Analysis of One-Hop Packet Delay in MANETs over IEEE 802.11 DCF*

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Abstract. In mobile *ad hoc* networks (MANETs), the estimation of packet end-to-end delay depends on that of one-hop packet delay. In this paper, we conduct an analysis of the one-hop packet delay in MANETs, where the medium access control (MAC) layer uses the IEEE 802.11 distributed coordination function (DCF) to share the medium. In the MANET, each node runs the IEEE 802.11 DCF and a routing protocol. It is assumed that all nodes are one-hop neighbors, and that any pair of nodes can send data over the wireless channel with a fixed data rate. The light traffic condition is used, i.e., each node generates packets at the network layer according to a Poisson process. By modeling each wireless node as an M/M/1 queueing system, we derive the mean one-hop packet delay analytically under the light traffic condition. Simulation analysis is carried out to verify the derived results. Results show that the mean one-hop packet delay increases with either the network size or the packet generation rate in networks subject to the light traffic condition. The mean one-hop packet delay derived in this paper is analytical and exact for networks under the light traffic condition. Results that can be found in the literature are usually based on the heavy traffic condition, and they tend to overestimate by a large amount the mean one-hop delay for networks with light traffic.

Keywords: Mobile *ad hoc* networks (MANETs), medium access control (MAC), IEEE 802.11, distributed coordination function (DCF), modeling and analysis, $M/M/1$ queue, packet sojourn time, one-hop delay.

1 Introduction

A mobile *ad hoc* network (MANET) consists of a collection of wireless mobile nodes that are dynamically connected. The mobile nodes can communicate with each other without the assistance of any pre-existing or centralized infrastructure. Because MANETs can be deployed rapidly and operated with no single point of failure in a whole network, the MANET technology plays a crucial role in military networks.

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An envisaged military application of a mobile network is a team of cooperative unmanned aerial vehicles, or UAVs, carrying out intelligence, surveillance, and reconnaissance (ISR). Cooperative control entails planning, coordination, and execution of a mission by two or more UAVs. Ideally, humans issue high-level commands to the robot team, such as searching an area for a certain amount of time. The team then responds to such orders, in the most efficient way. To act as an effective team, the UAVs will possess a certain level of autonomy in the execution of the mission enabled by their onboard systems and the sharing of information. The information passed from one UAV to another may pertain to vehicle state (position, velocity), vehicle and systems operational status (for example, current condition and quantity of energy), flight mode (for example, cruising or maneuvering), and mission-specific data (such as sensor information passed on to the commander). The probability of delays and packet loss increases with the amount of information communicated from one UAV to another. Co-operative control systems can usually tolerate relatively small delays. However, if the delays are too long, a team of UAVs may be destabilized, and safety of nearby humans is at risk. Therefore, it is of high importance to mitigate the effect of the delays on the multi-UAV cooperative control systems.

In military network applications, information delay (or packet delay) is an important design issue, since it has a significant impact on the performance of a system of systems (*e.g.*, networked control systems) that are connected with MANETs [8]. In MANETs, since nodes usually communicate over a same wireless channel, a medium access control (MAC) protocol is required to regulate the access of multiple nodes to the shared medium during packet transmission. The distributed coordination function (DCF), a MAC protocol in the IEEE 802.11 standard, has been widely used in MANETs [14]. It is a random access scheme based on a distributed channel access scheme denoted by carrier sense multiple access with collision avoidance (CSMA/CA) [1]. In DCF, a node having data to transmit contends for the shared medium using CSMA/CA. In addition, the request-to-send/clear-to-send (RTS/CTS) handshaking mechanism is used to tackle the hidden terminal problem, which can occur in all types of wireless networks, including MANETs [9].

In a delay-guaranteed MANET application, packet end-to-end delay is one of the most important metrics. It follows that accurately estimating packet end-to-end delay becomes an essential but challenging part of network analysis. Since packets often traverse multiple hops before reaching their destinations in MANETs, the end-to-end delay of a packet accumulates the amount of time consumed on each hop that the packet passes through. As a result, precisely estimating packet end-to-end delay is directly related to how accurately the one-hop packet delay is computed or approximated.

In this paper, we conduct an analysis of one-hop packet delay in an *ad hoc* network with IEEE 802.11 DCF being the underlying MAC protocol. This is the first phase of our study on the packet delay in DCF-based MANETs. More specifically, we consider a fixed number of wireless nodes, and each node runs the IEEE 802.11 DCF and a routing protocol (*e.g.*, the optimized link state routing

(OLSR) protocol [5]). It is assumed that all nodes are one-hop neighbors, and a pair of nodes can communicate data over the wireless channel with a fixed data rate. In addition, it is assumed that each wireless node generates packets (referred to as IP (internet protocol) packets in this paper) at the network layer according to a Poisson process. The generated packets are sent down to the MAC layer for transmission to the shared medium. In this paper, the Poisson process assumption for traffic is referred to as the light traffic condition. We define one-hop delay of an IP packet as the duration between the time of creation of the IP packet at a node and the time of its reception at a neighbor node.

In the literature, several studies on packet service time at the MAC layer have been reported when IEEE 802.11 DCF was assumed. In [2], an analytic and accurate model was developed to compute the throughput of IEEE 802.11 DCF. Based on the original or a modified version of the analytic model, the mean packet service time at the MAC layer was analyzed in [4], [6], [7], [13], [16]. All these studies were conducted under the heavy traffic condition, *i.e.*, packets are always available for transmission at each node. In [15], the packet service time at the MAC layer was analyzed under a non-heavy traffic condition for IEEE 802.11 DCF. It was claimed that the packet service time at the MAC layer can be better approximated by an exponentially distributed random variable. However, due to the complexity involved in computing the mean packet service time, the numerical analysis was only performed for certain values of the packet collision probability. The packet collision probability is expressed as a function of the mean packet service time together with other parameters. In [11], the mean one-hop packet delay was derived analytically for IEEE 802.11 DCF-based *ad hoc* networks under the light traffic condition. However, the expression for the mean packet service time at the MAC layer assumed a heavy traffic condition.

This paper focuses on providing an expression for the mean one-hop packet delay under the light traffic condition. It also provides an expression for the mean packet service time at the MAC layer under the same condition. In doing so, we consider each node to be an $M/M/1$ queueing system, in which the packet sojourn time corresponds to the one-hop packet delay. The packet sojourn time is the sum of the packet service time at the MAC and the network layer. Although a standard result of the queuing theory can apply to the mean packet sojourn time (*i.e.*, the mean one-hop packet delay), it requires the knowledge of the packet service time at the MAC layer. To calculate the mean packet service time at the MAC layer, we derive a non-linear system of equations, from which it can be numerically computed. Simulation analysis is carried out to verify the analytic result for the mean one-hop packet delay. Numerical and simulation results show that an estimate of the mean one-hop packet delay developed in [4] under the heavy traffic condition overestimates by a large amount the mean one-hop delay for networks with light traffic.

The rest of the paper is organized as follows: Section 2 describes *ad hoc* networks operating using IEEE 802.11 DCF as the MAC layer protocol. In Section 3, a systematic method is developed to estimate the mean one-hop packet delay. Numerical and simulation examples are presented to verify the resulting mean one-hop delay expression in Section 4. Finally, concluding remarks are given in Section 5.

2 MANETs over IEEE 802.11 DCF

Assume that N wireless nodes are distributed in an area. Each node runs the IEEE 802.11 DCF and a MANET routing protocol (*e.g.*, OLSR or the dynamic source routing (DSR) protocol [10]). It is assumed that IP packets, which could be either data or routing protocol control messages, are generated in each node according to a Poisson process with a rate of λ_d packets per second. In this study, we assume that all IP packets have the same length. Any two wireless nodes are one-hop neighbors and they can communicate with each other over a shared wireless channel with a same data rate. The wireless channel is assumed to be error-free for transmitting data, and thus errors are only caused by collisions due to simultaneous packet transmission to the shared medium. A node having an IP packet to transmit accesses the wireless channel based on the IEEE 802.11 DCF with the RTS/CTS mechanism. The parameters in the IEEE 802.11 DCF are defined below. The reader is referred to [15] for a demonstration of the transmission process and to [1] for details of the protocol.

- σ is the slot time size that equals the time needed by a node to detect transmission of a packet from any other node;
- T_{rts} is the time to transmit a RTS packet (including the physical layer header);
- T_{cts} is the time to transmit a CTS packet (including the physical layer header);
- T_{ack} is the time to transmit an acknowledgement (including the physical layer header);
- T_h is the time to transmit the header (including the MAC and the physical layer header) of an IP packet;
- T_d is the time to transmit an IP packet (either a data or a control packet);
- $SIFS$ represents the short inter-frame space;
- $DIFS$ represents the distributed inter-frame space;
- CW_{min} is the size of the initial contention window;
- CW_{max} is the size of the maximum contention window;
- R represents the retry limit of transmitting MAC frames, including RTS, CTS, and acknowledgement packets.

We define the one-hop delay of an IP packet as the time interval between the instant the packet is generated at the node and the instant it is received at a destined neighbor node.

3 Analysis of One-Hop Packet Delay

In this section, a non-linear system of equations is derived for solving the mean packet service time at the MAC layer. The mean one-hop packet delay is obtained from the mean packet service time at the MAC layer.

3.1 Mean Packet Service Time at MAC Layer

In [15], it is observed that the packet service time at the MAC layer approximately follows an exponential distribution. We define the following parameters.

1. CW_i is the contention window size of a packet for its i^{th} retransmission with the exponential back-off policy, for $i = 0, 1, \cdots, R$, *i.e.*,

$$CW_i = 2^i(CW_{min} + 1) - 1, \qquad i = 0, 1, \cdots, R; \tag{1}$$

2. T_s is the time period during which the medium is sensed busy due to successful transmission, *i.e.*,

$$T_s = T_{rts} + T_{cts} + T_h + T_d + T_{ack} + 3SIFS + DIFS; \tag{2}$$

3. T_c is the time period during which the medium is sensed busy due to a collision, *i.e.*,

$$T_c = T_{rts} + SIFS + T_{ack} + DIFS. \tag{3}$$

In the network steady state, the probability τ that a station transmits during a generic time slot, given that the station has one or more packets to transmit, is given by [7],

$$\tau = \frac{2(1 - 2p_c)(1 - p_c^{R+1})}{(CW_{min} + 1)(1 - p_c)(1 - (2p_c)^{R+1}) + p_c(1 - 2p_c)(1 - p_c^R)}. \tag{4}$$

In (4), p_c is the probability that a packet collides with another packet when transmitted during a generic time slot, and it is given by,

$$\begin{aligned} p_c &= 1 - [1 - (1 - p_0)\tau]^{N-1} \\ &= 1 - (1 - \mathbb{E}[S]\lambda_d\tau)^{N-1}, \end{aligned} \tag{5}$$

where, p_0 is the probability that a station doesn't have a packet to transmit, $p_0 = 1 - \mathbb{E}[S]\lambda_d$ for an $M/M/1$ queue (*e.g.*, see (8.6) in [12]), and S is the packet service time at the MAC layer. Equations (4) and (5) form a system of two equations with three unknowns, τ, p_c, and the mean packet service time $\mathbb{E}[S]$. A third equation in terms of these unknowns is required to solve the equation system. In the following, we derive an expression of $\mathbb{E}[S]$ in terms of τ and p_c, which will be combined with (4) and (5) to solve for the three unknowns.

Consider an arbitrary packet to be transmitted by a station and let $\mathbb{E}[S]$ be its mean service time at the MAC layer. As defined in [2], let P_{tr} denote the probability that there is at least one transmission during a generic time slot, and P_S be the probability that the transmission occurring in one station at a generic time slot is successful given that at least one station transmits during the time slot. Since, during a generic time slot, the packet is transmitted with probability τ and each of the remaining $N - 1$ stations transmits with probability $\mathbb{E}[S]\lambda_d\tau$, then,

$$P_{tr} = 1 - (1 - \tau)(1 - \mathbb{E}[S]\lambda_d\tau)^{N-1}. \tag{6}$$

There are two disjoint events that contribute to the probability that exactly one station transmits during a time slot. The first event is that the packet is transmitted while the remaining $N-1$ stations do not transmit; the second event is that the packet is not transmitted and exactly one of the remaining $N-1$ stations transmits. Therefore,

$$P_S = \frac{\tau\left(1-\mathbb{E}[S]\lambda_d\tau\right)^{N-1} + (N-1)\mathbb{E}[S]\lambda_d\tau(1-\tau)\left(1-\mathbb{E}[S]\lambda_d\tau\right)^{N-2}}{P_{tr}}. \tag{7}$$

By [2] (or [4]),

$$\mathbb{E}[SLOT] = (1-P_{tr})\sigma + P_{tr}P_S T_s + P_{tr}(1-P_S)T_c. \tag{8}$$

By conditioning on the event that the packet is not dropped, we have,

$$\mathbb{E}[S] = \mathbb{E}[SLOT]\left\{p_c^{R+1}\mathbb{E}\left[\sum_{i=0}^{R} U_i\right] + \mathbb{E}[X](1-p_c^{R+1})\right\}, \tag{9}$$

where

$$U_i \sim Uniform(0, CW_i), \qquad i = 0, 1, \cdots, R, \tag{10}$$

and

$$X = \sum_{i=0}^{R} \frac{p_c^i - p_c^{R+1}}{1-p_c^{R+1}} U_i. \tag{11}$$

Moreover,

$$\mathbb{E}[U_i] = \frac{CW_i}{2}, \qquad i = 0, 1, \cdots, R, \tag{12}$$

and

$$\mathbb{E}[X] = \mathbb{E}\left[\sum_{i=0}^{R} \frac{p_c^i - p_c^{R+1}}{1-p_c^{R+1}} U_i\right] = \frac{\sum_{i=0}^{R} p_c^i \mathbb{E}[U_i] - p_c^{R+1}\sum_{i=0}^{R}\mathbb{E}[U_i]}{1-p_c^{R+1}}. \tag{13}$$

By substituting (12) and (13) into (9),

$$\begin{aligned}
\mathbb{E}[S] &= \mathbb{E}[SLOT]\left\{p_c^{R+1}\sum_{i=0}^{R}\mathbb{E}\left[U_i\right] + \sum_{i=0}^{R} p_c^i\mathbb{E}[U_i] - p_c^{R+1}\sum_{i=0}^{R}\mathbb{E}[U_i]\right\} \\
&= \mathbb{E}[SLOT]\sum_{i=0}^{R} p_c^i\mathbb{E}[U_i] \\
&= \frac{\left\{(CW_{min}+1)(1-p_c)(1-(2p_c)^{R+1}) - (1-p_c^{R+1})(1-2p_c)\right\}\mathbb{E}[SLOT]}{2(1-p_c)(1-2p_c)}.
\end{aligned} \tag{14}$$

We now obtain a system consisting of equations (4), (5), and (14) with three unknowns τ, p_c, and $\mathbb{E}[S]$. The mean packet service time $\mathbb{E}[S]$ can be numerically computed from these three equations.

3.2 Mean One-Hop Packet Delay

When a node is modeled as an $M/M/1$ queueing system, the one-hop delay of a packet corresponds to the sojourn time of the packet in the system. Using a standard queueing result (*e.g.*, the mean one-hop packet delay $\mathbb{E}[W]$ under the light traffic condition is given by,

$$\mathbb{E}[W] = \frac{1}{\frac{1}{\mathbb{E}[S]} - \lambda_d} = \frac{\mathbb{E}[S]}{1 - \mathbb{E}[S]\lambda_d}. \quad (15)$$

4 Numerical and Simulation Results

In this section, simulations are performed to verify the mean one-hop packet delay result obtained in Section 3. An *ad hoc* network with the underlying distributed coordination function of IEEE 802.11 is simulated using the OPNET simulator. The routing protocol used is either OLSR or DSR. The system consisting of (4), (5), and (14) is coded in MATLAB to numerically compute the mean packet service time $\mathbb{E}[S]$, and then the mean one-hop packet delay $\mathbb{E}[W]$ from (15). For the purpose of comparison, the mean packet service time developed in [4] based on the heavy traffic assumption is also computed.

The wireless channel data rate is set to be 2 $Mbps$, and the values of the parameters used in the network and MAC layers are given in Table 1. The network size N and packet arrival rate λ_d vary in the analysis. The varying arrival rate enables a higher degree of realism in the simulations for many practical applications such as multiple UAV networking. In multiple UAV operations, the arrival rate changes between a pair of UAVs due for example to changes in their inter-vehicle separations, and cluttered conditions in urban environments.

Table 1. Parameters in Network and MAC Layers

Parameter	**Value**
PHY header	192 bits
MAC header+PHY header (T_h)	224 bits+192 bits (208 μs)
RTS packet (T_{rts})	160 bits+PHY header (176 μs)
CTS packet (T_{cts})	112 bits+PHY header (152 μs)
ACK packet (T_{ack})	112 bits+PHY header (152 μs)
IP packet (T_d)	8184 bits (4092 μs)
σ	20 μs
$SIFS$	10 μs
$DIFS$	50 μs
CW_{min}	31
R	6

In Fig. 1, we plot the mean one-hop packet delay results and those obtained through simulation. In the plot, the rate λ_d of generated IP packets at each node is set to be 8 packets per second, which is only applicable under the light

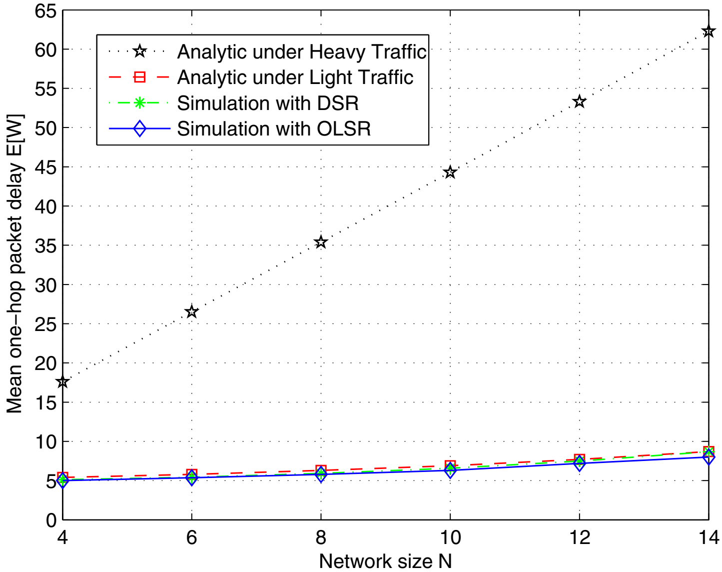

Fig. 1. Mean One-Hop Packet Delay $\mathbb{E}[W]$ *vs.* Network Size N

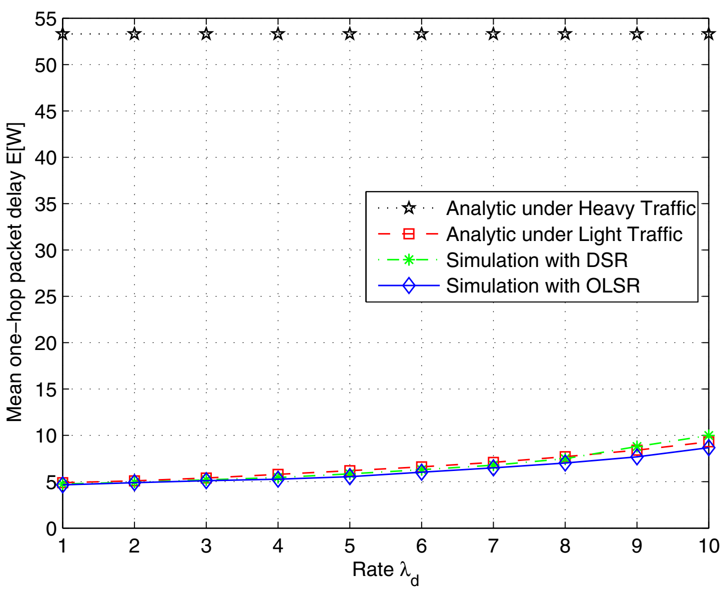

Fig. 2. Mean One-Hop Packet Delay $\mathbb{E}[W]$ *vs.* Rate λ_d

traffic condition, and the network size N varies from 4 to 14. When the network is under the light traffic condition, we use the mean packet service time at the MAC layer developed in [4] under the heavy traffic condition to see if it is suitable for approximating $\mathbb{E}[W]$. (In [4] the heavy traffic condition was simulated as opposed to our $M/M/1$ system modeled for light traffic.) From Fig. 1, we observe that the mean one-hop packet delay increases with the network size N. Moreover, the mean service time at the MAC layer computed under the heavy traffic condition overestimates by a large amount the value obtained by simulation when the network is under the light traffic condition. For a fixed rate λ_d, the discrepancy between the heavy traffic results and the simulation results increases as the network size N increases. For a fixed network size N , the mean one-hop packet delay for the two routing protocols is close to each other with DSR providing slightly larger mean packet delays than OLSR. More importantly, the numerical and simulation results in Fig. 1 show that the analytic result (15), which is derived based on the light traffic condition, is able to accurately estimate the mean one-hop packet delay with negligible differences between the analytic and simulation results.

The mean one-hop packet delay is plotted in Fig. 2 for $N = 12$ and λ_d varying from 1 to 10 (applicable only under the light traffic condition). As shown in Fig. 2, the mean one-hop packet delay calculated with the heavy traffic assumption is independent of the rate λ_d but overestimates the mean one-hop delay when networks are in fact under the light traffic condition. From Fig. 2, it is observed that the mean one-hop delay increases with the rate λ_d. Similar to the observation in Fig. 1, the mean one-hop delay is almost the same for the two routing protocols. Again, the numerical and simulation results show that our result (15) can accurately estimate the mean one-hop packet delay for a network with light traffic.

5 Conclusion

In this paper, an analysis of the mean one-hop packet delay in *ad hoc* networks using the IEEE 802.11 DCF as a MAC protocol was carried out. The light traffic condition was assumed. By considering a network node as an $M/M/1$ queueing system, an analytic result was obtained for accurately estimating the mean one-hop packet delay. Simulation analysis was performed to verify the accuracy of the analytic result. The numerical and simulation examples showed that the mean one-hop packet delay in a network of light traffic increases with either the network size or the packet generation rate. It was shown that the result analytically derived based on the heavy traffic condition tends to overestimate by a large amount the mean one-hop delay when the network is under the light traffic condition.

References

1. Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: Amendment 4, further higher data rate extension in the 2.4 GHz band. IEEE Standard 802.11g (2003)
2. Bianchi, G.: Performance analysis of the IEEE 802.11 distributed coordination function. IEEE Journal on Selected Area in Communications 18, 535–547 (2000)

3. Bisnik, N., Abouzeid, A.A.: Queueing network models for delay analysis of multihop wireless ad hoc networks. In: Proc. of the International Conference on Wireless Communications and Mobile Computing (IWCMC 2006), Vancouver, Canada, pp. 773–778 (2006)
4. Chatzimisios, P., Boucouvalas, A.C., Vitsas, V.: IEEE 802.11 packet delay - a finite retry limit analysis. In: Proc. of the IEEE Global Telecommunications Conference (Globecom 2003), San Francisco, USA, pp. 950–954 (2003)
5. Clausen, T., Jacquet, P. (eds.): Optimized link state routing protocol (OLSR). The Internet Engineering Task Force (IETF) Network Working Group, RFC 3626, Experimental (2003)
6. Elarbaoui, I., Refai, H.H.: Enhancement of IEEE 802.11 DCF backoff algorithm under heavy traffic. In: Proc. of 2008 IEEE/ACS International Conference on Computer Systems and Applications, Doha, Qatar, pp. 1082–1087 (2008)
7. Kang, K., Lin, X., Hu, H.: An accurate MAC delay model for IEEE 802.11 DCF. In: Proc. of the 2007 IEEE International Conference on Telecommunications and Malaysia International Conference on Communications, Penang, Malaysia, pp. 654–657 (2007)
8. Kopp, C.: NCW101: an introduction to network centric warfare, Part 4 - Ad Hoc Networking, Air Power Australia (2008)
9. Kumar, S., Raghavan, V.S., Deng, J.: Medium access control protocols for ad hoc wireless networks: A survey. Elsevier Ad Hoc Networks 4, 326–358 (2006)
10. Johnson, D., Maltz, D., Hu, Y.-C.: The dynamic source routing protocol for mobile ad hoc networks (DSR). The Internet Engineering Task Force (IETF) Network Working Group, RFC 4728, Experimental (2007)
11. Naimi, A.M., Jacquet, P.: One-hop delay estimation in 802.11 ad hoc networks using the OLSR protocol. INRIA research report no. 5327 (2004)
12. Ross, S.M.: Introduction to Probability Models, 8th edn. Academic Press, San Diego (2003)
13. Xiao, Y.: Performance analysis of IEEE 802.11e EDCF under saturation condition. In: Proc. of IEEE International Conference on Communications, Paris, France, pp. 170–174 (2004)
14. Xu, K., Gerla, M., Bae, S.: Effectiveness of RTS/CTS handshake in IEEE 802.11 based ad hoc networks. Elsevier Ad Hoc Networks 1, 107–123 (2003)
15. Zhai, H., Kwon, Y., Fang, Y.: Performance analysis of IEEE 802.11 MAC protocols in wireless LANs. Wiley Wireless Communications and Mobile Computing 4, 917–931 (2004)
16. Ziouva, E., Antonakopoulos, T.: CSMA/CA performance under high traffic conditions: Throughput and delay analysis. Elsevier Computer Communications 25, 313–321 (2002)