OFDMA-Based Reliable Multicasting MAC Protocol for WLANs

Byung-Seo Kim, *Member, IEEE*, Sung Won Kim, and Randy L. Ekl

***Abstract*—Although many wireless communication standards include multicast as well as unicast traffic in layer 2, most parts of the specifications are limited to unicast methods. In addition, although the existing wireless standards provide reliable unicast methods using an automatic repeat request (ARQ) and a retransmission, multicast packets are not reliably transmitted using these standards. To retransmit a multicast packet, the acknowledgements (ACKs) from the receivers need to be received by the sender to determine whether a retransmission is required. However, transmitting an ACK from each group member degrades the network performance due to the overhead induced by multiple ACK packet transmissions and channel access processes for the ACKs. To solve this problem, in this paper, a medium-access control protocol called the orthogonal frequency division multiplex access (OFDMA) based multicast ACK (OMACK), with minimum ACK overhead over wireless local area networks, is proposed. The proposed scheme uses one orthogonal frequency division multiplex (OFDM) symbol for the ACKs from all member stations (STAs), and each member STA indicates its packet reception status by utilizing a subcarrier within the OFDM symbol. The proposed scheme is thoroughly examined by using simulation and theoretical methods, and the results show that it significantly reduces the aforementioned overhead and, as a consequence, improves the performance of wireless networks.**

***Index Terms*—Medium-access control (MAC), multicast, orthogonal frequency division multiplex access (OFDMA), wireless LAN.**

I. Introduction

AS WIRELESS communication becomes an increasingly substantial part of our everyday life, many applications for wired networks have been adopted by wireless networks. One such application is multicast communication. Wireless communication is inherently broadcast in nature, i.e., all communication devices within the radio range of the transmitter can hear the transmission. The broadcast nature of wireless communication enables it to reach all of the intended receivers with only one transmission, so that it achieves better channel efficiency compared with the unicast method. Unlike broadcast, whose transmission targets all devices in the radio range, multicast targets some devices belonging to a particular receiver group. In contrast to the improved bandwidth efficiency of wireless multicast, there are still several design challenges to improve the reliability of wireless multicast.

Multicast has been extensively studied, focusing on the relatively high layers such as the network and transport layers shown in [1] and [2]. Whereas the network layer mainly focuses on the establishment and the management of multicast routing trees, studies on multicasting in the transport layer have focused on multicast traffic management (i.e., data propagation, error recovery). On the other hand, multicast and broadcast transmissions over wireless links have not been considered in depth in previous studies, except for the broadcasting of periodic control packets, such as beacon packets. Whereas reliable unicast methods over radio access networks (RANs) have been extensively studied, multicast traffic is unreliably delivered. In other words, the delivery of multicast traffic over RANs is not guaranteed since most wireless networks require neither an acknowledgement (ACK) nor a retransmission for multicast traffic transmissions. To compensate for this unreliability, the use of the lowest data rate is adopted for multicast transmissions since this allows for a more reliable transmission. In addition to using the lowest data rate, the transmission of multicast packets is enhanced by the incorporation of an additional error-correction code to improve the reliability of the transmission. However, considering the nature of wireless channels, such as their location dependence and time variation, the use of the lowest data rate or the additional error-correction code may not provide for a reliable transmission at all since, although these methods reduce the packet error probability of the multicast transmission, they do not absolutely eliminate the packet errors. To enable more reliable multicast, ACKs from the receivers and the retransmissions seem to be necessary components. To retransmit multicast packets, ACKs from the receivers need to be transmitted to the sender so that the latter knows whether a retransmission is required.

Multicast in the wireless local area network (WLAN) standard IEEE 802.11 is not well specified; only addressing and basic operations are detailed. To achieve reliable multicast over both ad hoc-based and centralized WLANs, many enhancements to the wireless medium-access control (MAC) protocol have been proposed [3]–[10]. The proposed methods have mainly focused on solutions for the hidden-node problem and the error-recovery process. The hidden-node problem disrupts a contention-free multicast transmission, and the error-recovery

Manuscript received December 22, 2006; revised July 3, 2007, October 24, 2007, and January 3, 2008. This work was supported by the Ministry of Information and Communication, Korea, under the Information Technology Research Center support program supervised by the Institute of Information Technology Advancement under Grant IITA-2008-(C1090-0801-0003). The review of this paper was coordinated by Prof. X. Shen.

B.-S. Kim is with the Department of Computer and Information Communication Engineering, HongIk University, Chungcheongnamdo 339-701, Korea (e-mail: jsnbs@hongik.ac.kr).

S. W. Kim is with School of Electrical Engineering and Computer Science, Yeungnam University, Gyeongsangbuk-do 712-749, Korea (e-mail: ksw@ieee.org).

R. L. Ekl is with Motorola Inc., Schaumburg, IL 60173 USA (e-mail: randy.ekl@motorola.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2008.917226

process enables the sender to know whether a multicast packet has been successfully received at all of the member stations (STAs). The error-recovery process, which requires feedback from the receivers, such as ACK packets, causes the wireless system to be less bandwidth efficient since this feedback represents overhead with respect to a default multicast operation. Moreover, the extent of this overhead increases as the number of the intended receivers increases.

A scheme with minimal ACK overhead, named the orthogonal frequency division multiplex access (OFDMA)-based multicast ACK (OMACK), is proposed in this paper. The proposed scheme uses one OFDM symbol for the ACKs from all the member STAs, and each member STA indicates its packet reception status by transmitting one of the two BPSK symbols on a previously assigned subcarrier within the OFDM symbol. Therefore, the time consumed for the error-recovery process is even less than that of the IEEE 802.11-based unicast packet transmission. In this paper, we first review the wireless multicast protocols proposed in the literature, as well as in various standards. In Section III, the motivation for, and a detailed description of, the proposed scheme are given. In Section IV, the proposed scheme is thoroughly evaluated through simulations as well as theoretical methods, and the enhanced performance that it offers is shown. Finally, our conclusion is given in Section V.

II. Related Works

A. Multicast Transmission in Wireless Communication Standards

Most wireless communication standards, such as IEEE 802.11, cdma2000, and WiMax, provide mechanisms to achieve a reliable unicast transmission by adopting an ACK mechanism, request-to-send/clear-to-send (RTS/CTS) handshaking, an automatic repeat request (ARQ), or a retransmission. In addition to specifying a unicast operation, these standards specify mechanisms of a multicast transmission. However, a common problem with the multicast methods in these standards is that there is no mechanism for a reliable multicast transmission. All of these standards specify that the multicast traffic be transmitted only once without an ARQ. Since the traffic is sent to multiple STAs and is not acknowledged by each receiver, the sender is not able to clarify whether the transmission is successful. As a result, the sender does not know if it should retransmit the multicast packet. For the IEEE 802.11 standard in [11], a multicast packet is transmitted without RTS/CTS/ACK handshaking, which, naturally, provides an unreliable transmission. Furthermore, all of the multicast packets are transmitted right after a beacon packet transmission. The rationale behind this is to prevent an STA in the power save mode from not receiving a multicast packet since all of the STAs have to be awake to receive the beacon packet. On the other hand, the multicast in cdma2000 and WiMax provides relatively reliable transmission methods. Cdma2000 1XEV-DO provides an error-correction code in the multicast MAC packet to reduce the MAC packet error rate (PER). This is the Reed–Solomon code, which is described in [12] and [13]. Normally, a MAC packet has only an error check sequence. Furthermore, as described in [14] and [15], Mobile WiMax proposes a multibase station access mechanism for multicasting. By receiving duplicates of the same packet from multiple base stations (BSs) at the same time, the spatial diversity at a mobile terminal is increased, and as a consequence, the PER can be reduced.

B. Reliable Multicast MAC Protocols

Reliable multicast has been studied relatively little compared with reliable unicast. In addition, most of the studies on this topic have focused on IEEE 802.11-based WLANs and mobile ad hoc networks. Reference [1] proposes the broadcast medium window (BMW). The BMW exchanges RTS/CTS/DATA/ACK packets with one of the member STAs, and then, RTS/ACK packets are exchanged with the entire member STAs. The RTS/ACK packets are transmitted through a contention-based channel access. As an enhanced version of the BMW, the batch-mode multicast MAC (BMMM) protocol is proposed in [5]. The transaction of the BMMM between the sender and the member STAs is a sequence of multiple RTS/CTS exchanges, data packet transmission, and multiple request ACK/ACK exchanges. During this sequence, there is no contention-based channel access. Therefore, compared with the BMW, the BMMM reduces the overhead resulting from the multiple contention periods of the access channel that is required to transmit the RTS/ACK.

Kuri and Kasera [4] proposed the leader-based protocol (LBP) for multicast to reduce the overhead that is caused by multiple CTSs and ACKs. A sender in the LBP selects one STA among the multicast group member STAs, which is called a leader. Then, only the leader responds with a CTS and an ACK corresponding to the RTS and the data packet, respectively. If a member STA receives a packet with an erroneous payload, it sends a negative acknowledgement (NACK) packet at the end of the data packet, and this NACK causes a collision with the ACK from the leader. If there is a collision after the transmission of the data packet, the sender recognizes that at least one STA failed to receive the data packet. In that case, it sends the data packet again. Fig. 1(a) illustrates an example scenario of the LBP. In the example scenario, receiver N fails to receive a data packet and sends a NACK packet at the end of the data packet transmission. This NACK packet results in a deliberate collision, causing the sender to retransmit the data packet.

The multicast aware MAC protocol (MMP) is proposed in [6]. Unlike the aforementioned protocols, the MMP does not use RTS/CTS handshaking but rather data/ACK. After a data packet is transmitted, all of the member STAs transmit their ACK packets to the sender following the preassigned sequential order, as shown in Fig. 1(b). In the example scenario, receiver N fails to receive a data packet and sends a NACK packet in its preassigned location. Thus, the sender retransmits the data packet. The scheme proposed in [7] focuses only on the hidden node problem. Therefore, the error-recovery process in [7] adopts one of the aforementioned schemes.

Unlike the aforementioned ARQ methods in wireless multicast, [8] focused on the data rate for multicasting. The data rate for the wireless multicast is commonly fixed to the lowest data rate to provide the better PER to all members, which

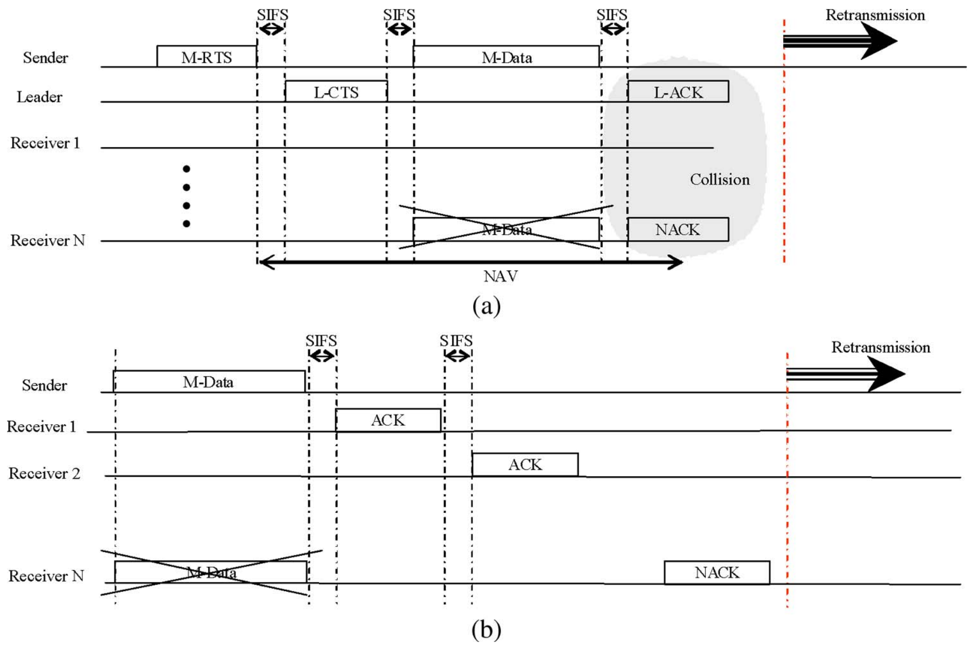


Fig. 1. Example scenarios of (a) LBP and (b) MMP.

experience different channel conditions. However, while providing the better PER, it reduces the channel efficiency. Therefore, in the scheme in this paper, the source collects the channel information from all member STAs and decides the best data rate to achieve a certain level of network performance. The proposed scheme chooses the minimum or average data rate among the possible rates for member STAs. Alternatively, the rate is chosen by averaging the weighted possible rates. Integrated cellular and ad hoc multicast in [9] also proposes to use the better data rate instead of using the lowest rate for multicasting. This addresses the rate issue for multicast over third-generation networks. The BS selects nodes, which have good channel quality, among all member nodes and multicasts the data with the best data rate possible for the selected nodes. Then, the selected member nodes forward the data to their neighboring member nodes in the IEEE 802.11 ad hoc mode. In other words, this scheme uses a high data rate for multicast by reducing the member size, and the selected members serve as proxies for the receivers with poor channel quality with the BS. An ad hoc routing algorithm is also required.

Besides the ARQ and the data rate for wireless multicast, Choi *et al.* [10] proposed a layer 2 forward error correction in the IEEE 802.11-based WLAN to enhance transmission reliability without an ARQ.

III. OFDMA-Based Reliable Multicast MAC Protocol

A. Motivation

The previously proposed error-recovery processes for multicasting can be categorized into two types—multiple ACKs and leader-based ACKs. For the multiple-ACK-based schemes, the sender can collect the information of multicast packet reception from all of the multicast group member STAs. However, ACK transmissions degrade the channel efficiency and reduce the overall network performance. This degradation is increased as the number of member STAs increases. On the other hand, leader-based ACK schemes reduce the overhead that is caused by multiple ACK packet transmissions by allowing only a leader to send an ACK. Note that the overhead of a leader-based ACK scheme is the same as that of unicast. However, when one of the member STAs fails to demodulate the Multicast RTS (M-RTS), the Leader CTS (L-CTS), or the MAC header of a multicast data packet, as shown in Fig. 1(a), it cannot send a NACK packet since it cannot recognize if the received packet is multicast and if it is the destination of this packet. Since the STA does not send a NACK, no collision is experienced at the sender. Therefore, leader-based ACK schemes may not be reliable in terms of the detection of failed transmissions.

B. OFDMA-Based Reliable Multicast for Centralized WLANs

In this paper, a new reliable multicast transmission method is proposed over the IEEE 802.11-based WLAN. Although the IEEE 802.11 standard specifies a distributed mode with a contention-based channel access, as well as a centralized mode with a polling-based channel access, WLANs that are deployed in the real world use a centralized architecture with a contention-based channel access. Therefore, the proposed scheme targets centralized WLANs with a contention-based channel access. As with the IEEE 802.11 standard, all of the multicast packets are transmitted right after a beacon packet to deal with the problem of STAs in the power save mode.

1) Reliable Multicast With the OMACK: A new type of an ACK is proposed, which is called the OFDMA-based multicast ACK (OMACK). This is the main innovation of the scheme that is proposed in this paper. In this paper, the OMACK is not only a proposed ACK method for multicast but also a new format of an ACK for multicast. Fig. 2 shows the structure of the OMACK. The OMACK is a simple packet consisting of a preamble and an OFDM symbol with a cyclic prefix,

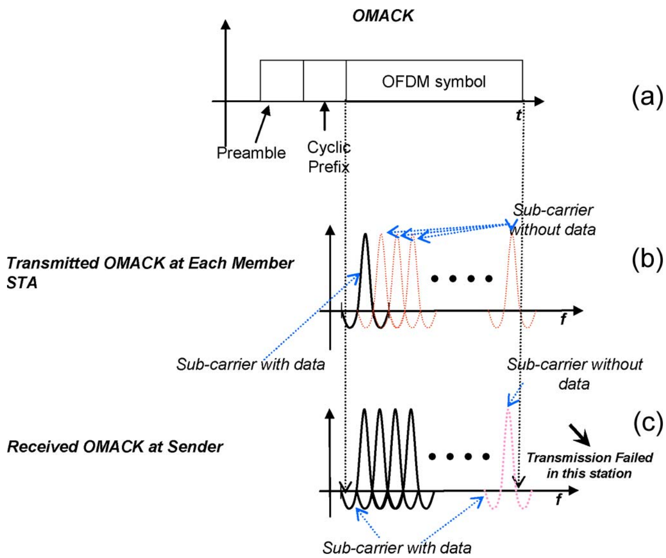


Fig. 2. (a) Generic OMACK structure. (b) OMACK transmitted by each STA. (c) Received OMACK at the sender.

as shown in Fig. 2(a). Each member STA has a preassigned unique subcarrier number for each group identification (ID). The process of assigning a unique subcarrier number is described in Section II-B2. When a member STA receives a multicast packet from the sender, it allocates a symbol on the preassigned subcarrier as an ACK for the packet. The symbol is one of the two BPSK symbols, i.e., 1 or -1. The successful reception of the multicast packet on the subcarrier is indicated by a 1, whereas a -1 indicates a failed reception. If a member STA cannot demodulate even the MAC header of the multicast data packet, it will not generate an OMACK. An OFDM symbol that is generated by each member STA for the ACK has only one subcarrier with a data symbol, and the other subcarriers are empty, as illustrated in Fig. 2(b). After the preamble is attached, the OFDM symbol is sent to the multicast sender. It is assumed that all of the member STAs send their OMACK at the same time after a short interframe space (SIFS) idle period. At the multicast sender, the subcarriers in the received OMACK are loaded with BPSK symbols to indicate each member's reception status, as shown in Fig. 2(c).

An example scenario of the proposed method is shown in Fig. 3. The sender multicasts a data packet to the member STAs, which are from receiver 1 to N. Since receiver N does not receive the multicast packet, it will not send an OMACK to the sender. After receiving the OMACK, the sender checks the subcarriers, which are assigned to the member STAs. If any one of the member STA's subcarriers is not allocated with any symbol or is allocated with the -1 BPSK symbol, the sender prepares to remulticast the previous data packet.

The time offset problem that is caused by imperfect time synchronization and different propagation delays from all of the member STAs is solved by using a longer cyclic prefix, as shown in [16]–[18], which is longer than the delay spread profiles. That is, transmission delays of member STAs due to nonsynchronization can be considered as the delay spread profiles of one transmission in the normal OFDM system.

2) Subchannel Assignment Process: The IEEE 802.11 standard does not specify a group-joining process. Since the WLAN is mainly designed as a wireless Internet extension, joining a group is performed by means of a layer 3 protocol such as the Internet Group Management Protocol (IGMP). When an STA wants to join a multicast group, it unicasts to the access point (AP) an IGMP Membership Query message as a payload of a MAC data packet. When the packet is received by the AP, it goes to layer 3. If the packet is an IGMP Query message, the AP creates a layer 2 multicast table with the group address and the address of the STA. An example of a layer 2 multicast table is shown in Fig. 4. Then, the AP evaluates each subcarrier's condition and selects the subcarrier that has the best quality among all available subcarriers. Selecting the subcarrier is defined as follows:

$$\alpha = \arg\max_{\alpha} \left(\mathrm{SNR}(\mathrm{CSI}_\alpha)\right), \quad \alpha \in \mathrm{ASC} \tag{1}$$

where $\mathrm{SNR}(\cdot)$ is the signal-to-noise ratio as a function of CSI_α, which is the channel state information of subcarrier α, and ASC is the set of currently available subcarriers. The selected subcarrier ID is sent back to the member STAs by piggybacking it on an ACK packet. The assigned subcarrier ID has to be unique for each STA within the same multicast group address.

IV. Performance Evaluations

In Section III, it is mentioned that the schemes that are proposed in the literature fall into two categories—multiple ACKs and leader-based ACKs. It is also mentioned that leader-based ACK schemes may fail to detect failed transmissions. As a consequence, the OMACK and the latest multiple-ACK-based scheme, which is the MMP, are evaluated and compared through an analytical method and simulations in this section.

Although the OMACK is compared with only the MMP in this paper, the advantage of the OMACK over the LBP can be estimated. When one receiver does not successfully receive multicast traffic from a source, the receiver might not be able to send a NACK, so that there is no collision with the ACK. Therefore, the source makes the wrong decision concerning the transmission. On the other hand, the OMACK definitely solves this problem. In this case, the receiver will not send an OFDM symbol. When the source receives an OMACK, the subcarrier that is assigned to the receiver will be empty so that the source detects the transmission failure. However, if a channel error on the multicast data packet is ignored, which is unrealistic, the OMACK has a small performance advantage over the LBP in terms of the protocol overhead since the size of an OMACK is smaller than that of an ACK in the LBP.

The notations used in this section are listed in Table I.

A. Transmission Probability

Consider a system consisting of N STAs forming a single subnet. Each STA always has a packet that is available for a transmission. In other words, we operate under saturation conditions, where the transmission queue of each STA is assumed to be always nonempty. There are R receivers belonging to the multicast group, i.e., $R \leq N$. All of the STAs are located in the

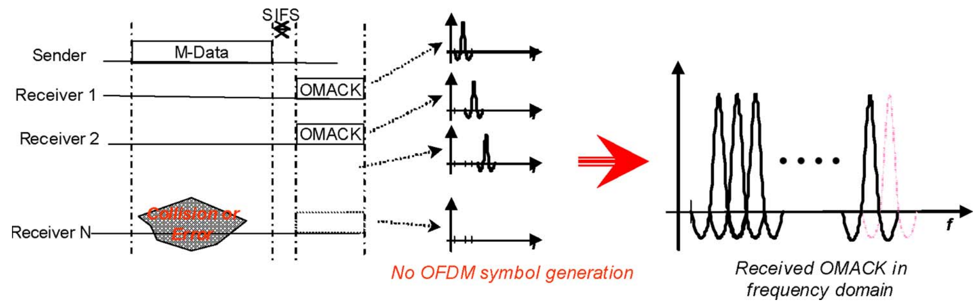


Fig. 3. Example scenario of an OMACK.

Group Address	Member MAC address	Sub-carrier ID
239.225.0.x	01-00-5e-7F-00-XX	10
	01-00-5e-7F-00-YY	15
	01-00-5e-7F-00-ZZ	22
239.225.0.x	01-00-8e-9F-00-XX	15
	01-00-8e-9F-00-YY	5

Fig. 4. Example of a layer 2 multicast table.

TABLE I
NOTATIONS USED IN THE PERFORMANCE EVALUATION

N	Number of STAs in a single subnet
R	Number of multicast receivers in the multicast group
M	Number of counter time slots required for all the multicast receivers to receive a packet correctly
B	Maximum backoff stage
X	Event in which an STA transmits a packet in a counter time slot
τ	Probability that an STA transmits a packet in a counter time slot
p	Packet loss probability
p_c	Packet loss probability with collision
p_e	Packet loss probability without collision
D	Packet transmission delay
S	Normalized system throughput
T_{ct}	Time duration of a counter time slot
σ	Time duration of an empty slot time

transmission range of the sender. The channel conditions, such as shadowing and fading, are assumed to generate a constant packet loss probability p_e for all of the wireless connections. The case where $p_e = 0$ is equal to the ideal channel conditions. We assume that the ACK packets are received with $p_e = 0$.

Let us adopt the notation $CW_b = 2 \times CW_{b-1}$, where $b \in \{1, \ldots, B\}$ is called the backoff stage, and B is the maximum backoff stage such that $CW_{\max} = 2^B CW_{\min}$. We assume that the STA discards the packets that are not successfully transmitted at the maximum backoff stage.

We assume that all of the STAs operate synchronously. A discrete and integer timescale is adopted: t and $t+1$ correspond to the beginnings of two consecutive decrements of the backoff time counter. We call the time interval between t and $t+1$ the "counter time slot." Note that the counter time slot (variable duration) is different from the slot time (constant duration). Since the decrement of the backoff time counter is stopped when the channel is deemed to be busy, the time interval between the beginnings of two consecutive counter time instants may be much longer than the constant slot time size σ.

Let us denote the event in which an STA transmits a packet in a counter time slot as X. We are interested in the unconditional probability $\tau = P(X)$ that an STA transmits a packet in a counter time slot. The probability that an STA is found in backoff stage i is given by [20]

$$P(b=i) = \tau \frac{P(b=i|X)}{P(X|b=i)}, \quad i \in (0, \ldots, B). \tag{2}$$

By summing this for all i's, we obtain

$$\sum_{i=0}^{B} P(b=i) = 1 = \tau \sum_{i=0}^{B} \frac{P(b=i|X)}{P(X|b=i)}. \tag{3}$$

From (3), τ can be expressed as

$$\tau = \frac{1}{\sum_{i=0}^{B} \frac{P(b=i|X)}{P(X|b=i)}}. \tag{4}$$

The transition probabilities of the backoff stage are given by

$$\begin{cases} P\left(b(t+1)=i+1|b(t)=i\right)=p, & \text{for } i=0,\ldots,B-1 \\ P\left(b(t+1)=0|b(t)=i\right)=1-p, & \text{for } i=0,\ldots,B-1 \\ P\left(b(t+1)=0|b(t)=B\right)=1 \end{cases} \tag{5}$$

where p is the probability that a packet that is transmitted will be lost. Let p_c be the probability that a packet that is transmitted will collide. We assume that the events of p_c and those of p_e are mutually exclusive. Then, we obtain

$$p = p_c + p_e. \tag{6}$$

Following [21], p is assumed to be a constant value, which is independent of the number of retransmissions that occur.

It readily follows that the conditional backoff stage probability $P(b=i|X)$ is a geometric distribution, i.e.,

$$P(b=i|X) = \frac{(1-p)p^i}{1-p^{B+1}}, \quad i \in (0, \ldots, B). \tag{7}$$

From the independence among transmission cycles and the renewal theory, we can obtain the conditional transmission probability $P(X|b=i)$ by dividing the average number of counter time slots that are spent for the transmission in a transmission cycle (exactly one counter time slot) by the average number of counter time slots that are spent by the STA during the whole cycle (the backoff and transmission cycle in backoff stage i). Since a counter time slot corresponds to a backoff counter decrement, it readily follows that

$$P(X|b=i) = \frac{1}{1+E[c_i]}, \quad i \in (0,\dots,B) \tag{8}$$

where $E[c_i]$ is the average value of the backoff counter that is extracted by an STA entering stage i. $E[c_i]$ is equal to $CW_i/2$ based on the assumption of a uniform distribution in the range (0, CW_i). By substituting (7) and (8) into (4), we obtain

$$\tau = \frac{1}{1+\frac{1-p}{1-p^{B-1}}\sum_{i=0}^{B} P^i E[c_i]}. \tag{9}$$

At the steady state, each remaining STA transmits a packet with probability τ. Thus, p_c can be expressed as

$$p_c = p - p_e = 1-(1-\tau)^{N-1}. \tag{10}$$

This corresponds to the probability that at least one of the $N-1$ remaining STAs transmits. Equation (10) can be rewritten as

$$\tau = 1-(1-p+p_e)^{\frac{1}{N-1}}. \tag{11}$$

Equations (9) and (11) represent a nonlinear system with two unknown parameters—τ and p—which can be solved using numerical techniques.

B. Packet Transmission Delay

Let M be the number of counter time slots that are required for the multicast receivers to successfully receive the multicast packet. Because the average number of counter time slots at backoff stage i before the transmission is $E[c_i]$, the average value of M is given by

$$E[M] = \sum_{i=0}^{B} (1+E[c_i])\, P[b=i]. \tag{12}$$

From (2), (7), and (8), (12) can be rewritten as

$$E[M] = \sum_{i=0}^{B} \tau\,(1+E[c_i])^2 \,\frac{(1-p)p^i}{1-p^{B+1}}. \tag{13}$$

Let T_H, T_{OMACK}, T_{SIFS}, and T_{DIFS} be the time duration of the packet header, the OMACK, the SIFS, and the distributed interframe space (DIFS), respectively. Let T_S, T_F, and T_P be the time duration of the successful packet transmission cycle of the OMACK, the unsuccessful packet transmission cycle of the OMACK, and a packet of the OMACK or the MMP, respectively. In the case of a basic access (without RTS/CTS handshaking), we obtain

$$E[T_S] = E[T_F] = T_H + E[T_P] + T_{\mathrm{SIFS}} + T_{\mathrm{OMACK}} + T_{\mathrm{DIFS}}. \tag{14}$$

The mean time of a counter time slot T_{ct} is calculated as follows. The probability that a sender sees an idle channel during a counter time slot is $P[\text{idle}] = (1-\tau)^N$, which takes time σ. The probability of a successful transmission during a counter time slot is $P[\text{success}] = (1-p_e)N\tau(1-\tau)^{N-1}$, which takes time T_S. The probability of an unsuccessful transmission during a counter time slot is $P[\text{fail}] = 1-P[\text{idle}]-P[\text{success}]$, which takes time T_F. Thus, the mean time of a counter time slot of the OMACK, i.e., $E[T_{ct}]$, is given by

$$\begin{aligned} E[T_{ct}] &= p[\text{idle}]\sigma|P[\text{success}]E[T_s] + P[\text{fail}]E[T_F] \\ &= (1-\tau)^N\sigma + N\tau(1-\tau)^{N-1}(1-p_e)E[T_S] \\ &\quad + \left[1-(1-\tau)^n - N\tau(1-\tau)^{N-1}\right. \\ &\qquad \left.\times (1-p_e)\right] E[T_F] \\ &= (1-\tau)^N\sigma + \left[1-(1-\tau)^n\right] E[T_F]. \end{aligned} \tag{15}$$

Here, the last equality comes from (14).

The mean time of a successful packet transmission cycle of the MMP, i.e., $E[T_S^{\mathrm{MMP}}]$, is given by

$$\begin{aligned} E\left[T_S^{\mathrm{MMP}}\right] &= E\left[T_F^{\mathrm{MMP}}\right] \\ &= T_H + E[T_P] + R\times(T_{\mathrm{SIFS}} + T_{\mathrm{ACK}}) + T_{\mathrm{DIFS}} \end{aligned} \tag{16}$$

where T_{ACK} is the time duration of the ACK. The mean time of the MMP's counter time slot is given by

$$\begin{aligned} E\left[T_{ct}^{\mathrm{MMP}}\right] &= p[\text{idle}]\sigma| + P[\text{success}]E\left[T_S^{\mathrm{MMP}}\right] \\ &\quad + P[\text{fail}]E\left[T_F^{\mathrm{MMP}}\right] \\ &= (1-\tau)^N\sigma + N\tau(1-\tau)^{N-1} \\ &\quad \times (1-p_e)E\left[T_S^{\mathrm{MMP}}\right] \\ &\quad + \left[1-(1-\tau)^N - N\tau(1-\tau)^{N-1}\right. \\ &\qquad \left.\times (1-p_e)\right] E\left[T_F^{\mathrm{MMP}}\right] \\ &= (1-\tau)^N\sigma + \left[1-(1-\tau)^N\right] E\left[T_F^{\mathrm{MMP}}\right]. \end{aligned} \tag{17}$$

Here, the last equality comes from (16).

The packet transmission delay is defined as the time period from the start of a packet becoming a head-of-line in the queue to the end of the packet's removal from the queue [18]. The packet's removal is caused by the successful reception by all of the members or a collision after the maximum backoff stage is reached. When the sender obtains data from a higher layer protocol, a packet containing these data is constructed and transmitted. Following this, the sender must process every ACK or OMACK that is received for the packet. Whenever the sender fails to receive ACKs from all receivers or an OMACK, including all subcarriers that allocated positive symbols for the data packet, the packet must be remulticasted, the backoff stage must be increased, and the backoff timer must be restarted.

Let us denote the packet transmission delay of an OMACK by D^{OMACK}. Considering that the sender contends for the channel for M counter time slots before the removal of the packet from the queue, the average packet transmission delay of an OMACK is

$$E[D^{\mathrm{OMACK}}] = E[M]E[T_{ct}]. \tag{18}$$

The average delay expression in (18) is consistent with the one found in [19]. A packet transmission in the MMP is completed at the end of multicast receivers' ACKs. Thus, the packet transmission delay of the MMP is

$$E[D^{\mathrm{MMP}}] = E[M]E\left[T_{ct}^{\mathrm{MMP}}\right]. \tag{19}$$

As the number of nodes increases, the proportion of $E[T_F^{\mathrm{MMP}}]$ in $E[T_{ct}^{\mathrm{MMP}}]$ increases more than that of $E[T_F]$ in $E[T_{ct}]$, which results in an increase in the packet delay. Also, note that in (18), the packet delay increases as the number of the receivers increases. These trends will be shown in the numerical results.

C. Throughput

Let S be the normalized system throughput, which is defined as the fraction of time that the channel is used to successfully transmit packets. We can express S as follows:

$$S = \frac{E[\text{time duration of a successfully transmitted packet}]}{E[\text{time duration of a counter time slot}]} = \frac{P[\text{success}]E[P]}{E[T_{ct}]}. \tag{20}$$

The throughput of the OMACK is given by

$$S^{\mathrm{OMACK}} = \frac{(1-P_e)N\tau(1-\tau)^{N-1}E[P]}{E[T_{ct}]}. \tag{21}$$

In a similar way, the throughput of the MMP is given by

$$S^{\mathrm{MMP}} = \frac{P[\text{success}]E[P]}{E\left[T_{ct}^{\mathrm{MMP}}\right]} = \frac{(1-P_e)N\tau(1-\tau)^{N-1}E[P]}{E\left[T_{ct}^{\mathrm{MMP}}\right]}. \tag{22}$$

D. Numerical Results

We compared the analysis results with the results obtained from the IEEE 802.11 distributed-coordination-function-based simulator. This simulator is an event-driven custom simulation program, which was used in [22]. This simulator, which is written in the C++ programming language, follows all the IEEE 802.11 protocol details for each independently transmitted STA. The values of the parameters that are used to obtain the numerical results for the analytical model and the simulation runs are summarized in Table II. The values of these parameters are based on the IEEE 802.11a standard [19]. All of the simulation results in the plots are obtained with a 95% confidence interval. p_e is set to 0.08, as mentioned in the standard [19].

Fig. 5 shows the variation of the throughput of the OMACK and the MMP with the number of STAs where R is set to 5. The analytical results (lines) practically coincide with the simulation results (symbols). The throughputs of the OMACK and the MMP decrease as the number of STAs increases. This comes from the increase in the number of packet collisions. The throughput of the OMACK is higher than that of the MMP. This is because the MMP incurs more overhead than the OMACK does due to the use of multiple ACKs. The difference in the throughput between the OMACK and the MMP remains constant because of the constant number of receivers R.

TABLE II
PARAMETER VALUES

Parameter	Value
CWmin	15
CWmax	1023
SIFS time	16 us
DIFS time	34 us
Slot time	9 us
MAC header	272 bits
PHY header	46 bits +Padding Bits
Preamble	16 us
ACK packet time	44 us
OMACK packet time	20 us
Packet payload	8192 bits
Channel bit rate	6 Mbps

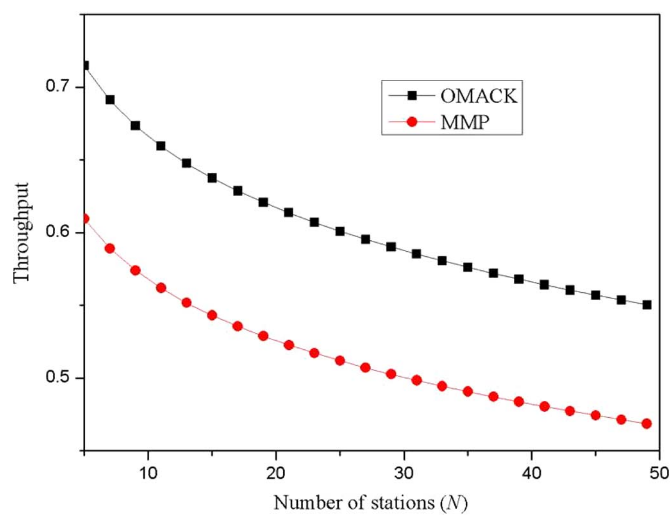


Fig. 5. Number of STAs and the throughput for a constant number of receivers ($R = 5$).

Fig. 6 shows the delay as a function of the number of STAs, where R is kept constant. It is noted that the delay of the OMACK is less than that of the MMP because the OMACK requires less overhead in terms of the number of ACKs. The difference in the delay between the two methods becomes larger as the number of STAs increases. This is explained by (18) and (19). The difference in the delay that is obtained by subtracting (18) from (19) is

$$\text{Delay\_difference} = E[M]\left[1-(1-\tau)^N\right] \cdot \{(R-1)\cdot T_{\mathrm{SIFS}} + R\cdot T_{\mathrm{ACK}} - T_{\mathrm{OMACK}})\}. \tag{23}$$

Based on (23), as the number of STAs N increases, $[1-(1-\tau)^N]$ exponentially increases. Thus, the difference in the delay increases as N increases.

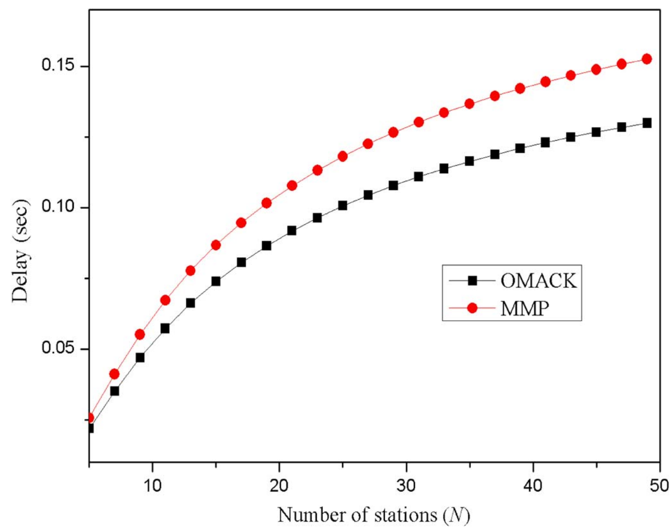


Fig. 6. Number of STAs and the delay for a constant number of receivers ($R = 5$).

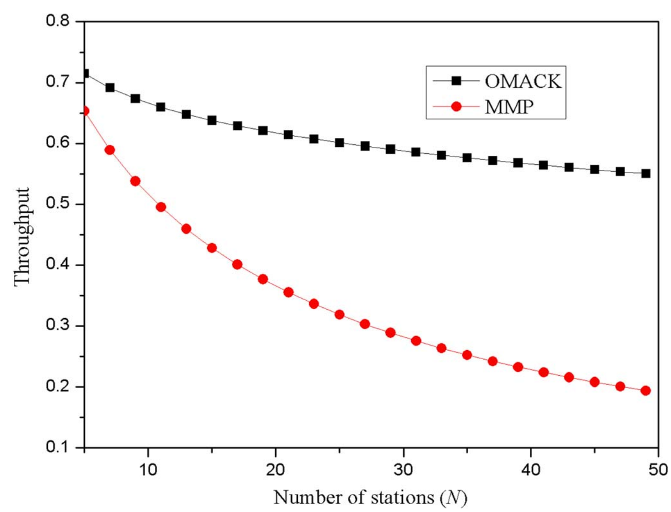


Fig. 7. Number of STAs and the throughput for a variable number of receivers ($R = N - 2$).

Figs. 7 and 8 show the variation of the throughput and the delay of the OMACK and the MMP according to the change of N, respectively. The value of R is set to $N - 2$, i.e., two less than the entire STAs in a network. The performance of the OMACK is independent of the number of receivers. This is because the number of ACKs is constant in the OMACK, irrespective of the number of receivers. However, the performance of the MMP is largely dependent on the number of receivers, as shown in (19). This is because the overhead of the MMP increases as the number of the receivers increases. Thus, the difference in the performance between the two methods becomes larger as the number of the receivers increases.

Figs. 9 and 10 show the variation of the throughputs and the delays of the OMACK and the MMP as the number of the multicast receivers increases. The number of nodes N is set to 25. These figures illustrate the dependence of the performance on the number of receivers. It is also shown that the performance of the OMACK is constant, whereas that of the MMP degrades, as the number of the multicast receivers increases. This comes from the increased overhead resulting from the use of multiple ACKs in the MMP. The OMACK maintains one OFDM system, no matter how many group members there are. On the other

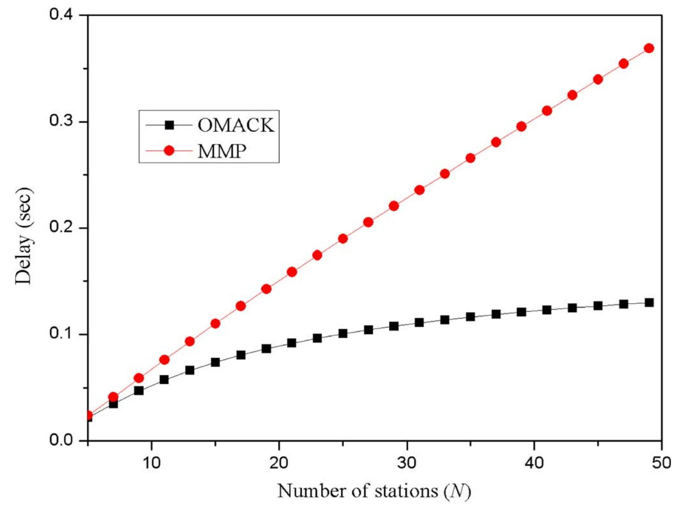


Fig. 8. Number of STAs and the delay for a variable number of receivers ($R = N - 2$).

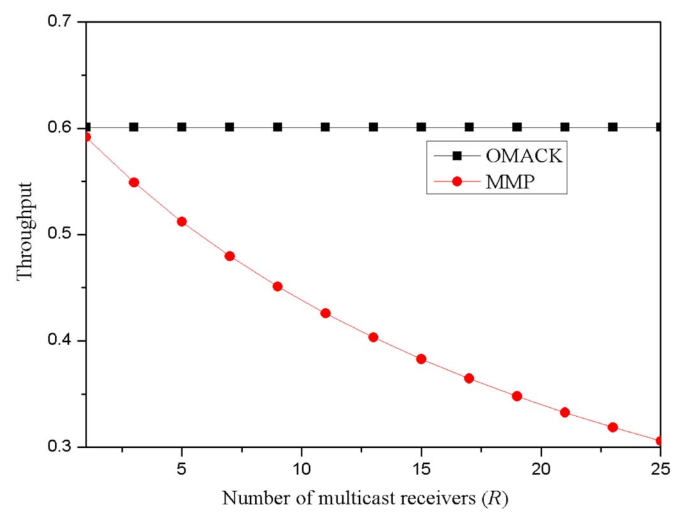


Fig. 9. Number of multicast receivers and the throughput.

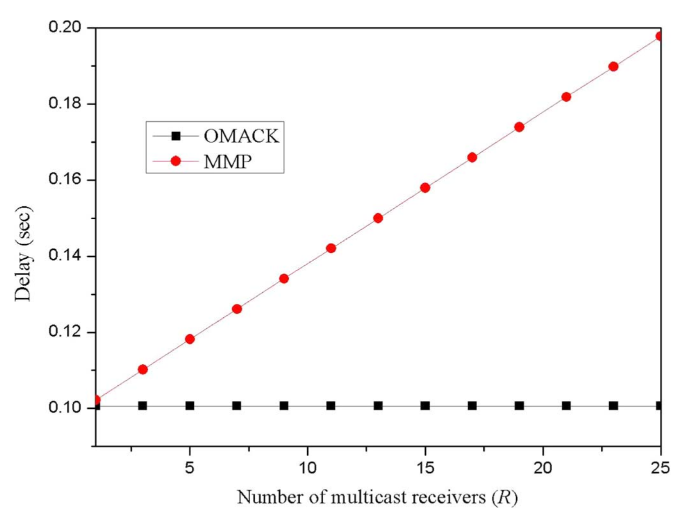


Fig. 10. Number of multicast receivers and the delay.

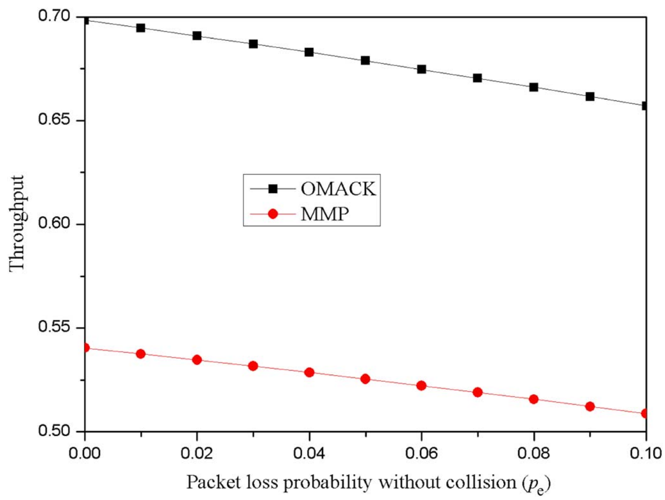


Fig. 11. Packet loss probability without the collision and the throughput.

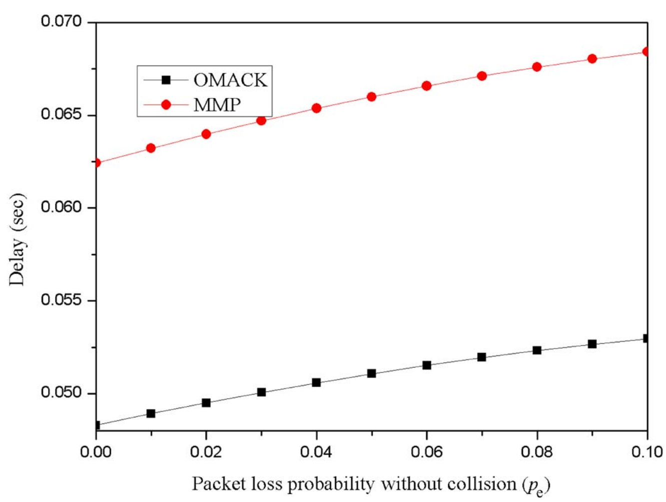


Fig. 12. Packet loss probability without the collision and the delay.

hand, as mentioned before, the ACK-associated overhead in the MMP increases as the number of the group members increases.

Figs. 11 and 12 show the throughput and the delay as a function of the packet loss probability without collision p_e, respectively, where N is set to 10, and R is set to 8. Note that p_e corresponds to the PER without a collision. The throughput decreases as p_e increases, and the delay increases as p_e increases. This is because more remulticasting occurs as the PER increases. The difference in performance between the two methods is almost constant because the difference in the overhead is constant.

V. Conclusion

In this paper, we have proposed a new reliable multicast scheme over the IEEE 802.11-based WLAN. The major innovation is the use of an OFDMA mechanism for acknowledging whether a multicast packet is successfully received by each group member STA. Each member STA is preassigned with a unique subcarrier number that is aligned with a multicast group. When STAs successfully receive a multicast packet, they send an OFDM symbol, which is called an OMACK, by allocating one bit in their own subcarrier. When the original sender receives the OFDM symbol, it checks if there are any subcarriers without any bits. If there is a subcarrier with no bits, the multicast packet transmission is considered to be a failure. The OMACK and the MMP have been compared and evaluated through an analytical method as well as simulations. The performance of the OMACK outperforms that of the MMP in terms of the throughput and the delay. In other words, the OMACK provides a reliable error recovery mechanism for multicast transmissions with minimum overhead.

The proposed scheme provides a unique feature that allows the sender to collect statistics on multicast packet reception for each member STA. Such statistics can be utilized to make a decision concerning the necessity for a retransmission. In a future work, a retransmission method for failed multicast could be studied.

References

[1] K. Obraczka, “Multicast transport protocols: A survey and taxonomy,” *IEEE Commun. Mag.*, vol. 36, no. 1, pp. 94–102, Jan. 1998.

[2] A. El-Sayed, V. Roca, and L. Mathy, “A survey of proposals for an alternative group communication service,” *IEEE Netw.*, vol. 17, no. 1, pp. 46–51, Jan./Feb. 2003.

[3] K. Tang and M. Garcia, “MAC reliable broadcast in ad hoc networks,” in *Proc. IEEE MILCOM*, Oct. 2001, pp. 1008–1013.

[4] J. Kuri and S. K. Kasera, “Reliable multicast in multi-access wireless LANs,” *Wireless Netw.*, vol. 7, no. 4, pp. 359–369, Jul. 2001.

[5] M. T. Sum, L. Huang, A. Arora, and T. H. Lai, “Reliable MAC layer multicast in IEEE 802.11 wireless networks,” *Wireless Commun. Mob. Comput.*, vol. 3, no. 4, pp. 439–453, Jun. 2003.

[6] H. Gossain, N. Nandiraju, K. Anand, and D. P. Agrawal, “Supporting MAC layer multicast in IEEE 802.11 based MANET’s: Issues and solutions,” in *Proc. IEEE LCN*, Nov. 2004, pp. 172–179.

[7] C.-W. Bao and W. Liao, “Performance analysis of reliable MAC-layer multicast for IEEE 802.11 wireless LANs,” in *Proc. ICC*, May 2005, vol. 2, pp. 1378–1382.

[8] J. Kim and D.-H. Cho, “Enhanced adaptive modulation and coding schemes based on multiple channel reportings for wireless multicast systems,” in *Proc. VTC*, Sep. 2005, vol. 2, pp. 725–729.

[9] R. Bhatia, L. Li, H. Luo, and R. Ramjee, “ICAM: Integrated cellular and ad hoc multicast,” *IEEE Trans. Mob. Comput.*, vol. 5, no. 8, pp. 1004–1014, Aug. 2006.

[10] S. Choi, Y. Choi, and I. Lee, “IEEE 802.11 MAC-level FEC scheme with retransmission combining,” *IEEE Trans. Commun.*, vol. 5, no. 1, pp. 203–211, Jan. 2006.

[11] IEEE 802.11 WG, *Draft Supplement to STANDARD FOR Telecommunications and Information Exchange Between Systems—LAN/MAN Specific Requirements—Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Medium Access Control (MAC) Enhancements for Quality of Service (QoS)*, Jan. 2005. IEEE 802.11e/D13.0.

[12] 3GPP2 Specification, *CDMA2000 High Rate Broadcast-Multicast Packet Data Air Interface Specification*, Feb. 2006. 3GPP2 C.S0054-A, ver. 1.0.

[13] J. Wang, R. Sinnarajah, T. Chen, Y. Wei, and E. Tiedemann, “Broadcast and multicast service in cdma2000,” *IEEE Commun. Mag.*, vol. 42, no. 2, pp. 76–82, Feb. 2004.

[14] IEEE 802.16 WG, *Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems. Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands*, Jun. 2005. IEEE P802.16e/D9.

[15] *Mobile WiMax—Part I: A Technical Overview and Performance Evaluation*, Feb. 2006, WiMax Forum.

[16] Z. Cao, U. Tureli, and Y.-D. Yao, “Deterministic multiuser carrier-frequency offset estimation for interleaved OFDMA uplink,” *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1585–1594, Sep. 2004.

[17] S. Kaiser and W. A. Krzymien, “Performance effects of the uplink asynchronism in a spread spectrum multicarrier multiple access system,” *Eur. Trans. Commun.*, vol. 10, no. 4, pp. 399–406, Jul./Aug. 1999.

[18] S. Kapoor, D. J. Marchok, and Y.-F. Huang, "Adaptive interference suppression in multiuser wireless OFDM system using antenna arrays," *IEEE Trans. Signal Process.*, vol. 47, no. 12, pp. 3381–3391, Dec. 1999.

[19] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer in the 5 GHz Band,* IEEE Std. 802.11a-1999, Sep. 1999.

[20] G. Bianchi and I. Tinnirello, "Remarks on IEEE 802.11 DCF performance analysis," *IEEE Commun. Lett.*, vol. 9, no. 8, pp. 765–767, Aug. 2005.

[21] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

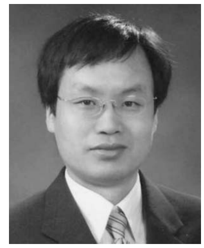
[22] S. W. Kim, B. Kim, and Y. Fang, "Downlink and uplink resource allocation in IEEE 802.11 wireless LANs," *IEEE Trans. Veh. Technol.*, vol. 54, no. 1, pp. 320–327, Jan. 2005.

[23] D. Towsley, J. Kurose, and S. Pingali, "A comparison of sender-initiated and receiver-initiated reliable multicast protocols," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 3, pp. 398–406, Apr. 1997.

[24] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "IEEE 802.11 packet delay: A finite retry limit analysis," in *Proc. IEEE Globecom*, Dec. 2003, vol. 2, pp. 950–954.

Byung-Seo Kim (S'04–M'05) received the B.S. degree in electrical engineering from In-Ha University, In-Chon, Korea, in 1998 and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Florida, Gainesville, in 2001 and 2004, respectively.

Between 1997 and 1999, he was with Motorola Korea Ltd., Paju, Korea, as a Computer Integrated Manufacturing Engineer in Advanced Technology Research and Development. From January 2005 to August 2007, he was with Motorola Inc., Schaumburg, IL, as a Senior Software Engineer in Networks and Enterprises. Since September 2007, he has been with the Department of Computer and Information Communication Engineering, HongIk University, Chungcheongnamdo, Korea, as an Assistant Professor. His research interests include the design and the development of efficient link-adaptable MAC protocols, cross-layer architectures, multi-MAC structures, and resource-allocation algorithms for wireless networks.



Sung Won Kim received the B.S., M.S., and Ph.D. degrees from Seoul National University, Seoul, Korea, in 1990, 1992, and 2002, respectively.

From January 1992 to August 2001, he was a Researcher with the Research and Development Center, LG Electronics, Korea. From August 2001 to August 2003, he was a Researcher with the Research and Development Center, AL Tech, Korea. From August 2003 to February 2005, he was a Postdoctoral Researcher with the Department of Electrical and Computer Engineering, University of Florida, Gainesville. Since March 2005, he has been with the School of Electrical Engineering and Computer Science, Yeungnam University, Gyeongsangbuk-do, Korea, where he is currently an Assistant Professor. His research interests include resource management, wireless networks, mobile networks, performance evaluation, and embedded systems.

Randy L. Ekl received the B.S. degree with a triple major in electrical engineering, computer science, and mathematics from Rose-Hulman Institute of Technology, Terre Haute, IN, and the M.S. degree with a double major in electrical engineering and computer science from the University of Illinois, Chicago.

For 24 years, he has been with Motorola, Inc., Schaumburg, IL, where he has worked in both managerial and technical positions. He was named an Associate Member of the Motorola Science Advisory Board, which is one of the highest awards for technical achievement within the company. He is the holder of 13 granted patents and has 22 pending patents. He has been the Chairman of several Motorola patent committees. He is currently with the Advanced Technology group within the Government and Public Safety business, driving cognitive radio technology maturation for TV Whitespace systems. Immediately prior to this, he made significant contributions to Public Safety Broadband systems.