A Survey on IEEE 802.11 MAC Analytical Modeling for MAC Performance Evaluation

Ung Heo*, Changfang Yu*, Kang-soo You**, Jae-ho Choi***

Abstract

The paper surveys various analytical models for IEEE 802.11 medium access control protocols and critically discusses recent issues developing in wireless mobile ad hoc networks and their MACs. The surveyed MAC protocols include the standard IEEE 802.11 MAC suites such as IEEE 802.11 DCF, IEEE 802.11 PCF, IEEE 802.11e EDCA, and IEEE 802.11 ad hoc mode; and also the newer, de facto MAC protocols. We study the analytic models of the standard MAC suites followed by the newer analytic models that have been published in recent years. Also, the paper tries to include most of current literatures discussing analytic modeling of MAC in conjunction to some critical issues such as contention among ad hoc nodes, hidden terminal problems, and real-time service support.

Keywords: IEEE 802.11 MAC suite, MAC performance modeling, Markov chain, IEEE 802.11 DCF IEEE 802.11e EDCA, Real-time support, Ad-hoc networks.

I. Introduction

Wireless local area networks (WLAN) using the IEEE802.11 series of standards have experienced an exponential growth in the new decade. In WLAN, due to the shared nature of wireless channels and the intrinsic scarcity of its bandwidth, the medium access control (MAC) protocol is one of the major elements that determines performance and channel utilization.

Throughput and delay analysis of contention-based random multiple access technique based on CSMA has long been studied since the 1970s [2]. Accompanying the standardization and rapid deployment of IEEE 802.11 WLANs in the 1990s, the performance analysis of MAC protocols became a popular research item. The related MAC terminologies such as the contention-based DCF, CSMA with CA (CSMA/CA) began to appear [1].

In the new millenium, driven by the rapid growth of WLAN traffic volume and the different needs of applications, the IEEE 802.11 Task Group E has been working for several years to enhance the current best effort 802.11 MAC to support a QoS-aware WLAN. One of the results is EDCA, which is one of the main and mandatory schemes in 802.11e [6]. It parameterizes the DCF CSMA/CA scheme with prioritized EB to achieve differentiated QoS. In recent years, the performance of EDCA has been explored by using simulations [16] - [22], and also by analytical evaluations [23] - [26]. Most of the EDCA analytical studies are based on the DCF analysis model.

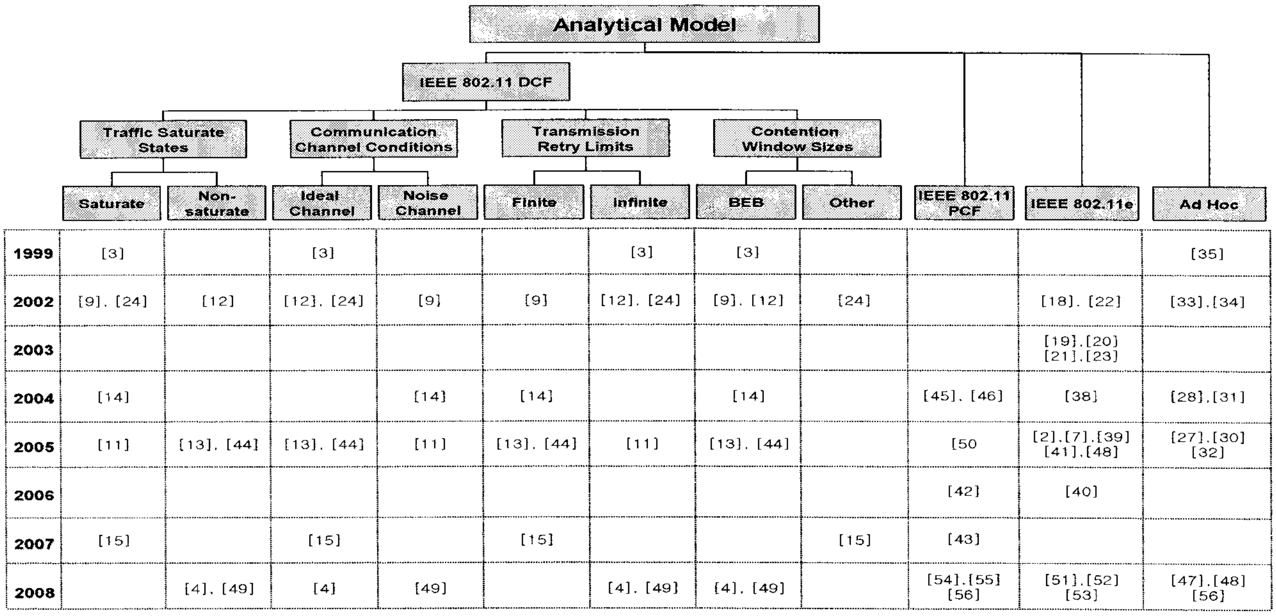
Recently, a number of studies also have been conducted to evaluate the performance of the IEEE 802.11 MAC in the context of multi-hop wireless networks [27]-[32]. These studies have shown that the relay traffic at intermediate nodes has a significant impact on the performance of IEEE 802.11 based networks. There are some studies on interactions between 802.11 MAC protocols and network-layer forwarding paths in ad hoc networks [33]-[35]. These studies have shown that data transmission in ad hoc networks involves cross-layer interactions between MAC-layer channel access and network-layer data forwarding. Furthermore, these interactions have a significant impact on the throughput and delay in the system.

In this paper, we perform a survey on the analytic models related to the performance issues of IEEE 802.11 MAC protocols for wireless mobile networks. We classify these models into the some major categories as shown in Fig.1. Those include IEEE 802.11 series standards such as IEEE 802.11 DCF, IEEE 802.11 PCF, IEEE 802.11e EDCA, IEEE 802.11 ad hoc mode, and modified protocols. In the following, Section II presents the analytic model for IEEE 802.11 DCF. Section III discusses the analytic models for real-time support, and in Section IV, the analytic models for ad-hoc networks are presented including the recent development for

---

* 전북대학교 ** 전주대학교
***전북대학교, 전자공학부, 영상정보신기술연구소.

투고 일자 : 2011. 2. 14 수정완료일자 : 2011. 4. 28
게재확정일자 : 2011. 4. 30



	Traffic Saturate States		Communication Channel Conditions		Transmission Retry Limits		Contention Window Sizes				
	Saturate	Non-saturate	Ideal Channel	Noise Channel	Finite	Infinite	BEB	Other	IEEE 802.11 PCF	IEEE 802.11e	Ad Hoc
1999	[3]		[3]			[3]	[3]				[35]
2002	[9], [24]	[12]	[12], [24]	[9]	[9]	[12], [24]	[9], [12]	[24]		[18], [22]	[33],[34]
2003										[19],[20] [21],[23]	
2004	[14]			[14]	[14]		[14]		[45], [46]	[38]	[28],[31]
2005	[11]	[13], [44]	[13], [44]	[11]	[13], [44]	[11]	[13], [44]		[50	[2],[7],[39] [41],[48]	[27],[30] [32]
2006									[42]	[40]	
2007	[15]		[15]		[15]			[15]	[43]		
2008		[4], [49]	[4]	[49]		[4], [49]	[4], [49]		[54],[55] [56]	[51],[52] [53]	[47],[48] [56]

Fig. 1. Classification on MAC analytic modeling

real-time service support. Finally, the conclusions are made in Section V.

II. Analytical Model for IEEE 802.11 DCF

A. IEEE 802.11 DCF

IEEE 802.11 DCF is based on the CSMA/CA protocol. If a station has a frame to transmit, it checks the channel status to see if the channel is idle. If the channel is sensed idle for an interval of DCF inter-frame space (DIFS) and its back-off counter value is zero, the station immediately initiates its transmission. If the channel is sensed to be busy or the back-off counter value is non-zero, the station will defer its transmission until the channel becomes idle for a DIFS interval and also the back-off counter value reaches zero. Unless the channel is idle, it freezes the back-off counter. The back-off counter is set by the system with a randomly chosen value in the range of [0, CW], where CW is the current contention window size having a value in the range of [CW_{min}, CW_{max}]. If the source successfully receives an acknowledgement (ACK) frame after a short inter-frame space (SIFS) idle period, the transmission is assumed to be successful.

In the IEEE 802.11 DCF, a binary exponential back-off counter (BEB) is used, i.e., the value of CW is dynamically controlled by the back-off algorithm. If a frame transmission fails, the current contention window size is doubled up to the maximum value CW_{max}. The station can have a retransmission attempt to transmit the frame after the system selects a new back-off counter value from the increased contention window. On the other hand, if the transmission is successful, the source station resets its contention window to the minimum value CW_{min}.

B. Markov Chain Model of Bianchi

In [3], Bianchi presented the saturation throughput performance of IEEE 802.11 DCF. The DCF performance evaluation uses his analytic model for DCF using a 2-D Markov chain. After him, more investigations are followed for different conditions and assumptions. He put together a milestone because most of studies related to analytic modeling of IEEE 802.11 MAC for its performance evaluation refer to his model. The Bianchi's model relies on the following fundamental assumptions for simplicity:

- The mobile stations always have packet to transmit. He calls this the saturation condition.
- There are no hidden terminals and there is no capture effect. The capture effect means that a terminal which perceives a higher signal-to-noise ratio (SNR) relative to other terminals captures the channel.
- At each transmission attempt and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability.
- The transmission channel is ideal and packet errors are only due to collisions.

The analytic model based on these assumptions is presented for the saturation throughput evaluation in the WLAN. By virtue of the strategy employed for reducing the collision probability of the packets transmitted from the stations attempting to access the channel simultaneously, a random process *b(t)* is used to represent the back-off counter of a given station. The back-off counter is decremented at the start of every idle back-off slot and when it reaches zero, the station transmits and a new value for *b(t)* is set. The value of *b(t)* after each transmission depends on the size of the contention window from which it is drawn. Therefore, it depends on the station's transmission history, rendering it a non-Markovian process. To overcome this problem and get to the definition of a Markovian process, a second process *s(t)* is defined representing the size of the contention window from which *b(t)* is drawn, where $W_i = 2^i W, i = s(t)$. Recall that a back-off time counter is initialized depending on the number of failed transmissions for the transmitted packet. It is chosen in the range [0, W_i-1] distribution, where W_i is the contention window at the back-off stage *i*. At the first transmission attempt, the contention window size is set equal to a minimum value $W_0 = W$, and the process *s(t)* takes on the value $s(t) = i = 0$. The back-off stage *i* is incremented in unitary steps after each unsuccessful transmission up to the maximum value *m*, while the contention window is doubled at each stage up to the maximum value $CW_{\max} = 2^m W$. The back-off counter is decremented as long as the channel is sensed idle and stopped when it is detected busy. The station transmits when the back-off time counter reaches zero. A two-dimensional Markov process $< s(t), b(t) >$ are defined, based on two assertions, as follows:

- The probability that a station will attempt a transmission in a generic time slot is constant across all time slots.
- The probability that any transmission experiences a collision is constant and independent of the number of collisions already suffered.

The Markov process includes transition probabilities as follows:

$$\begin{array}{lll} P\{i,k|i,k+1\} = 1 & k \in (0, W_i - 2) & i \in (0,m) \\ P\{0,k|i,0\} = (1-p)/W_0 & k \in (0, W_0 - 1) & i \in (0,m) \\ P\{i,k|i-1,0\} = p/W_i & k \in (0, W_i - 1) & i \in (0,m) \\ P\{m,k|m,0\} = p/W_m & k \in (0, W_m - 1) & \end{array} \tag{1}$$

where indices and parameters are summarized in Table 1.

In practical networks, however, the traffic at each station is mostly unsaturated, so it is important to derive a model accounting for practical network operations. In [4]-[7], the Bianchi process model is extended in order to consider unsaturated traffic conditions by introducing a new idle state, not present in the original Bianchi model. In the unsaturated traffic case, the extended model assumes that the station transmission buffer becomes empty, after a successful completion of a packet transmission.

Cleary, the second and fourth assumptions made by Bianchi may not be valid in real setting, specially, when the station is mobile and when the channel is not ideal. On that account, the authors of [9] look at the impact of channel induced errors and the received SNR on the achievable throughput in a system with rate adaptation whereby the transmission rate of the terminal is adapted based on either direct or indirect measurements of the link quality. In [10], the model is extended to account for channel errors while, in [11], the authors investigate the saturation throughput in both congested and error-prone Gaussian channel, by proposing a simple and accurate analytical model for the

Table 1. The Bianchi model definitions

$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr}\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s) T_s}$ S : normalized system throughput P_{tr} : probability that there is at least one transmission in the considered slot time P_s: probability of successful transmission T_s: average time the channel is busy T_c: average time the channel is sensed busy due to the collision σ : duration of an empty slot time $E[P]$: average packet payload size
$P_{tr} = 1 - (1 - \tau)^n$ n : number of station contend on the channel
$P_{tr} = 1 - (1 - \tau)^{n-1}$ p : conditional collision probability
$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$ τ : Probability that a station transmits in a randomly chosen slot time i : back-off stage value W : contention window m : maximum back-off stage value

DCF behavior. In [49], the authors also provide throughput analysis of IEEE 802.11 protocol at the data link layer in non-saturation traffic conditions considering the impact of both transmission channel and capture effects in a Rayleigh fading environment. Here, collisions can occur with probability P_c on the transmitted packets, while transmission errors due to the channel can occur with probability P_e. Its model assumes that collision and transmission error events are statistically independent. In this scenario, a packet is successfully transmitted if there is no collision (this event has probability $1-P_c$) and the packet encounters no channel errors during transmission (this event has probability $1-P_e$). The probability of successful transmission is therefore equal to $(1-P_c)(1-P_e)$. It goes further to investigate the capture effect that the channel is captured by a station whose power level is stronger than other stations transmitting at the same time in a mobile environment. This may be due to relative distances and/or channel conditions for each user and may happen whether or not the terminals exercise power control.

Also, the third assumption made by Bianchi means that after 6^{th} retransmission the back-off window should always stay at its maximum value because the system tries to transmit infinitely. In [13], however, the Bianchi model is extended by taking into account both transmission errors and packet retry limits on the IEEE 802.11 MAC protocol. In its mathematical model, the packet is dropped, when it reaches the last back-off stage and experiences another collision or an error. In [15], to improve the saturation throughput and decrease the packet drop probability of a wireless LAN, a new back-off algorithm, called hybrid back-off algorithm, which can replace IEEE 802.11 DCF, is proposed. In the hybrid back-off algorithm, the stations increase their contention window linearly after experiencing several collisions. Actually, in the binary exponential back-off (BEB) of the IEEE 802.11 standards, when a new packet is to be transmitted, the station should set *CW* as an initial value of CW_{min}. The *CW* should be doubled every time the transmission fails, until it reaches CW_{max}. Then, *CW* shall remain at the value until it is reset. *CW* is reset after every successful transmission or reaches the retry limit. The continuous collision indicates that there is large number of stations, and the network is in a congestive traffic condition. In such a case, *CW* should increase quickly to adapt to the condition. But, in BEB, the small CW_{min} slows down the binary exponential increase not quick enough in some stages. For such a case, the hybrid back-off algorithm can be an effective remedy. Here, *CW* still increase exponentially in the beginning, and after several retrials, *CW* will increase linearly between any stages with a certain slope, which controls the rate of *CW* increase. For another modification on the Bianchi, the authors in [12] presented an extended analytic model under traffic conditions that correspond to the maximum load that the network can support in a stable condition.

III. Analytical Model for Real-Time Support

Driven by the rapid growth of WLAN traffic volume and the different needs of applications, the IEEE 802.11 Task Group E has been working for several years to enhance the current best-effort 802.11 MAC to support a QoS-aware WLAN. EDCA, one of the main and mandatory schemes in 802.11e, parameterizes the DCF CSMA/CA scheme with prioritized EB to achieve differentiated QoS. In recent years, the performance of EDCA has been explored by means of not only simulation but also analytical evaluations. Most of the EDCA analytical studies are based on the modifications of DCF analysis mentioned above.

A. IEEE 802.11e EDCA

EDCA is designed to enhance the DCF mechanism and to provide a distributed access method that can support service differentiation among classes of traffic. It can provide up to four ACs. EDCA assigns smaller *CW*s to ACs with higher priorities to bias the successful transmission probability in favor of high-priority ACs in a statistical sense. Indeed, the initial *CW* size can be set differently for different priority ACs. To achieve differentiation, instead of using fixed DIFS used in DCF, here, AIFS is applied. AIFS for a given AC is defined as follows:

$$AIFS = SIFS + AIFSN \times aSlotTime \qquad (2)$$

where AIFSN is AIFS number and determined by the AC and physical settings, and SlotTime is the duration of a time slot. The AC with the smallest AIFS has the highest priority. In EDCA, both the physical carrier sensing and the virtual sensing methods are similar to those in the DCF. However, there is a major difference in the countdown procedure when the medium is determined to be idle. In EDCA, after a AIFS period, the back-off counter decreases by one at the beginning of the last slot of the AIFS, while in DCF, this is done at the beginning of the first time slot interval following a DIFS period. For a given station, frame traffics of different ACs are buffered in different queues. Each AC within a station behaves like a virtual station. It contends for access to the medium and independently starts its back-off after sensing the medium idle for at least one AIFS period. When a collision occurs among different ACs within the same station, the higher priority AC is granted the opportunity for physical transmission, while the lower priority AC suffers from a virtual collision, which is similar to a real collision outside the station. IEEE 802.11e also defines a transmission opportunity (TXOP) limit as the interval of time during which a particular station has the right to initiate transmissions. During an EDCA TXOP, a station may be allowed to transmit multiple data frames from the same AC with a SIFS gap between an ACK and the subsequent data frame [2], [36]-[37]. This is also referred to as contention free burst (CFB).

B. Markov Chain Model for EDCA

In [38], the author presented an analytical model for the saturation throughput of EDCF, which was a draft of IEEE 802.11e EDCA. This model considers the differentiation of both *CW* sizes and AIFS values of ACs. However, it is limited to two different ACs. They assumed that each station has only one queue for each AC. In the standard, each station may have four queues for four different ACs. Similarly, in [2], the authors proposed a unified performance model to study the saturation throughput and delay performance of EDCA by differentiating both *CW* sizes and AIFS values of four different ACs. However, they also assumed that each station has only one queue for each one of four different ACs. Xiao in [39] proposed back-off-based priority schemes for DCF and EDCF by differentiating the *CW* sizes, but he did not consider different AIFS values or the VCH scheme in the standard. When a virtual collision occurs, he assumed that a VCH does not choose one queue to transmit a frame and a virtual collision always causes to induce an external collision that occurs among different stations. Using this assumption, each queue becomes equivalent to an independent station. On the other hand,

Chen in [40] enhanced the EDCA by proposing two call admission control schemes and a rate control scheme. He considered that there are at most four transmit queues for four different priorities in each active node. However, they treated each queue as an independent node. Recently, to analyze the throughput and delay performance of the EDCA, Tantra et.al. in [41] presented a model which considers four queues for four different ACs with the VCH scheme in the standard. This model is limited to three high-priority ACs and one low-priority AC according to different AIFS values.

C. IEEE 802.11 PCF and its Markov Chain Model

In IEEE 802.11, PCF is provided to support QoS related services, since DCF cannot guarantee QoS requirements in general. While much analytic studies have been done for the performance of DCF by numerous researchers, however, works for PCF are relatively less because of its contention-less nature.

In [42], the authors analyze the performance of a new pointer-based MAC protocol hat was designed to significantly improve the energy efficiency of user terminals in wireless local area networks. Actually, wireless portable devices must operate with the highest possible energy efficiency while still maintaining a minimum level and quality of service to meet the user's need. This protocol is capable of reducing energy consumption of a station for remaining awake and listening to the channel.

In [50], the authors provided a new MAC scheme based on a gated polling mechanism. This gated polling can provide a better throughput performance especially when the system is heavily loaded. Moreover, in [43], the authors introduced a 3-gated polling scheme to improve this result further by adding more chances for the heavily loaded station. Using the theoretical analysis and simulation, it also verifies that the performance of the novel scheme is close to that of exhaustive polling.

PCF has inherent problems costing system performance. In some cases stations would hardly get an opportunity to be polled, which causes bandwidth starvation. Also, there might be a case where a station with no traffic can get the same transmission opportunity as one with traffic. Not only it deteriorates the overall performance but also wastes resources. These are typical problems making it difficult for the PCF to be implemented in IEEE 802.11 products. Besides, most researches have focused on the performances of the PCF polling schemes according to the system configurations and traffic models in a restricted environment such as the ideal channel condition [44]. In this case the performances of polling schemes can be estimated and predicted easily. Generally, the performance of a MAC protocol greatly depends on the channel conditions. In [45], in order to overcome discussed shortcomings of PCF and to build up an efficient polling scheme under various channel conditions, the authors proposed the enhanced PCF polling scheme along with performance analysis.

In [46], the authors introduced another polling scheme. Their model is based on mixed service with batch arrivals to efficiently serve the real-time traffic. By using the Markov chain theory, the mean of polling period and queue length for real-time traffic are derived and the performance analysis is followed.

IV. Analytical Model for Ad Hoc Networks

An ad hoc network is a collection of wireless mobile hosts that can communicate in a self-organized manner without any established infrastructure or centralized administration. Most of researches involving ad hoc networks include not only MAC layer but also network layer due to the routing problem.

In [47], the author focus on performance evaluation of multi-path transmission over multi-hop IEEE 802.11-based ad hoc networks. The analytic models are developed to emulate the impact of IEEE 802.11-based multi-path multi-hop transmission on the frame service time under unsaturated conditions. This time is crucial for estimating the end-to-end delay in the system. The throughput of multi-hop multi-path transmission in IEEE 802.11-based networks is also investigated. This study is conducted from a cross-layer perspective rather than only focusing on the operation and performance analysis of the IEEE 802.11 MAC.

In [48], the authors utilized service differentiation techniques in IEEE 802.11e Enhanced Distributed Coordination Function. It is achieved by altering the way each station gains medium access, and establishing access priorities among the stations that compose an ad hoc network. Some quality of service metrics were considered in order to provide service differentiation in the MAC sub-layer and to evaluate the ad hoc networks performance. Those metrics include throughput, latency, jitter and packet drop ratio. The service differentiation is performed by packet size variation, Arbitration Inter-frame Space (AIFS) size alteration, and BEB calculus. Simulations showed the validity of the differentiation technique combined in the IEEE 802.11e MAC sub-layer, to establish thresholds to QoS metrics, to provide medium access priorities, and to keep the high level of ad hoc network utilization.

The recent development in the PCF part can be found in [56]. The authors proposed a novel medium access control protocol, called time slot reservation based coordination function (TRCF), for supporting a real-time traffic such as voice call in an one-hop ad hoc network. Even though the Bianchi model developed for the IEEE 802.11 DCF under an AP coordination is not appropriate for the real-time service MAC in MANET, his Markov chain approach inspires this work for establishing the similar analytic model for TRCF and combining it in the PCF part of IEEE 802 MAC protocol. The extended version for supporting multi-hop voice call support can be also found in [57]. Here, the time synchronization between the nodes and the adaptive routing in the ad hoc network are discussed along with TRCF combination in the IEEE 802.11 PCF MAC protocol while keeping the DCF part untouched for the standard consideration.

V. CONCLUSION

In this paper, we have presented a survey on the IEEE 802.11 MAC protocol and discussed various analytic models for IEEE 802.11 DCF, IEEE 802.11e EDCA, and IEEE 802.11 PCF medium access control protocols. The model proposed by Bianchi for the IEEE 802.11 DCF MAC made a big impact on the subsequent studies in this analytical modeling area using a Markov chain theory. After his, more extended studies following after him. Those studies filled the gap found in the original Bianchi work. They showed an enhancement in coping with more practical situations found in a typical wireless LAN.

In addition, the extensions are made in the IEEE 802.11e EDCA for supporting a service differentiation in the coordinated environment. Recently, literatures are available for the investigation involving ad hoc networks. The analytic models are proposed for IEEE 802.11 DCF modifications that can be deployed in an ad hoc network. Also, new MACs and their analytic models are developed for supporting real-time services in an ad hoc network. For the voice calls in one-hop and multi-hop situations are also investigated by combining a time slot reservation based MAC protocol in the IEEE 802.11 PCF part. The complexity involved when working with an ad hoc network because it needs to consider MAC and networking together, simultaneously. Since the IT technology develops rapidly, the time will come in the near future so that the accurate time synchronization and robust network management even in the ad hoc network environment for the real-time services become feasible and also economic.

References

[1] IEEE Std. 802.11-1999 IEEE Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, *IEEE*, Aug. 1999.

[2] J. Hui, M. Devetsikiotis, "A unified model for the performance analysis of IEEE 802.11e EDCA," *IEEE Trans. on Comm.*, vol. 53, no. 9, pp. 1498-1510, Sep. 2005.

[3] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *in Communications, IEEE Journal*, vol. 18, pp. 535-547, Mar. 2000.

[4] C. Mingxin, D. W. Gan, Z. Guangxi, "A Unified Model for Performance Analysis of 802.11 in Heterogeneous Traffic and Saturation Condition," *in Proc, IEEEICC08*, pp. 2264-2649, May 2008.

[5] J.V Sudarev, L.B White, S. Perreau, "Performance analysis of 802.11 CSMA/CA for infrastructure networks under finite load conditions," *IEEE Workshop*, pp. 6, Sep. 2005.

[6] W. Tianlin, H. H. Refai, "Network performance analysis on IEEE 802.11g with different protocols and signal to noise ratio values," *Proc. IFIPWOCN2005*, pp. 29-33, Mar. 2005.

[7] M. P. da Silva, C. B. Westphall, "Performance analysis and service differentiation in the MAC sublayer of IEEE 802.11e ad hoc networks," *Proc. AICT/SAPIR/ELETE2005*, pp. 434-440, Jul. 2005.

[8] IEEE Std. 802.11 e/Draft 6.0, IEEE Standard for Wireless medium access control (MAC) and physical layer (PHY) specifications: Medium access control (MAC) enhancements for quality of service (QoS), *IEEE*, Nov. 2003.

[9] D. Qiao, S. Choi, and K. G. Shin, "Goodput analysis and link adaptation for IEEE 802.11a wireless LANs," *IEEE Trans. Mobile Computing*, vol. 1, no. 4, Oct.-Dec. 2002.

[10] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "Influence of channel BER on IEEE 802.11 DCF," *IEE Electron. Lett.*, vol. 39, no. 23, pp. 1687-1689, Nov. 2003.

[11] Q. Ni, T. Li, T. Turletti, and Y. Xiao, "Saturation throughput analysis of errorprone 802.11 wireless networks," *J. Wireless Commun. Mobile Comput.*, vol. 5, no. 8, pp. 945-956, Dec. 2005.

[12] E. Ziouva and T. Antonakopoulos, "CSMA/CA performance under high traffic conditions: Throughput and delay analysis," *Comp. Comm.*, vol. 25, pp. 313 - 321, Feb. 2002.

[13] Y. S. Liaw, A. Dadej, and A. Jayasuriya, "Performance analysis of IEEE 802.11 DCF under. limited load," *Proc. of Asia-Pacific Conference on Communications*, pp. 759-763, 2005.

[14] P. Chatzimisios, A. C. Boucouvalas and V. Vitsas, "Performance analysis of IEEE 802.11 DCF in presence of transmission errors", *Proc. the IEEE International Conference on Communications (ICC2004)*, vol. 7, pp. 3854-3858, Jun. 2004.

[15] P. Xiangyu, J. Letian, X. Guozhi, "Performance Analysis of Hybrid Backoff Algorithm of Wireless LAN," *Proc. in Wireless Communications, WiCom2007*, pp. 2853-2856, Sep. 2007.

[16] Lindgren, A. Almquist, and O. Schelén, "Evaluation of quality of service schemes for IEEE 802.11 wireless LANs," *Proc. 26th Annu IEEE Conf. Local Computer Netw.*, pp. 348-351, Nov. 2001.

[17] Lindgren, A. Almquist, and O. Schelén, "Quality of service schemes for IEEE 802.11 wireless LANs: An evaluation," *ACM Mobile Netw. Appl.*, pp. 223-235, Jun. 2003.

[18] S. Mangold, S. Choi, P. May, O. Klein, G. Hiertz, and L. Stibor, "IEEE 802.11e wireless LAN for quality of service (invited paper)," *Proc. Eur. Wireless*, vol. 1, Florence, Italy, pp. 32-39, Feb. 2002.

[19] S. Choi, J. D. Prado, N. S. Shankar, and S. Mangold, "IEEE 802.11e contention-based channel access (EDCF) performance evaluation," *Proc. ICC*, pp. 1151-1156, May 2003.

[20] H. L. Truong and G. Vannuccini, "The IEEE 802.11e MAC for quality of service in wireless LANs," *Proc. SSGRR*, 2003.

[21] D. He and C. Q. Shen, "Simulation study of IEEE 802.11e EDCF," *Proc. 57th IEEE Semiannu. VTC*, pp. 685-689, Apr. 2003.

[22] Grilo and M. Nunes, "Performance evaluation of IEEE 802.11e," *Proc. PIMRC*, pp. 511-517, Sep. 2002.

[23] S. Mangold, *Analysis of IEEE802. 11e and application of game models for support of quality-of-service in coexisting wireless networks*, doctoral dissertation, Aachen Univ., Aachen, Germany, Jun. 2003.

[24] D. Qiao and K. G. Shin, "Achieving efficient channel utilization and weighted fairness for data communications in IEEE 802.11 WLAN under the DCF," *Proc. IWQoS*, pp. 227-236, May 2002.

[25] J. Zhao, Z. Guo, Q. Zhang, andW. Zhu, "Performance study ofMAC for service differentiation in IEEE

802.11," *Proc. Globecom*, pp. 778-782, Nov. 2002.

[26] G. Bianchi and I. Tinnirello, "Analysis of priority mechanisms based on differentiated inter frame spacing in CSMA-CA," *Proc. VTC*, pp. 1401-1405, Fall, 2003.

[27] Mukherjee, A., Li, W., and Agrawal, D.P.: 'Performance analysis of IEEE 802.11 for multi-hop infrastructure networks,' *Proc. Globecom'05*, pp. 3439-3444, 2005.

[28] F. Alizadeh-Shabdiz, S. Subramaniam, "MAC layer performance analysis of multi-hop ad hoc networks," *Proc. Globecom'04*, pp. 2781-2785, 2004.

[29] Tickoo, B. Sikdar, "A queueing model for finite load IEEE 802.11 random access MAC," *Proc.ICC'04*, pp. 175-179, 2004.

[30] J. He. Kaleshi, D. Munro, A. Wang, Y. Doufexi, A. McGeehan, J. Fan, "Performance investigation of IEEE 802.11 MAC in multihop wireless networks," *Proc. MSWiM'05*, pp. 242-249, 2005.

[31] M. Carvallo, J. J. Garcia-Luna-Aceves, "A scalable model for channel access protocols in multihop ad hoc networks," *Proc. MobiCom'04*, pp. 330-344, 2004.

[32] Barowski, Y., Biaz, S., and Agrawal, P., "Towards the performance analysis of IEEE 802.11 in multi-hop ad hoc networks," *Proc. WCNC'05*, pp. 100-106, 2005.

[33] Li, J., Blake, C., De Couto, D., Lee, H., and Morris, R., "Capacity of ad hoc wireless networks," *Proc. MobiCom'01*, pp. 61-69, 2001.

[34] Fang, Y., and McDonald, A.B, "Cross-layer performance effects of path coupling in wireless ad hoc networks power and throughput implications of IEEE 802.11 MAC," *Proc. IPCCC'02*, pp. 281-290, 2002.

[35] Royer, E.M., Lee, S., and Perkins, C.E., "The effects of MAC protocols on ad hoc network communication," *Proc. WCNC'00*, pp. 543-548, 2000.

[36] IEEE Std. 802.11e/Draft 5.0, IEEE Standard for Wireless medium access control (MAC) and physical layer (PHY) specifications: Medium access control (MAC) enhancements for quality of service (QoS), *IEEE*, Jul. 2003.

[37] S. Choi, J. D. Prado, S. Shankar, and S. Mangold, "IEEE 802.11e contention-based channel access (EDCF) performance evaluation," *Proc. IEEE ICC'03*, Vol .2, pp. 1151-1156, May 2003.

[38] J. W. Robinson and T. S. Randhawa, "Saturation throughput analysis of IEEE 802.11e enhanced distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 5, pp. 917-928, Jun. 2004.

[39] J. Hui andM. Devetsikiotis, "A unified model for the performance analysis of IEEE 802.11e EDCA," *IEEE Trans. Commun.*, vol. 53, no. 9, pp. 1498-1510, Sep. 2005.

[40] X. Chen, H. Zhai, X. Tian, and Y. Fang, "Supporting QoS in IEEE 802.11e wireless LANs," *IEEE Trans. Wireless Comm.*, vol. 5, no. 8, pp. 2217-2227, Aug. 2006.

[41] J. W. Tantra, C. H. Foh, and A. B. Mnaouer, "Throughput and delay analysis of the IEEE 802.11e EDCA saturation," *Proc. IEEE ICC*, pp. 3450 - 3454, Jun. 2005.

[42] G. A. Safdar, W. G. Scanlon, "Performance analysis of an improved power-saving medium access protocol for IEEE 802.11 point coordination function," *Proc. IEE Proceedings*, vol. 153, pp. 697-704, Oct. 2006.

[43] L. Yan, Z. Guangxi, "Performance Analysis of Three Gated Service Polling Scheme on Wireless Network," *Proc. ISWPC'07, 2nd International Symposium*, Feb. 2007.

[44] P. P. Pham, S. Perreau, "Jayasuriya, A.;Performance Analysis of the IEEE 802.11 DCF," *Proc. Asia-Pacific Conference*, pp. 764-768, Oct. 2005.

[45] K. Taekon, K. ChangYeul, "Chil-Youl Yang; Performance analysis of polling schemes with IEEE 802.11a WLAN," *IEEE VTC*, vol 3, pp. 1564-1568, May 2004.

[46] F. Huifang, S. Yantai, "Performance analysis of real-time traffic in wireless LANs," *Proc. Electrical and Computer Engineering, Canadian Conference*, vol. 2, pp. 1013-1016, May 2004.

[47] L. Zhao, J. G Delgado-Frias, K. Sivakumar, "Performance analysis of multipath transmission over 802.11-based multihop ad hoc networks: a cross-layer perspective Communications," *IET Comm.*, vol. 2, pp. 380-387, Feb. 2008.

[48] M. P. da Silva, C. B. Westphall, "Performance analysis and service differentiation in the MAC sublayer of IEEE 802.11e ad hoc networks," *Proc. AICT/SAPIR/ELETE'05*, 2005.

[49] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin. "Unsaturated Throughput Analysis of IEEE 802.11. in Presence of Non *Ideal Transmission Channel and Capture Effects," IEEE Trans. on Comm.*, vol. 7, pp. 1276-1286, Apr. 2008.

[50] LI Yan, ZHAO Dong-feng, DING Hong-wei, GAO Fei, "Study on queue scheme of gated polling

multi-access communication systemm," *Journal on communications*, vol. 26, no. 3, pp. 99-105, 2005.

[51] R. Anne, R. H. Boudewijn, H. Geert, C. Lucia, "Cloth Bottleneck Analysis for Two-Hop IEEE 802.11e Ad Hoc Networks," *Proc. ASMTA. LNCS*, pp. 279-294, 2008.

[52] Sueng Jae Bae, Hyung Joo Kim, Min Young Chung, "Performance Evaluation of IEEE 802.11e EDCA with DCF Improvement Algorithms," *Proc. LNCS*, vol. 5072, pp. 896-905, 2008.

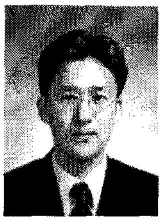
[53] I Shyan Hwang, Hsin Hao Chang, "Performance Assessment of IEEE 802.11e EDCF Using Three-dimension Markov Chain Model," *Mathematical Sciences*, vol. 2, pp. 139-151, 2008.

[54] Lam, R.Y.W. Leung, V.C.M. Chan, H.C.B, "Analysis of a Polling Protocol for Packet Voice Transport over IEEE 802.11 Wireless LANs," *VTC. IEEE*, pp. 1641-1645, May 2008.

[55] G. A. Safdar, W. G. Scanlon, "Performance Analysis of Improved IEEE 802.11 Infrastructure Power Saving Under Time-Correlated Channel Errors," *Proc. LNCS*, pp. 36-42, Mar. 2008.

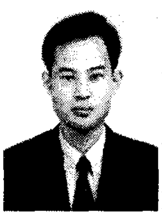
[56] Ung Heo, Jaeho Choi, "Isochronous MAC Protocol for Real-Time Support in MANET," *Proc. ISITC2007*, pp. 378-382, Nov. 2007.

[57] Ung Heo, *New MAC for Real-Time Service Support Using IEEE 802.11 PCF and its Analytic Model for Performance Evaluation*, Ph.D Dissertation, Chonbuk National University, 2011.



Ung Heo received his bachelor's, master's and doctor's in computer engineering from the Chonbuk National University, Korea in 2002 2004, and 2011, respectively.
He is now with Chonbuk National University as an adjunct professor. His research interests include wireless and mobile communications and networks and communication protocol performance modeling.

Changfang Yu received his bachelor's in computer science from South Central University in 2009. He is currently with Chonbuk National University for his master's in electronic engineering.
His research interests include wireless networks and network security.



Kang-soo You received his master's in computer engineering and doctor's in image engineering from Chonbuk National University, Korea, in 1994 and 2005, respectively.
Currently, he is with the School of Liberal Arts as a full-time lecturer at Jeonju University, Korea. His current research interests are multimedia communications and AR.

Jae-ho Choi received his B.S.E.E., M.S.E.E., and Ph.D. in computer engineering from North Carolina State University, Raleigh, NC, USA in 1985, 1988, and 1993, respectively.
He is currently with Chonbuk National University as a full professor in electronic engineering. His research interests are ubiquitous and multimedia communications and networks.