Notice that the probability that node D receives the packet P from node S is p_1, and the probability that node D receives P from the relay node R is $\frac{p_2}{2(n-2)}$. Since R can be either one of the available $j-1$ relay nodes, and also notice that the events that node D receives the P from node S or other relay nodes are mutually exclusive and independent, by summing the probabilities of these j events up, the (6) follows.

Similarly, given that there are already $j-1$ relay nodes carrying the P, in the next time slot node S may deliver out a new copy of P to any one of the remaining $n-1-j$ nodes. Since that these $n-1-j$ events are also mutually exclusive and independent, and the probability that node S delivers out a copy to a single node is $\frac{p_2}{2(n-2)}$, the probability that node S will deliver out a new copy for P can then be determined as $\frac{n-1-j}{2(n-2)}p_2$. We complete the proof for the Lemma 2. ■

A general packet under the 2HR-f routing may experience the following two correlated FIFO queues, i.e., the local queue at the source node S and the virtual queue at the destination node D. As shown in Fig. 2, the local queue at the S stores the locally generated packets while the virtual queue at node D stores the sequence numbers of those packets not received yet by node D, and a new entry $SN(P)$ is put to the end of the virtual queue whenever a packet P is moved to the head-of-line of the local queue. In the local queue, every time S finishes the copy distribution for the head-of-line packet, S moves it out of the queue and moves ahead the remaining packets waiting behind it; while in the virtual queue, every time node D receives a packet whose sequence number equals to the head-of-line entry, i.e., $RN(D)$, node D moves the head-of-line entry out of the virtual queue and moves ahead the remaining entries.

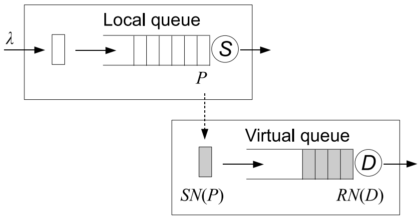
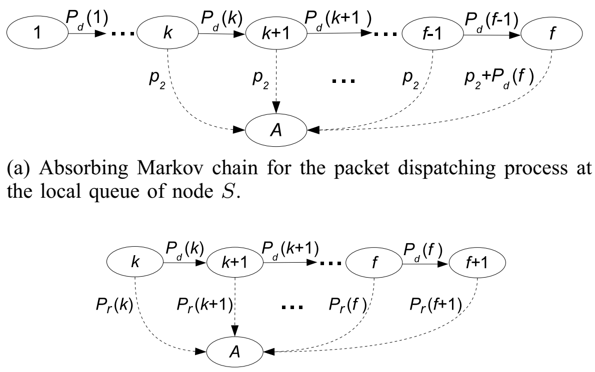


Fig. 2. Illustration of the local queue at the source S and the virtual queue at the destination D. Every time a local packet arrives at the S, it is put to the end of the local queue; every time a packet P is moved to the head-of-line of the local queue, the corresponding packet sequence number $SN(P)$ is put to the end of the virtual queue.



(a) Absorbing Markov chain for the packet dispatching process at the local queue of node S.

(b) Absorbing Markov chain for the packet receiving process at the virtual queue of node D.

Fig. 3. Absorbing Markov chains for a general packet P, given that the D starts to request for the P when there are already k copies of P in the network. For each transient state, the transition back to itself is not shown for simplicity.

Based on the definition of the two correlated FIFO queues, the delivery process of a general packet P can be defined by an automatic feedback control system [13]. Suppose that there are k copies of P in the network when the destination node D starts to request for the P, $1 \leq k \leq f+1$, then the packet dispatching process at the the local queue and the packet receiving process at the virtual queue can be defined by two finite-state absorbing Markov chains shown in Fig. 3a and Fig. 3b, respectively. After some derivations similar to that in [14], the following lemma follows.

Lemma 3: For packet P of the tagged flow, suppose that there are k copies of P in the network when the destination node D starts to request for the P, $1 \leq k \leq f+1$. If we use $X_S(k)$ and $X_D(k)$ to denote the corresponding service time of packet P at the S and the D, respectively, then we have

$$\mathbb{E}\{X_S(k)\} = \begin{cases} \sum_{i=1}^{k-1} \frac{1}{P_d(i)} + \frac{1}{p_1+P_d(k)} \\ \quad \cdot\left(1 + \sum_{j=1}^{f-k} \phi_1(k,j)\right) & \text{if } 1 \leq k \leq f, \\ \sum_{i=1}^{f} \frac{1}{P_d(i)} & \text{if } k = f+1. \end{cases} \tag{8}$$

$$\mathbb{E}\{X_D(k)\} = \begin{cases} \frac{1}{p_1+p_2/2}\left(1 + \sum_{j=1}^{f-k} \phi_2(k,j)\right. \\ \quad \left. + \frac{P_d(f)}{P_r(f+1)}\phi_2(k, f-k)\right) & \text{if } 1 \leq k \leq f-1, \\ \frac{1}{p_1+p_2/2}\left(1 + \frac{P_d(f)}{P_r(f+1)}\right) & \text{if } k = f, \\ \frac{1}{P_r(f+1)} & \text{if } k = f+1. \end{cases} \tag{9}$$

where

$$\phi_1(k,j) = \prod_{t=1}^{j} \frac{P_d(k+t-1)}{p_1 + P_d(k+t)}$$

and

$$\phi_2(k,j) = \prod_{t=1}^{j} \frac{P_d(k+t-1)}{p_1 + p_2/2}$$

B. Expected End-to-End Packet Delay Analysis

With the above theoretical framework, we present here an analytical study of the expected end-to-end delay in MANET with the general transmission range control (by υ) and packet redundancy control (by f). We first introduce the following definition about the expected end-to-end delay.

Definition 2: The end-to-end delay of a packet is defined as the time it takes to reach the destination after it is locally generated at the source. The expected end-to-end packet delay is obtained by averaging over all packets of the n traffic flows in the long term, and without incurring any ambiguity, it is called the packet delay for brevity.

Notice that the end-to-end packet delay includes not only the packet delivery delay [5], but also the packet queuing delay at the source. If we denote by T_e the end-to-end packet delay, then we have the following theorem.

Theorem 1: For a cell partitioned mobile ad hoc network where nodes move according to the i.i.d. mobility model, each node could transmit to the cells which have a horizontal and vertical distance of no greater than $\upsilon - 1$ cells away from its current cell, $1 \leq \upsilon \leq \lfloor \frac{m+1}{2} \rfloor$, and it follows the 2HR-f scheme for packet routing, $1 \leq f \leq n-2$. If we denote by μ the per node (flow) throughput capacity (i.e., the network can stably support any input rate $\lambda < \mu$), then the expected end-to-end packet delay $\mathbb{E}\{T_e\}$ can be determined as follows:

1) if the throughput capacity μ is determined as $\mu = \frac{1}{\mathbb{E}\{X_S(1)\}}$ under the given parameters υ and f, then we have

$$\mathbb{E}\{T_e\} = \frac{\rho}{1-\rho}\mathbb{E}\{X_S(1)\} + \mathbb{E}\{X_D(1)\} \tag{10}$$

2) if the throughput capacity μ is determined as $\mu = \frac{1}{\mathbb{E}\{X_D(f+1)\}}$ and $\mathbb{E}\{X_S(f+1)\} \leq \mathbb{E}\{X_D(f+1)\}$ under any given parameters υ and f, then we have

$$\mathbb{E}\{T_e\} = \frac{\mathbb{E}\{X_D(f+1)\}}{1-\rho} \tag{11}$$

where ρ is the system load and $\rho = \lambda/\mu$.

Proof: According to the Theorem 1 in [13], the throughput capacity μ of the considered MANETs can be determined as

$$\mu = \min\left\{\frac{1}{\mathbb{E}\{X_S(1)\}}, \frac{1}{\mathbb{E}\{X_D(f+1)\}}\right\} \tag{12}$$

Without loss of generality, we focus on a newly generated packet at node S, say packet P. We can see that the end-to-end delay of packet P, i.e., T_e, consists of the following three parts:

- the *queuing delay* at the local queue, i.e., the time elapsed between the time slot when P is locally generated at node S (i.e., when P is put to the end of the local queue) and the time slot when P is moved to the head-of-line of the local queue, we denote this part by $W_S(P)$;
- the *queuing delay* at the virtual queue, defined as the time elapsed between the time slot when the packet sequence number $SN(P)$ is put to the end of the virtual queue (i.e., when node S starts to deliver copies for the P) and the time slot when the entry $SN(P)$ is moved to the head-of-line of the virtual queue, we denote this part by $W_D(P)$;
- the *service time* at the destination node D, defined as the time elapsed between the time slot when D starts to request for the P (i.e., when the entry $SN(P)$ is moved to the head-of-line of the virtual queue) and the time slot when node D receives P, we denote this part by $X_D(P)$.

From the above discussion, obviously we have

$$\mathbb{E}\{T_e\} = \mathbb{E}\{W_S(P)\} + \mathbb{E}\{W_D(P)\} + \mathbb{E}\{X_D(P)\} \tag{13}$$

We first derive (10). According to (12), if the throughput capacity μ is determined as $\mu = \frac{1}{\mathbb{E}\{X_S(1)\}}$ under the given transmission range parameter υ and redundancy parameter f, we can see that on average, node D starts to request for each packet when there is only one copy of the packet in the network, i.e., node D is requesting for the packet P when node S starts to deliver copies for packet P. Thus, we have

$$\mathbb{E}\{W_D(P)\} = 0 \tag{14}$$

$$\mathbb{E}\{X_D(P)\} = \mathbb{E}\{X_D(1)\} \tag{15}$$

Since the service time of each packet at the local queue is mutually independent and has a mean value of $\mathbb{E}\{X_S(1)\}$, in order to simplify the analysis, we use M/M/1 FIFO queue to approximate the queuing process at the local queue. Thus, the $W_S(P)$ can be determined as

$$W_S(P) = \frac{\rho}{1-\rho}\mathbb{E}\{X_S(1)\} \tag{16}$$

where $\rho = \lambda/\mu$.

Substituting (14), (15) and (16) into (13), it follows (10).

Regarding the case that $\mu = \frac{1}{\mathbb{E}\{X_D(f+1)\}}$ and $\mathbb{E}\{X_S(f+1)\} \le \mathbb{E}\{X_D(f+1)\}$, according to the Lemma 5 in [14], we can see that nearly each packet is received at the D when there are $f+1$ copies of the packet in the network, and the copy distribution process is always faster than the packet reception process. Thus, we have

$$\mathbb{E}\{W_S(P)\} = 0 \quad (17)$$

$$\mathbb{E}\{X_D(P)\} = \mathbb{E}\{X_D(f+1)\} \quad (18)$$

Similar to the above, we treat the waiting process of the entry $SN(P)$ at the virtual queue as a M/M/1 FIFO queuing for simplicity. Then we have

$$\mathbb{E}\{W_D(P)\} = \frac{\rho}{1-\rho}\mathbb{E}\{X_D(f+1)\} \quad (19)$$

Substituting (17), (18) and (19) into (13), it follows the (11), which then finishes the proof. ■

IV. Numerical Results

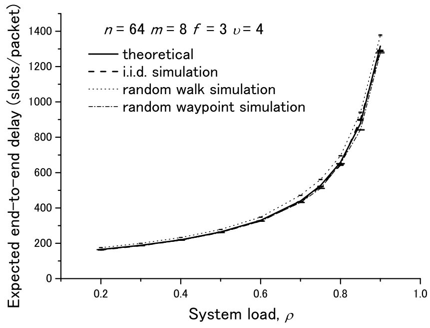
A. Simulation Setting

We developed a specific network simulator in C++ to simulate the packet delivery process in a 2HR-f MANET, which is now available at [15]. Similar to the settings in [16], the guard factor Δ here is fixed as $\Delta = 1$. Besides the i.i.d. mobility model, we also implemented the simulator for the popular random walk model and random waypoint model, which are defined as follows:

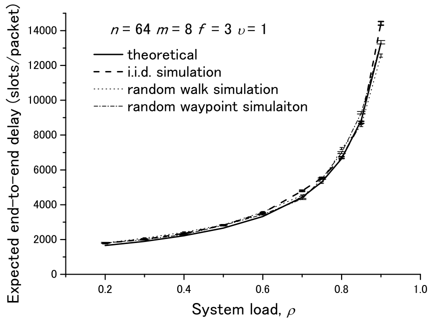
- **Random Walk Model [2]:** At the beginning of each time slot, each node either stays inside its current cell or moves to one of its eight adjacent cells. The decision regarding its mobility action is independently and randomly made by each node, and thus each moving action happens with the same probability $1/9$.
- **Random Waypoint Model [17]:** At the beginning of each time slot, a two-dimensional vector $\nu = [\nu_x, \nu_y]$ is independently and randomly generated by each node, where the values of ν_x and ν_y are uniformly drawn from $[1/m, 3/m]$. The node then moves a distance of ν_x and ν_y along the horizontal direction and the vertical direction, respectively.

B. Theoretical vs. Simulation Results

Extensive simulations have been conducted to verify the developed theoretical models regarding the expected end-to-end packet delay. The results of two network scenarios ($n = 64$, $m = 8$) and ($n = 256$, $m = 16$) are presented (the other scenarios can be easily obtained by our simulator as well [15]). For each network scenario, we examine two simulation settings of f and υ, i.e., ($f = 3$, $\upsilon = 4$) and ($f = 3$, $\upsilon = 1$) for network scenario ($n = 64$, $m = 8$), ($f = 6$, $\upsilon = 6$) and ($f = 6$, $\upsilon = 1$) for network scenario ($n = 256$, $m = 16$), where simulation settings of ($f = 3$, $\upsilon = 4$) and ($f = 6$, $\upsilon = 6$) and simulation settings of ($f = 3$, $\upsilon = 1$) and ($f = 6$, $\upsilon = 1$) correspond to the Case 1 and the Case 2 discussed in Theorem 1, respectively.



(a) Simulation setting ($f = 3$, $\upsilon = 4$) with per node throughput capacity $\mu = 7.60 \times 10^{-3}$ (packets/slot).



(b) Simulation setting ($f = 3$, $\upsilon = 1$) with per node throughput capacity $\mu = 7.53 \times 10^{-4}$ (packets/slot).

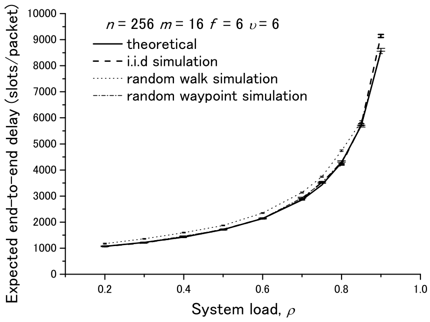
Fig. 4. Comparisons between the simulation results and the theoretical ones for the expected end-to-end packet delay under network scenario ($n = 64$, $m = 8$).

The comparisons between the simulated results and theoretical ones under the two network scenarios are summarized in Fig. 4 and Fig. 5, respectively. Notice that all the simulation results of the expected end-to-end packet delay are reported with the 95% confidence intervals.

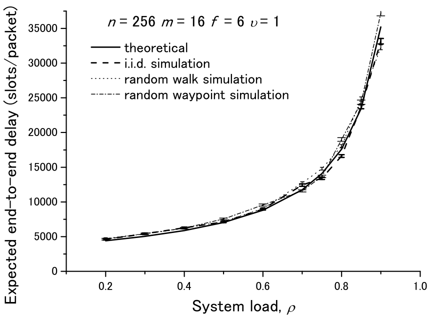
Figs. 4 and 5 show clearly that under both the network scenarios, our theoretical models can accurately characterize the packet delay performance of the considered 2HR-f MANETs. For the simulation settings of Case 1 (resp. Case 2) under the two network scenarios, the theoretical expected end-to-end packet delay in Fig. 4a and Fig. 5a (resp. Fig. 4b and Fig. 5b) matches nicely with the simulated ones there.

It is further observed from both Figs. 4 and 5 that, as the system load ρ increases up and approaches 1 (i.e., the traffic input rate λ approaches the throughput capacity μ), the packet delay there rises up sharply and becomes extremely sensitive to the variations of ρ. The skyrocketing behavior of packet delay when ρ approaches 1 serves as an intuitive validation for the throughput capacity μ.

It is interesting to notice that in Figs. 4 and 5 as ρ varies from 0.1 to 0.9, for both the two simulation settings there the simulated packet delays under the random walk model and the random waypoint model have very similar behaviors with that under the i.i.d. mobility model. This indicates that, although



(a) Simulation setting ($f = 6$, $\upsilon = 6$) with per node throughput capacity $\mu = 1.17 \times 10^{-3}$ (packets/slot).



(b) Simulation setting ($f = 6$, $\upsilon = 1$) with per node throughput capacity $\mu = 2.84 \times 10^{-4}$ (packets/slot).

Fig. 5. Comparisons between the simulation results and the theoretical ones for the expected end-to-end packet delay under network scenario ($n = 256$, $m = 16$).

our theoretical model is developed for the expected end-to-end delay under the i.i.d. model, it could also be used to nicely capture the varying tendencies of the end-to-end delay under the random walk and random waypoint models.

V. Conclusion and Future Work

In this paper, we have investigated the end-to-end delay of a mobile ad hoc network adopting general node transmission range control (by υ) and packet redundancy control (by f). In particular, after modeling the packet delivery process with two correlated FIFO queues, we derived closed-form expressions rather than order sense ones for the expected end-to-end delay under any feasible traffic input rate. Extensive simulations were conducted to verify the developed theoretical packet delay results. It's interesting to notice that, although our theoretical model was developed for the ideal i.i.d. mobility model, the theoretical delay results also matched nicely with that under the random walk and random waypoint models.

As indicated by our theoretical framework, the complicated packet delivery process in a 2HR-f MANET with power control can be defined by two correlated FIFO queues (with parameter k, $1 \leq k \leq f+1$), where the network can be stable with any value of k under the general settings of f and υ. The closed-form results regarding the expected end-to-end packet delay in this paper were derived for any feasible traffic input rate under two simple cases where the network will become stable at $k = 1$ and $k = f + 1$. Therefore, one of our future research directions is to extend our theoretical models to analyze the expected end-to-end packet delay under other settings of f and υ which make the network stable at $2 \leq k \leq f$.

Acknowledgment

Part of this work was supported through the A3 Foresight Program by the Japan Society for the Promotion of Science (JSPS), the National Natural Science Foundation of China (NSFC), and the National Research Foundation of Korea (NRF).

References

[1] J. Andrews, S. Shakkottai, R. Heath, N. Jindal, M. Haenggi, R. Berry, D. Guo, M. Neely, S. Weber, S. Jafar, and A. Yener, "Rethinking information theory for mobile ad hoc networks," *IEEE Communications Magazine*, vol. 46, no. 12, pp. 94–101, December 2008.

[2] A. E. Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Optimal throughput-delay scaling in wireless networks-part i: The fluid model," *IEEE Transactions on Information Theory*, vol. 52, no. 6, pp. 2568–2592, June 2006.

[3] J. Mammen and D. Shah, "Throughput and delay in random wireless networks with restricted mobility," *IEEE Transactions on Information Theory*, vol. 53, no. 3, pp. 1108–1116, 2007.

[4] M. J. Neely and E. Modiano, "Capacity and delay tradeoffs for ad-hoc mobile networks," *IEEE Transactions on Information Theory*, vol. 51, no. 6, pp. 1917–1936, June 2005.

[5] A. E. Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Throughput-delay trade-off in wireless networks," in *INFOCOM*, 2004.

[6] X. Lin, G. Sharma, R. R. Mazumdar, and N. B. Shroff, "Degenerate delay-capacity tradeoffs in ad-hoc networks with brownian mobility," *IEEE/ACM Transactions on Networking, Special Issue on Networking and Information Theory*, vol. 52, no. 6, pp. 2777–2784, June 2006.

[7] G. Sharma, R. Mazumdar, and N. B. Shroff, "Delay and capacity trade-offs for mobile ad hoc networks: A global perspective," *IEEE/ACM Transactions on Networking*, vol. 15, no. 5, pp. 981–992, October 2007.

[8] M. Grossglauser and D. N. Tse, "Mobility increases the capacity of ad hoc wireless networks," in *INFOCOM*, 2001.

[9] M. Garetto, P. Giaccone, and E. Leonardi, "Capacity scaling in ad hoc networks with heterogeneous mobile nodes: The subcritical regime," *IEEE/ACM Transactions on Networking*, vol. 17, no. 6, pp. 1888–1901, December 2009.

[10] P. Gupta and P. R. Kumar, "Critical power for asymptotic connectivity in wireless networks," Stochastic Analysis, Control, Optimization and Applications: A Volume in Honor of W.H. Fleming, W. M. McEneaney, G. Yin, and Q. Zhang, pp. 547–566, 1998.

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

[12] S. R. Kulkarni and P. Viswanath, "A deterministic approach to throughput scaling in wireless networks," *IEEE Transactions on Information Theory*, vol. 50, no. 6, pp. 1041–1049, June 2004.

[13] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, "Impact of power control on throughput and delay in mobile ad hoc networks," Graduate school of information sciences, Tohoku university, 2011, technical report 201107.01. [Online]. Available: http://distplat.blogspot.com

[14] ——, "Delay and capacity in ad hoc mobile networks with f-cast relay algorithms," *IEEE Transactions on Wireless Communications*, vol. 10, no. 8, pp. 2738–2751, August 2011.

[15] C++ simulator for the 2hr-f manet with power control. [Online]. Available: http://distplat.blogspot.com

[16] The network simulator ns-2. [Online]. Available: http://www.isi.edu/nsnam/ns/

[17] S. Zhou and L. Ying, "On delay constrained multicast capacity of large-scale mobile ad-hoc networks," in *INFOCOM*, 2010.