Science in China Series F: Information Sciences

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Packet delay analysis on IEEE 802.11 DCF under finite load traffic in multi-hop ad hoc networks

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In this paper, the average packet delay on IEEE 802.11 DCF under finite load traffic in multi-hop ad hoc networks is analyzed. We employ a Markov chain model to analyze the probability of transmission at each node in an arbitrary slot and derive the channel access delay. We model each node using an M/G/1 queue and derive the queueing delay. The model is extended from analyzing the single-hop average packet delay to evaluating the end-to-end packet delay in multi-hop ad hoc networks without assuming the traffic to be in a saturation state. To validate our analytic results, we have done extensive simulation. The analytic and the simulation results match very well.

IEEE 802.11 DCF, packet delay, multi-hop, finite load

1 Introduction

The IEEE 802.11 is the standard[1] to specify wireless local area networks (WLANs). Although it specifies two fundamental access mechanisms, distributed coordination function (DCF) and point coordination function (PCF), DCF is more widely accepted by the researchers, as well as by the telecommunication industries. Therefore, in this paper, we focus our analysis on the multi-hop end-to-end delay performance of the DCF mechanism.

There have been considerable amounts of work on the performance evaluation of IEEE 802.11 DCF through either simulation or mathematical modeling. The performance of the DCF protocol was studied by simulation in refs. [2, 3]. Some analytic models to study the performance of DCF scheme under the saturated or non-saturated traffic in single-hop or multi-hop ad hoc networks have been proposed. The proposals in refs. [4—6] studied the performance in terms of throughput

Received April 2, 2007; accepted June 12, 2007
doi: 10.1007/s11432-008-0008-2
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Supported by the National Natural Science Foundation of China (Grant Nos. 60472078 and 90604013)

and the models in refs. [7—9] studied the performance in terms of access delay and average packet delay in single-hop ad hoc networks under saturated load. Both the analytic model in ref. [10] on throughput and the delay analysis in refs. [11, 12] were set up under non-saturated traffic in single-hop scenarios. Models in refs. [13—15] investigated the throughput with non-saturated traffic in multi-hop ad hoc networks. However, there has been no solution to present the end-to-end delay under non-saturated traffic in a multi-hop scenario to the best of our knowledge.

In this paper, we evaluate the average packet delay in an IEEE 802.11 MAC under finite load traffic in multi-hop ad hoc networks. The packet delay can be classified into two categories: 1) medium access delay (D), which also includes the delay for data transmissions and retransmissions; 2) queueing delay (W), which is the delay at interface queue (IFQ). The medium access delay includes the total time from the time point a station begins to contend the channel for a transmission to the successful transmission of the data frame. Namely, the medium access delay is the total time needed to transmit a frame in the MAC layer. We employ a Markov chain model to analyze the probability of transmission at each node in an arbitrary slot and derive the wireless channel access delay. We model each node as an M/G/1 queue and derive the queueing delay at a node. Thus the average delay from the time a packet arrived at current node to the time it can be successfully received by the next hop node can be calculated. The model is extended from analyzing the single-hop average packet delay to evaluating the end-to-end packet delay in multi-hop ad hoc networks without assuming the traffic being in a saturation state. The major contribution of this paper is to analyze the average packet delay for IEEE 802.11 DCF by using an analytic model under finite load traffic in multi-hop ad hoc networks. To the best of our knowledge, it has never been presented before, especially for multi-hop ad hoc networks.

The paper is organized as follows. In section 2, we introduce and derive our Markov chain model for finite load sources. Then, we provide a detailed analysis of packet service time and queuing time in single-hop ad hoc networks in sections 3. Section 4 extends the analysis to the multi-hop ad hoc networks. The analytic results were compared with data derived from simulation in section 5. We conclude the paper in section 6.

2 Markov model for IEEE 802.11 DCF in finite load

We model the DCF scheme at MAC layer using an M/G/1 queue. We proposed a Markov chain model to describe the scheme in Figure 1, which evolves from the model presented in ref. [4]. We have included the NoPK state in which the node does not have any packet to transmit. Packets arrive at nodes according to a Poisson process with average rate λ packets/s. We assume that the wireless channel condition is ideal (error-free and no capture).

The model consists of an aggregation of states that a node can reside in. The points C_0, C_1, and C_2 in Figure 1 represent connection points, which are not states. The queue will be checked at point C_0 after each successful transmission or after having reached the maximum number of the retransmissions m. If there is a packet, the node enters into backoff state directly. Otherwise, the node enters into the post-backoff state (on the left part of the Markov chain in Figure 1). This is because after each successful transmission, the node must enter into a backoff even if there is no packet in the queue. If no packet arrives during the post-backoff, the node will enter the empty queue state (the probability is p_{nk}) and stay at this state until a new packet arrives. If a packet arrives at the node with an empty queue, the node senses the medium. If the medium is idle (no transmission), the node transits to state FirstPK and sends the packet immediately. On the other hand, if the medium is sensed busy, the node goes to point C_1 and then enters into backoff, and the packet will be transmitted after the backoff timer reaches 0. When a packet arrives, the medium is sensed idle with probability p_{idle} and it is sensed busy with probability p_{busy}. For a node, we use the tuple (i, k) to represent the different states in the backoff stages, with i being the backoff stage number $i = 0,1, \ldots m', \ldots, m$, and k being the value of the backoff timer in the range $[0, W_i-1]$. W_i is the size of the CW at stage i and is computed by $W_i=2^iW_0$, if $i\leqslant m'$. Otherwise, if $i\in[m', m]$, W_i is kept at its maximum value $W_{\max}=2^{m'}W_0$. With m, we denote the maximum number of packet retransmissions before the packet is dropped. According to ref. [1], the default value for m' is 5 and it is 7 for m. $b_{i,k}$ which is denotes the probability to be on the state (i, k). For the state Empty, we denote its state probability with b empty. q denotes the probability of having an empty queue. The probability of failure is denoted by p. We use b_{C_0} and b_{C_1} to denote the probability that the node arrives at point C_0 and C_1, respectively.

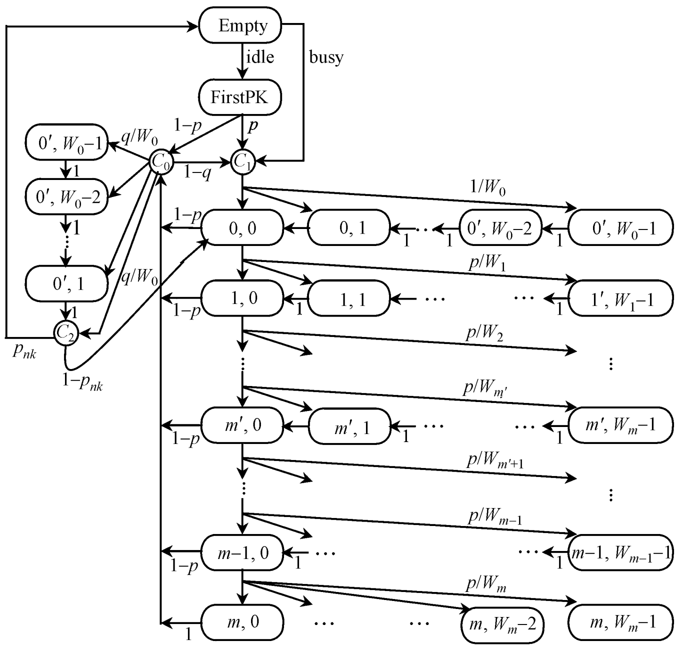

Figure 1 Finite Load Markov chain model.

In order to obtain the expression of the state steady probabilities of a node, in the first step, we need to express all state probabilities in terms of $b_{0,0}$. Then, we use the normalization condition to obtain $b_{0,0}$ itself. From the balance equation in the steady state, we can obtain the following relations:

$$b_{0',k} = \frac{W_0 - k}{W_0} q b_{C_0}, \tag{1}$$

$$b_{i,0} = p^i b_{0,0}, \tag{2}$$

$$b_{i,k} = \frac{W_i - k}{W_i} p^i b_{0,0}, \tag{3}$$

$$\tau = \sum_{i=0}^{m} b_{i,0} + b_{\text{empty}} p_{\text{idle}} (1 - e^{-\lambda\sigma}) = b_{0,0} \left(\frac{1 - p^{m+1}}{1 - p} \right) + b_{\text{empty}} (1 - \tau)^n (1 - e^{-\lambda\sigma}), \quad (4)$$

where τ denotes the probability that a node transmits in a randomly selected time slot, and p denotes the collision probability of a transmitted node. σ denotes the duration of one system time slot. It is known that a node can send a packet only at state (i, 0) or state FirstPK. The probability of state FirstPK equals the probability that during a slot σ, at least one packet arrives at the empty queue, and the medium is sensed idle. Therefore, the node transmits from state Empty to state FirstPK and sends the packet immediately. The probability b_{empty} to be in state Empty is equal to

$$b_{\text{empty}} = b_{C_0} q p_{nk,}, \quad (5)$$

where p_{nk} means that the probability of not receiving any packet during the time spent in the post-backoff stage is

$$p_{nk} = e^{-\lambda (W_0 + 1)\bar{\sigma}/2}, \quad (6)$$

where b_{C_0} can be obtained from

$$\begin{aligned} b_{C_0} &= \sum_{i=0}^{m-1} b_{i,0} (1 - p) + b_{m,0} + (1 - p) b_{\text{empty}} p_{\text{idle}} \\ &= (1 - p) b_{0,0} (p^0 + \cdots + p^{m-1}) + p^m b_{0,0} + (1 - p) b_{\text{empty}} p_{\text{idle}} \\ &= b_{0,0} + (1 - p) b_{\text{empty}} p_{\text{idle}}, \end{aligned} \quad (7)$$

$b_{0,0}$ is obtained by using the normalization condition:

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} + \sum_{k=1}^{W_0 + 1} b_{0',k} + b_{\text{empty}} (1 + p_{\text{idle}}). \quad (8)$$

3 Delay analysis of single-hop ad hoc networks

In this section, we analyze the average packet delay in single-hop ad hoc networks. In a single-hop ad hoc network, all the nodes can hear each other. In our model, we use an M/G/1 queue to analyze the queueing delay of the DCF scheme. Let q denote the probability of having no packet in the buffer. In an M/G/1 queue, q is simply equal to q=MAX (0,1–λD), where D is the average service time that a packet spends in the MAC layer (from the packet leaves the MAC buffer until it is successfully transmitted or reaches the retry limit). We consider two cases: one with an empty queue, the other with a nonempty queue. Therefore, D has to be conditioned on q and is equal to

$$D = (1-q)\, E(S_b) + qT_{\text{no}}, \quad (9)$$

where $E(S_b)$ and T_{no} denotes the average service time of a packet that at its arrival, it finds the queue being nonempty and empty, respectively.

For $E(S_b)$

$$E(S_b) = \bar{\sigma} \sum_{s=0}^{m} p^s \frac{W_s - 1}{2} + T_s \sum_{s=0}^{m} p^s (1 - p) + T_c \left(\sum_{s=1}^{m} p^s (1 - p) s + (m + 1) p^{m+1} \right), \quad (10)$$

where T_s is the time for a successful transmission, and T_c is the average time the channel is sensed busy by each station during a collision. Let H = PHY_{hdr} + MAC_{hdr} be the packet header, and δ be the propagation delay. T_s and T_c equal to

$$T_s = DIFS + RTS + CTS + H + E[P] + ACK + 3SIFS + 4\delta,$$
$$T_c = DIFS + RTS + CTS + SIFS + \delta, \tag{11}$$

where $E[P]$ is the average packet length.

The first term in eq. (10) accounts for the total time needed to attain a transmission state, which is called (i, 0) in Figure 1. The second term is the expected value of the time needed to actually accomplish the physical transmission and the receipt of the ACK. The third term accounts for the expected time of collisions.

The collision probability p in single-hop ad hoc networks is equal to the probability that at least one of the other $n-1$ nodes transmits a packet. Therefore, p can be written as follows:

$$p = 1 - (1-\tau)^{n-1}. \tag{12}$$

The probability that at least one node transmits is

$$p_{\mathrm{tr}(n)} = 1 - (1-\tau)^n. \tag{13}$$

The probability that the transmitted packet is successful is

$$p_{\mathrm{s}(n)} = \frac{n\tau(1-\tau)^{n-1}}{p_{\mathrm{tr}(n)}}. \tag{14}$$

$\bar{\sigma}$ is the average time between successive counter decrements

$$\begin{aligned}\bar{\sigma} &= (1 - p_{\mathrm{tr}(n-1)})\sigma + p_{\mathrm{tr}(n-1)} p_{\mathrm{s}(n-1)} (T_s + \sigma) + p_{\mathrm{tr}(n-1)} (1 - p_{\mathrm{s}(n-1)})(T_c + \sigma) \\ &= (1-\tau)^{n-1}\sigma + (n-1)\tau(1-\tau)^{n-1}(T_s + \sigma) + \left[1 - (1-\tau)^{n-1} - (n-1)\tau(1-\tau)^{n-1}\right](T_c + \sigma).\end{aligned} \tag{15}$$

Now we can obtain

$$E(S_b) = \frac{\bar{\sigma}W(1-(2p)^{m+1})}{2(1-2p)} - \frac{\bar{\sigma}(1-p^{m+1})}{2(1-p)} + T_s(1-p^{m+1}) + T_c p \frac{1-p^{m+1}}{1-p}. \tag{16}$$

The average service time of a packet when it arrives an empty queue can be found

$$T_{\mathrm{no}} = (1-\tau)^n\, t_{\mathrm{idle}} + [1-(1-\tau)^n]\, t_{\mathrm{busy}}. \tag{17}$$

When a packet arrives in an empty queue, two cases exist. One is that the packet arrives when the channel is idle; while another is that the channel is busy.

$$t_{\mathrm{idle}} = p[T_c + E(S_b)] + (1-p)T_s, \tag{18}$$

$$t_{\mathrm{busy}} = E(S_b). \tag{19}$$

Finally, combining eqs. (16) and (17), the expression of average service time of packet can be obtained.

Under M/G/1 assumption, an accurate analysis of the average packet delay requires the knowledge of the second moment of the service time of packets at the MAC layer. Note that this quantity is not easy to obtain, we use a simple analysis to obtain the expected queueing delay W in the M/G/1 buffer. We assume that the average access delay of packets equals to the sum of an exponential random variable with expected value $1/\mu$ and T_s. Let X denote the access delay of packets, thus $E[X]=T_s+1/\mu=D$, and $D[X]=1/\mu^2$. We can obtain μ and the second moment of the average access delay of packets is

$$E[X^2] = D[X] + (E[X])^2 = 1/\mu^2 + D^2 = (D-T_s)^2 + D^2,$$

where $E[X]$ and $D[X]$ are the mean and the variance of X, respectively. D is given in formula (9).

We now have the second moment of X and use it in the Pollaczek-Khinchin formula[16] to obtain the expected queueing delay (W) in the M/G/1 buffer

$$W = \frac{\lambda E[X^2]}{2(1-\rho)} = \frac{\lambda[(D-T_s)^2 + D^2]}{2(1-\rho)}, \quad (20)$$

where $\rho = \lambda D$. The average packet delay for our system is then the sum of average access delay D and the obtained queueing delay W,

$$E[\text{end-to-end delay}] = D + W.$$

4 Delay analysis of multi-hop ad hoc networks

A single-hop ad hoc network is a fully connected network, in which there is no hidden terminal problem. While in multi-hop ad hoc networks, the presence of hidden terminals substantially degrades the performance of the protocol. The IEEE 802.11 standard provides a four-way handshaking technique to solve this problem. We generalize the analysis one-hop by one-hop in the same method as used in single-hop scenario to analyze the performance of multi-hop ad hoc networks with considering hidden terminal problem.

Figure 2 gives a hidden area (H_A) of node S. We assume that the transmission range is R and n nodes are randomly placed within the range. We will calculate the number of hidden terminals of node S, which is denoted by H_n. If each neighbor of node S has the same probability to be selected as a receiver of S, the average distance d between node S and the reciver is given by $d = \frac{2}{3}R$. According to eq. (17), H_A can be computed by

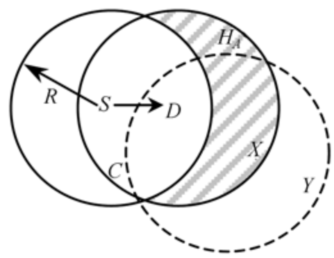

Figure 2 Hidden area of node S.

$$H_A = \pi R^2 - 2R^2\left(\arccos\left(\frac{d}{2R}\right) - \frac{d}{2R}\sqrt{1-\left(\frac{d}{2R}\right)^2}\right). \quad (21)$$

Then we can obtain the number of hidden terminals of node S

$$H_n = \frac{H_A}{\pi R^2} n \approx 0.4164n. \quad (22)$$

Because of the hidden nodes, the collision probability p in multi-hop ad hoc networks is much higher than that in single-hop ad hoc networks. When node S initiates communication by transmitting an RTS in a given time slot, the transmission will be successful if and only if all of the following events happen in the same slot. Firstly, no RTS is transmitted by any node in the transmission areas of node S and D. Secondly, no CTS is transmitted by any node which located in the transmission area of node D. For the first event, if a hidden node X transmits an RTS, it will collide with the RTS from node S at the node D. For the same reason, a CTS transmitted by a node in the transmission area of D will definitely effect node D's reception of the RTS from node S. The probabilities of both events can be analyzed as follows.

Let p_1 denote the probability of the first event. There are average H_n nodes in the hidden area, thus

$$p_1 = (1-\tau)^{n-1} + H_n. \quad (23)$$

Let p_2 denote the probability of the second event. The probability of node X transmitting a CTS equals the probability of successfully receiving an RTS, and the destination of the RTS is just node *X*. The probability of successfully receiving an RTS is $\tau(1-p)$. Since the destination node is selected from the neighbors with equal probability, the probability of node *X* is selected as the destination is $1/n$. Because of the first condition, an RTS received by *X* must be transmitted by a *D*'s hidden node, *Y*, for example. There are H_n nodes in this area. Thus, p_2 can be written as follows:

$$p_2 = \left(1 - \frac{H_n}{n}\tau(1-p)\right)^{n-1}. \tag{24}$$

Using eqs. (22) and (23), the probability of failure, p, can be expressed as

$$p = 1 - p_1 p_2. \tag{25}$$

After p was founded, we obtain average packet delay for 1-hop in multi-hop ad hoc networks with the same method as used in single-hop analysis. If the average number of hops counted per packet is n_p, and the average delay per hop is $E(T)$, the average end-to-end delay will be $n_p*E(T)$. We should note that if the number of packet transmissions, on average, at each hop is 2, the actual load of every node will be doubled of the input load from the outside. Therefore, we can calculate the average delay per hop $E(T)$ using $n_p\lambda$ as equivalent arrival rate.

5 Performance evaluation

To verify our analytic results, we compared our analytic results with simulation results obtained from the Qualnet simulator[18]. We validate our delay analysis with two scenarios: single-hop and multi-hop ad hoc networks.

All the parameters used in our analytic model and simulation follow the parameters in ref. [4] for DSSS. RTS/CTS mode of 802.11 DCF is used as the MAC layer protocol. The minimum backoff window size is 32 and maximum window size is 32×2^5. The transmission rates are equal for all transmitters. The buffer size of each node is set to 50 packets in the simulations. The number of the queueing packets is not more than 50 in the simulation. Thus, the buffer space can be regarded as infinite.

In the single-hop scenario, we studied the case of 10 and 20 active nodes. The packet arrival rate was increased so than the system load reached saturation gradually. Figure 3 compares the medium access delay for the analytic results and the simulation results under different system load in the case of 10 and 20 active nodes. We can see that the medium access delay increases when the system load increases. When the system load is large enough (i.e., the system load reached saturation), however, the medium access delay will not increase. This is mainly due to the reason that packets arrive so fast that the system cannot consume them. The increased number of active nodes causes the increase of collision probability, and thus the medium access delay become longer. Figure 4 compares the simulation and analytic results on the average delays for the 10 and 20 node cases. It can be seen when the channel utilization factor gradually increases to 1, the average delay approaches infinity. This is because when the system load is high, the queue becomes very long, and the queueing delay trends to infinite.

Figure 5 illustrates the relationship of maximum access delay and the network size. It can be seen that the maximum access delay increases with the number of the node in the network. This is because the collision probability will increase due to the increased network size.

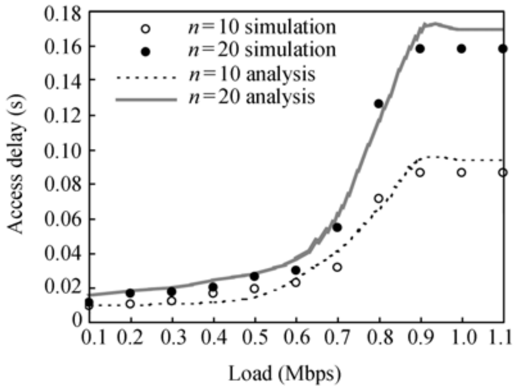

Figure 3 Access delay in single-hop scenario.

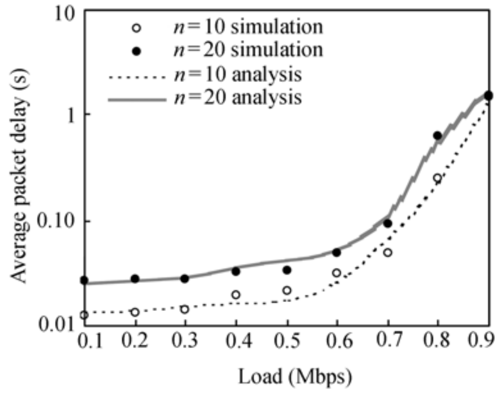

Figure 4 Average packet delay in single-hop scenario.

In order to validate our delay analysis for a multi-hop network with different load, a 120-node network was considered, in which the nodes were placed randomly in a square service area of 1500 m × 1500 m. All nodes transmission radius was 250 m. Each node acted both as transmitter and receiver. Thus, the average number of active node in the transmission range was about 10. We also assume that the network is relatively stable during the transmission of data packet or control message. Routes had been determined.

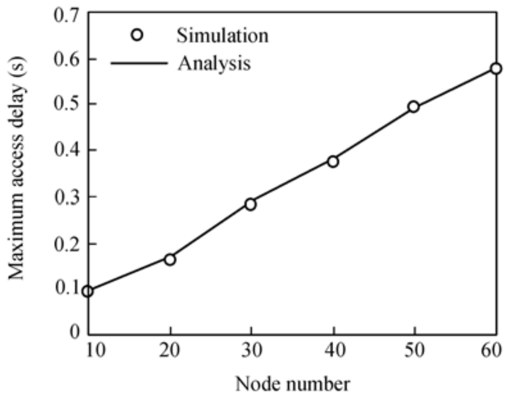

Figure 5 Maximum access delay vs. node number.

Figure 6 shows the 1-hop and 2-hop access delay in multi-hop scenario, respectively. We can see that the access delay reached the maximum delay rapidly in 2-hop case. This is mainly due to the reason that in 2-hop case, the load of the medium was increased. Therefore, the collision probability and the access delay were increased. Figure 7 gives the average end-to-end packet delay in the multi-hop scenario. The packet delay increased more rapidly with the increase of packet arrival rate in 3-hop case than in 1-hop case. This is because the more hops in the

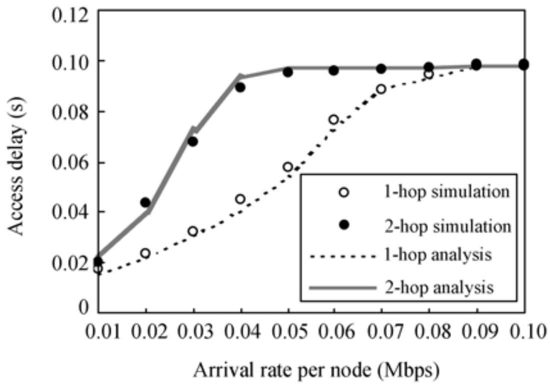

Figure 6 Access delay in multi-hop scenario.

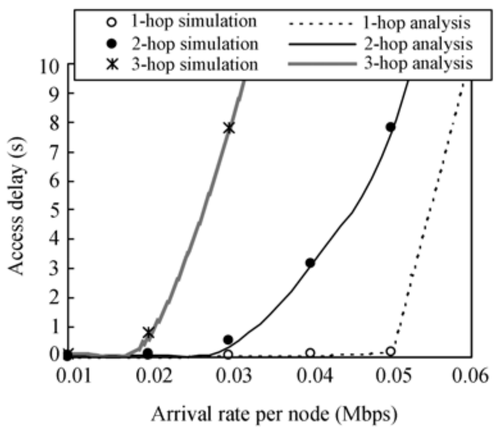

Figure 7 Packet delay in multi-hop scenario.

transmission, the more load in the system. Thus, the access delay and the queueing delay are all increased, and the packet delay increased rapidly.

6 Summary and conclusion

In this paper, a Markov chain model is employed to analyze the channel access delay. We have modeled each node by using an M/G/1 queue and have derived the queueing delay. The model has also been extended from analyzing the single-hop average packet delay to evaluating the end-to-end packet delay in multi-hop ad hoc networks under different traffic loads. To our knowledge, our solution is the first analysis on the end-to-end packet delay of the multi-hop ad hoc networks with finite load. Simulations have been conducted to verify the analytical results. Moreover, the simulation results have been matched quite well by the analytical results. In the future, we will do more simulations to validate the analytic results in different scenarios, and other traffic models will be considered.

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