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Rate-Adaptive MAC Protocol for Wireless Multicast Over OFDMA-Based MANETs

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Abstract Unlike in unicast transmissions, a feedback channel has not been implemented for multicast transmission over Mobile ad hoc networks (MANET), due to the increase in the overhead with increasing group member size. As a result, rate-adaptation for wireless multicast has not been considered either. In this paper, a novel rate-adaptive Medium Access Control protocol is proposed to allow dynamic rate-adaptation for wireless multicast transmission over MANETs by utilizing the orthogonality of the subcarriers in an Orthogonal Frequency-Division Multiplexing system. In the proposed rate-adaptation method, each member station is assigned a unique subcarrier and by using this subcarrier, its preferred data rate in the current channel condition is reported to the multicast source. Due to their orthogonality, the feedbacked packets simultaneously transmitted by the group members can be distinguished at the source. Therefore, the source chooses the most appropriate data rate for all member stations. By using this method, the data rate for wireless multicast is able to be adaptively changed, so that the overall network performance is improved.

Keywords Multicast · MAC · Rate-adaptation · OFDMA

1 Introduction

Multicast (or Group Communication) is the transmission of data to a group of stations (STAs) identified by a single destination address. Multicast in wireless networks takes advantage of the broadcast-channel nature of wireless networks to efficiently disseminate common information to multiple location-independent receivers simultaneously such that much less

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wireless resources are consumed. Thus, multicast has the potential to be a bandwidth-efficient technique for group communication. This makes it possible to provide many applications over wireless networks such as teleconferencing, public safety operation, and tactical communications, which are group-call-oriented and mission-critical, requiring both accurate and timely data delivery [1]. Furthermore, the recent roll-out of Internet Protocol TeleVision (IPTV) makes wireless multicast even more attractive. Before wireless communications became popular as a communication method, many researchers extensively studied multicast transmissions over wired networks. Therefore, the common approaches to achieve fast and reliable multicast have been based on the network layer [1,2]. Particularly, the focus of these studies on multicast is the question of how to set up the route over wired internet clouds. Over wired networks, the Medium Access Control (MAC) protocol does not have a significant impact on multicast transmissions. In addition, the transmission of multicast data is delivered to the group members without errors, since the wired channel is reliable. Therefore, multicast over wired networks has focused on building an optimal route from the multicast source to the member STAs which are spread over the internet clouds.

However, the situation is different in the case of multicast over wireless networks. Since wireless channels have time-varying characteristics and are error-prone, the data is not guaranteed to be delivered to the destination. Therefore, local recovery has to be performed at each hop over wireless ad hoc networks. This error recovery process is done by the MAC protocols. Adding local recovery to the MAC layer can greatly improve the end-to-end performance. However, this recovery process by the MAC protocol is performed only for unicast transmissions. On the other hand, wireless multicast is used as a broadcast method, i.e., there is not error recovery process, because this would cause too much overhead as the number of member STAs increases. The IEEE 802.11 standard, the widely-used MAC and physical (PHY) layers for Mobile Ad hoc Networks (MANET), only supports reliability for unicast with the Request-To-Send (RTS)/Clear-To-Send (CTS)/DATA/ACKnowledgement (ACK) scheme. For multicast or broadcast, it simply transmits the data frames once without any recovery mechanism and with the lowest data rate. This absence of recovery implies that there is not feedback channel from the member STAs because this would cause overhead whose extent would increase as the number of member STAs increases. Since there is not feedback channel, multicast transmission cannot cope with channel changes. As a consequence, multicast uses the lowest data rate for the sake of reliability.

Recently, the provision of multicast reliability at the MAC layer has received increasing attention. As a part of the enhancement of reliability for wireless multicast, the studies on reliable wireless multicast in [3–7] tried to adopt Automatic Repeat reQuest (ARQ), which requires a feedback channel. However, these studies could not solve the overhead issues. Increasing the multicast reliability always sacrifices bandwidth efficiency. Recently, our prior research work in Kim et al. [8] proposed an efficient ARQ method for wireless multicast over ad hoc networks, called Orthogonal Frequency-Division Multiple-Access (OFDMA)-based ACK (OMACK). OMACK applies OFDMA characteristics to the ACK frame format. All of the member STAs send their status regarding the packet reception by using the pre-assigned subcarriers in an OFDM symbol at the same time. Since all of the subcarriers are orthogonal to each other, the source STA can check the packet transmission statuses with as small an overhead as one OFDM symbol.

Regarding the data rate for multicast transmission, there are also a few studies as shown in [9–13]. These protocols are assumed to operate over a centralized network environment. Furthermore, these protocols, except the one in Bhatia et al. [10], assume that the central STA can obtain the channel information from all of the member STAs and that the channel information is periodically updated. However, this is not applicable to MANET, since the periodic transmission of the channel information increases the overhead, which would degrade the network performance. Furthermore, even if the central STA collected all of the channel information, this information could not be used at the moment of transmitting the data. Therefore, the best method is to collect the channel condition information from all of the member STAs right before the actual data is transmitted. However, this method has not been able to be implemented over MANET.

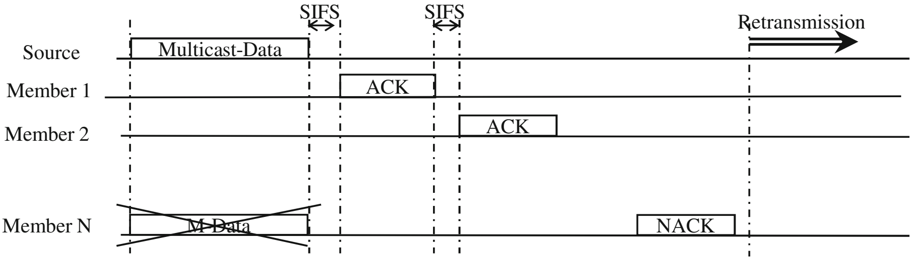
In this paper, an efficient method of realizing rate-adaptation is proposed based on the technique proposed in our previous work, OMACK [8]. The proposed method requires only a few additional OFDM symbols to implement a feedback channel from all member STAs. In spite of the overhead added by this additional OFDM symbol, the network throughput and delay performances are improved. In Sect. 2, the reliability and rate-adaptation of wireless multicast are investigated, and related issues are studied. Moreover, OMACK is illustrated in the same section. In Sect. 3, the motivation for the development of the proposed method is presented, followed by a detailed description of its operation. In Sect. 4, the proposed method is evaluated through simulations and the performance improvements due to the method are demonstrated. Finally, the conclusion is given in the last section.

2 Related Works

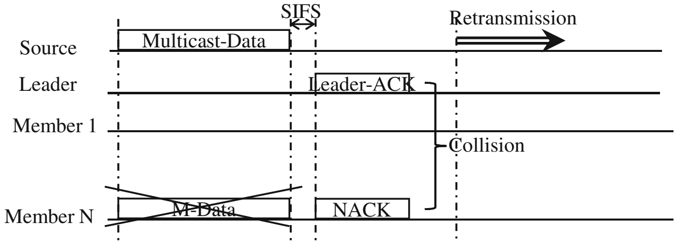
2.1 Reliable Multicast Transmission in Wireless Communication Standards

Most wireless communication standards, such as IEEE802.11, Code Division Multiple Access (CDMA) 2000, and WiMax, mainly specify mechanisms for reliable unicast transmissions. These standards do also specify mechanisms of multicast transmission, but without ARQ. Since the traffic is sent to multiple STAs and is not acknowledged by any of them, the multicast source is not able to clarify whether or not the transmission is successful. Thus, it does not know if it should retransmit the multicast packet or not. As a result, reliability over multicast is not guaranteed. For example, multicast transmission in the IEEE 802.11 standard [14] does not implement RTS/CTS/ACK handshaking, which is necessary for reliable transmission over ad hoc networks. On the other hand, multicast in CDMA2000 and WiMax provide relatively reliable transmission. CDMA2000 1XEV-DO provides an error correction code in the multicast MAC packet to reduce the MAC packet error rate. This code is the Reed-Solomon code, described in [15,16]. Further, as described in [17,18], Mobile WiMax proposes a Multi-Base Station (Multi-BS) access mechanism for multicasting. By receiving duplicates of the same packet from multiple BSs at the same time, the spatial diversity at the mobile terminal is increased and, as a consequence, the packet error rate can be reduced. Except for wireless standards, many studies have been conducted with the goal of achieving reliable wireless multicast, as shown in [9–13]. These methods may be classified into two groups; Leader-based Acknowledgement and Multiple Acknowledgement.

Broadcast medium window (BMW) proposed in Tang and Garcia [3] exchanges RTS/CTS/DATA/ACK packets with one of the member STAs, and then RTS/ACK packets are exchanged with the entire member STAs. As an enhanced version of BMW, the Batch Mode Multicast MAC (BMMM) protocol is proposed in Sun et al. [4]. The transaction of BMMM between the sender and member STAs is a sequence of multiple RTS/CTS packet exchanges between the sender and member STAs, data packet transmission, and multiple Request ACK (RAK)/ACK packet exchanges between the sender and member STAs. During this sequence, there is not contention-based channel access. Therefore, compared to BMW, BMMM reduces the overhead due to the multiple contention periods required to access the channel for transmitting



(a)



(b)

Fig. 1 Example scenarios of **a** MMP and **b** LMP

RTS/ACK packets. The Multicast aware MAC Protocol (MMP) proposed in Gossain et al. [5] is illustrated in Fig. 1a. MMP uses DATA/ACK without RTS/CTS. After a data packet is transmitted, all of the member STAs transmit their ACK packets to the sender following the pre-assigned sequential order. In Kuri and Kasera [6], the Leader-Based Protocol (LBP) was proposed to reduce the overhead caused by multiple CTSs and ACKs, as shown in Fig. 1b. One STA among the group member STAs is selected as the leader. Then, the leader responds with CTS and ACK packets corresponding to RTS and multicast data packets. If it fails to receive a data packet, it sends a No-ACKnowledgement (NACK) packet at the end of the data packet to causes a collision with the ACK packet from the leader. The scheme proposed in Bao and Liao [7] focuses only on the hidden node problem. Therefore, the error recovery process in Bao and Liao [7] adopts one of the aforementioned schemes.

2.2 Data Rate for Wireless Multicast

A representative MAC protocol for MANET is the CSMA/CA-based protocol, which is standardized as IEEE 802.11. Multicast transmission in the IEEE 802.11 standard uses the lowest data rate possible, since it is the most reliable data rate applicable to any member STA. Furthermore, since there is not feedback channel to allow a member STA to inform the sender of the current channel condition, applying a higher data rate than the lowest data rate for a multicast data frame might deteriorate the reliability over wireless multicast. That is, since the feedback channel for wireless multicast has been excluded from consideration, rate adaptation over wireless multicast has not been considered either Note that the channel state information needs to be fed back from the receivers in order to implement the rate adaptation. However, a few studies have proposed rate adaptation methods for wireless multicast targeting a centralized network architecture.

The protocol in Bhatia et al. [10] targets CDMA2000 cellular networks. To use a higher data rate than the base data rate, it uses unicast transmissions by utilizing routing protocols among the member STAs in the cellular networks. In Ge et al. [11], before data transmission, a source STA having an optimal data rate queries the channel by individually exchanging control packets. It transmits the data packet when at least T of M members are ready. This means that their channel meets the conditions required for the source's data rate. Otherwise, it backs off for a random duration and queries the channel again. Therefore, the data rate and T are associated with each other. In addition, it adopts erasure coding at the transport layer to enhance the reliability. However, applying this method to wireless ad hoc networks may cause much overhead due to the abundance of individual queries. Furthermore, it does not include dynamic rate adaptability. The paper in Wang et al. [12] defines a reward function as the performance optimization target and adjusts the data rate to maximize the reward. The proposed optimization algorithm varies the instantaneous BER constraint of each mobile multicast receiver according to its individual cumulated BER. This paper assumes that the base STA has perfect knowledge of not only the channel condition of all receivers, but also the status of the packets received by the multicast members. The theoretical evaluation for power and rate adaptation over cellular networks was studied in Wang et al. [13]. This assumes that the source has perfect knowledge of the channels.

In the centralized networks such as cellular system, knowing such information at the base STA does not cause much overhead because specific channels or time slots are assigned for the user. The channels and slots always exist no matter they are actually used or not. However, in distributed networks including MANET, there is not such specific channel or slot. For a sender to know the perfect channel information, the information has to be feedbacked from nodes and the feedbacks cause additional channel usages, which are overheads over networks.

2.3 OFDMA-Based ARQ for Wireless Multicast Over MANETs

Our prior research work in Kim et al. [8] proposed a new type of acknowledgement for wireless multicast, called the OFDMA-based Multicast ACK (OMACK). OMACK is not only an acknowledgement method for multicast, but also a new format of ACK. OMACK is a simple packet consisting of a preamble and an OFDM symbol with a cyclic prefix, as shown in Fig. 2a. During the process of joining a multicast group, each group member STA is assigned a unique subcarrier ID for each group ID by the multicast source. The subcarrier ID is one of the available data subcarriers in an OFDM symbol. When a member STA receives a multicast packet from the multicast source, it allocates a symbol on the assigned subcarrier as an acknowledgement for the packet. This symbol is one of the two Binary Phase Shift Keying (BPSK) symbols, 1 or -1. The successful reception of the multicast packet is indicated by loading a 1 on the subcarrier, whereas a -1 indicates a failed reception. If a member STA cannot demodulate the MAC header of the multicast data packet, it will not generate an OMACK. The OFDM symbol generated by each member STA as the acknowledgement has only one subcarrier with a data symbol (1 or -1) and the other subcarriers are empty. As illustrated in Fig. 2b, the OFDM symbols of members 1, 2, and 3 have only one subcarrier with data information. After being attached to the preamble, the OFDM symbol is sent to the multicast source. It is assumed that all of the member STAs send their OMACK at the same time after a Short Inter-Frame Space (SIFS) idle period.

In general IEEE802.11-based ad hoc networks, all STAs are synchronized with each other using beacon frame sent by a STA acting as an access point or a leader. Particularly, in clustering-based ad hoc network, all nodes within a cluster are synchronized with each other. An

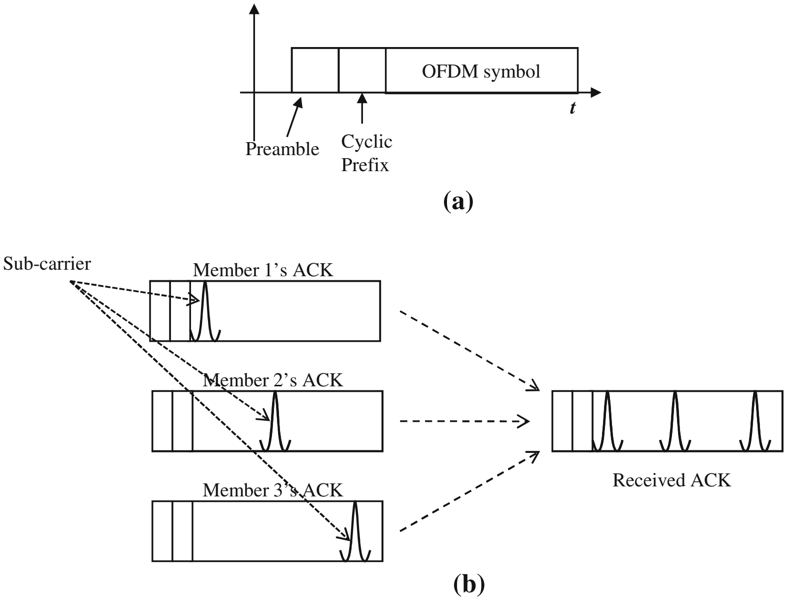


Fig. 2 **a** Generic OMACK structure **b** OMACK transmitted by each STA (*left*) and a received OMACK at the source (*right*)

important assumption that we make in this paper is that each user is allowed to transmit and to receive at the same time, but only on different subcarriers, as it has also been performed in related work [19–21]. Although this assumption may have practical limitations with the current transceiver design, it is still of much theoretical interest, as it enriches the resource-allocation problem by allowing each user to simultaneously act as a source, a destination, and a relay.

An example of an ACK packet received at the source is shown in Fig. 2b. The multicast source is able not only to receive simultaneously the ACK packets without collision due to subcarrier orthogonality, but also to distinguish each subcarrier. By checking the data information on all of the subcarriers, the multicast source knows the status of the multicast transmission. The time offset problem, due to imperfect time-synchronization and different propagation delays from all of the member STAs, is solved by using the longer cyclic prefix shown in [22–25], which is longer than the delay spread profiles. If the longer prefix is required, the overhead will increase, but it is minor. Even though the longer cyclic prefix is used, the size of it should be less than an OFDM symbol which is 3.2μs. In addition, because conventional ACK packet requires more than 3 OFDM symbols, the proposed method needs much smaller overhead than a conventional system.

3 Proposed MAC Protocol for Rate-Adaptive Wireless Multicast Service

3.1 Motivation

As described in Sect. 2.2, the prior arts on rate adaptation over wireless multicast were focused on centralized networks. Therefore, they assume the existence of periodic feedback

Fig. 3 New CTS frame format for rate adaptation over wireless multicast

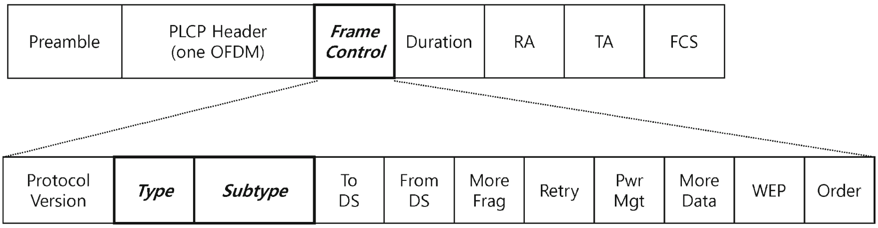


Fig. 4 RTS format defined IEEE 802.11

channels, so that a central STA can estimate and update the channel state information of each one of the member STAs. However, this assumption is hardly applicable to the MANET environment. Moreover, the distributed network environment does not consider the feedback channel from the member STAs due to the overhead issue.

However, our recent works described in Sect. 2.3 makes rate-adaptation over wireless multicast feasible by extending the basic idea of OMACK to rate-adaptability. The proposed protocol is designed for MANET using the IEEE 802.11-based layer-2 protocol.

3.2 Control Frames for Rate Adaptation

For rate adaptation over wireless multicast, the RTS and CTS frame formats defined in the IEEE 802.11 standard are modified as shown in Figs. 3 and 4. The new CTS frame has two more fields after the legacy CTS frame format, as shown in Fig. 3. The first field, named "*RTS Reception*", is composed of one OFDM symbol and is used to indicate the RTS reception state at a member STA. The second field, named "*CSI Indication*", is used to indicate the current relative channel state information at the member STAs. The number of OFDM symbols in "*CSI Indication*" can be one or three. Each one of the additional OFDM symbols is composed of N data subcarriers, and each member STA is assigned to one or three of these subcarriers. When a member STA sends a CTS frame, it will set its own subcarriers to $1/-1$ (BPSK) or one of the BPSK symbols. The details of when and how to use one or three OFDM symbols for "*CSI Indication*" are given in the next subsection.

In order to inform all of the member STAs of the use of rate-adaptation for wireless multicast, the "*Type*" subfield of the frame control field in the RTS frame shown in Fig. 4 is set to 01, which means it is a control frame as defined in the IEEE 802.11 standard [14]. The "*Subtype*" subfield of the frame control field in the RTS frame uses one of the values in the range from 0000 to 0111 to indicate a tentative data rate for a multicast data packet to be transmitted with after RTS-CTS handshaking. The values from 0000 to 0111 are defined as "*Reserved*" bits in the standard [14]. That is, having 0 in the first bit in the "*Subtype*" subfield indicates that the packet is a revised RTS packet for multicast data transmission. The tentative data rate might be changed after RTS-CTS handshaking. The values of the last three bits corresponding to the specific data rate are shown in Table 1.

In addition, we propose one more control frame for the proposed scheme. This new control frame, called Multicast Rate Adaptation (MRA), is shown in Fig. 5. The control frame is

Table 1 Values for the last three bits in the subtype field aligned with the data rate

Last three bits in subtype	Data rate (Mbps)
000	6
001	9
010	12
011	18
100	24
101	36
110	48
111	54

Preamble	PLCP Header (one OFDM)	Frame Control	Duration	RA	TA	***Rate Control (2 bit)***	FCS

Fig. 5 Multicast rate adaptation (MRA) control frame

used to inform the source STA of how many bits are used for member nodes to report their data rate preference and how many OFDM symbols in "*CSI Indication*" are used. When the "*Rate Control*" subfield in Fig. 5 is set to 00, it means that one bit and one OFDM symbol will be used. When a value of 10 is used in the "*Rate Control*" subfield, three bits and one OFDM symbol are used. When a value of 11 is used, three bits and three OFDM symbols are used. If the number of member nodes is higher than a threshold number at the moment when the first multicast data transmission is ready, the control frame is mandatorily multicasted by the source STA before the first multicast data transmission. Details on the usage of the control frame are provided in the subsequent section.

3.3 Subcarrier Assignment Process

The subcarrier assignment process is initiated in conjunction with the multicast join process, because the join process is the first step for multicast transmission. In fact, the IEEE 802.11 standard does not specify the group join process. Thus, we adopt the process proposed in Kim et al. [8], which is the Internet Group Management Protocol (IGMP) snooping protocol. When a STA wants to join a multicast group, it unicasts to a multicast source an IGMP membership query message as the payload of a MAC data packet, since WLAN is mainly designed as a wireless internet extension. If the packet is an IGMP query message, the multicast source 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. 6. In addition, it assigns Group Member Identifications (IDs), G_{IDs}, starting from 1. Then, the AP evaluates each subcarrier's condition and selects the subcarrier which has the best quality among all of the available subcarriers. The details on how to choose a subcarrier will be illustrated below. The selected subcarrier's ID, S_{ID} as well as the G_{ID}, are sent back to the member STAs. The assigned subcarrier ID has to be unique for each member STA within the same multicast group ID. The detailed message format for these processes is not provided in this paper, since its focus is how to implement link adaptability for wireless multicast. Since the join process is conducted once, it is assumed that the message exchange will not deteriorate the network performance.

As mentioned in the previous section, the "*CSI Indication*" field might contain one or three OFDM symbols. The number of OFDM symbols used in the field depends on the number of

Group Address	Member MAC address	Group Member ID	Sub-carrier ID	Data Rate
239.225.0.x	01-00-5e-7F-00-XX	1	1	6Mbps
	01-00-5e-7F-00-YY	2	3	
	01-00-5e-7F-00-ZZ	3	4	
239.225.0.x	01-00-8e-9F-00-XX	1	1	12Mbps
	01-00-8e-9F-00-YY	2	3	

Fig. 6 An example of a layer-2 multicast table

bits that are used to indicate the channel condition. If one bit indication for the appropriate data rate is used, one OFDM symbol is used for the field in the CTS packet. On the other hand, if three bits are used, one or three OFDM symbols are used depending on the number of member STAs. The reason for having alternative options for the "*CSI Indication*" field is to minimize the overhead as much as possible. Three OFDM symbols might decrease the network performance while obtaining better rate information at the multicast source. The performances for these alternatives will be evaluated in Sect. 4. The information on how many bits and OFDM symbols are used is provided by sending the MRA control frame shown in Fig. 5. The source will send the frame before the first multicast packet is transmitted. An MRA transmission might not use RTS/CTS handshaking. However, an OMACK packet will be sent next from all member STAs, so as to retransmit the MRA in the case of packet error.

When using one bit to indicate the appropriate data rate for the current channel condition, one subcarrier position is assigned to each multicast member STA. As mentioned above, the assigned subcarrier is the one with the best channel quality among the unassigned subcarriers. When using three bits, there are two different cases depending on the number of members. The first case is where the number of member STAs is less than $\lfloor \frac{N}{3} \rfloor$, where N is the total number of subcarriers in one OFDM symbol. In this case, one subcarrier ID will be assigned to each member STA, which satisfies the following rule,

$$S_{\text{ID}}(G_{\text{ID}}) = \arg \max_{n \in \text{Unused}} f(n), \quad \text{if } M \leq \left\lfloor \frac{N}{3} \right\rfloor, \tag{1}$$

where G_{ID} is the multicast group ID and S_{ID} is the subcarrier ID, which is one of the integers from 0 to $N-1$. Unused is a group of unassigned S_{ID}s and n is a multiple of 3 in Unused. M is the number of member STAs. That is, a member STA is assigned an S_{ID} which is a multiple of 3 $\{0, 3, \dots\}$. In addition, $f(n) = \frac{\sum_{i=0}^{2} \text{SNR}_{n+i}}{3}$, where SNR_{n+i} is the signal-to-noise ratio of the $n+i$th subcarrier. Although each member is assigned with one subcarrier ID, it will use three subcarriers to inform the source STA of the appropriate data rate. For example, if m is the selected S_{ID}, then the member will use three subcarriers which are m, $m+1$, and $m+2$. In this case, the "*CSI Indication*" in the CTS frame is composed of only one OFDM symbol.

The second case is where the total number of members is larger than $\lfloor \frac{N}{3} \rfloor$. In this case, the subcarrier ID to be assigned to a member will be:

$$S_{\mathrm{ID}}(G_{\mathrm{ID}}) = \arg \max_{n \in \mathrm{Unused}} \mathrm{SNR}_n, \quad \text{if } M > \left\lfloor \frac{N}{3} \right\rfloor. \tag{2}$$

Although only one S_{ID} is assigned, three OFDM symbols are used for the "*CSI Indication*" in a CTS frame. Since one subcarrier on each OFDM symbol is used, each member uses three subcarriers to inform the source STA of the appropriate data rate.

In summary, in the case where three bits are used to feedback the appropriate data rate, the "*CSI Indication*" in a CTS frame may have one or three OFDM symbols depending on the number of members. However, it is possible for the total number of members to be small at the initial join process, but it may be larger later on. In this case, the source sends an MRA control frame to change the number of OFDM symbols in the "*CSI Indication*". The "*Rate Control*" subfield is set to 11, which indicates that three bits and three OFDM symbols are used.

3.4 Protocol Operation

In the multicast join process, it is assumed that the source knows the current number of member STAs and that the assignments of G_{ID} and S_{ID} are completed. Furthermore, the source STA sends an MRA control packet to the member STAs to inform them of how many bits and OFDM symbols will be used for the upcoming multicast data transmission. When the source STA has a multicast data frame to send, the proposed protocol is operated as follows.

Step 1 The multicast source sends an RTS frame. The first bit in the "*Subtype*" subfield is set to 0. The remaining three bits in the "*Subtype*" subfield represent the rate to be used for the data packet. If the multicast data transmission is the first transmission for the multicast group, the data rate will be 6 Mbps, which is the lowest data rate defined in IEEE 802.11a. The rate set can be changed according to the OFDM-based wireless system.

Step 2 After receiving the RTS frame, the member STAs estimate the channel condition, which can be represented by the Signal-to-Noise Ratio (SNR). Each member chooses the best data rate suitable for the estimated current channel conditions. We assume that the data rate is selected based on a predetermined threshold [26,27]. That is, the chosen data rate, R, is

$$R = R_i, \quad \text{if } \Gamma_i \leq \mathrm{SNR} < \Gamma_{i+1}, \tag{3}$$

where R_i is the ith rate in the rate set, and Γ_i is the SNR threshold determining the use of R_i.

Step 3 After comparing the chosen data rate, R, with that represented in the "*Subtype*" subfield of the RTS frame, the member STA sets its assigned subcarriers with certain values, viz. 1/−1 (BPSK) or one of the BPSK symbols depending on how many bits and OFDM symbols are used, which is decided in the MRA control frame. The details on how to set the values on the subcarriers are illustrated in the following subsection. Once the values on the subcarriers are allocated, the CTS frame is formatted.

Step 4 The member STAs send their CTS frames to the multicast source after SIFS.

Step 5 After receiving the CTS frames, the multicast source checks the "*RTS Reception*" OFDM symbol in the CTS frame. If 1's are allocated over the expected subcarriers (members' subcarriers), then it checks "*CSI Indication*" to find the best data rate for

Table 2 Data rate adjustment rule according to bit-map-adjustment OFDM

Symbol on a subcarrier in previous CTS	Symbol on a subcarrier in current CTS	Indication of data rate adjustment from data rates in "*Subtype*" subfield of RTS frame
−1	−1	Decrease one level
−1	1	Do not change
1	−1	Do not change
1	1	Increase one level

the multicast data transmission. After the source checks the members' preferences concerning the data rate for the pending multicast data packet, it decides the data rate to use for forming the data packet. The process used to decide the data rate is illustrated in Sect. 3.5. If SNR is lower than the threshold value of the lowest data rate, the source STA holds its transmission and moves to a backoff stage for the retransmission. That means, if the channel condition is not good, multicast data is not transmitted.

Step 6 Finally, the chosen data rate at the multicast source is stored in the multicast table shown in Fig. 6. Then, the multicast data frame is generated according to the data rate, and sent to the member STAs.

Step 7 The member STAs demodulate the received data frame by using the data rate found in the "*Rate*" subfield in the header of the data frame.

3.5 Bit Allocation on Subcarriers for Informing Appropriate Data Rate

3.5.1 Case Where One Bit is Used

As mentioned in Step 3 in Sect. 3.4, based on the chosen data rates (obtained in Step 2 in Sect. 3.4) and the data rates in the "*Subtype*" subfield of the RTS frame, the member STA chooses one of three actions, i.e. to increase, to decrease, or not to change the data rate for the subsequent data frame. According to its decision, the member STA sets the value in the subcarrier to 1 to increase or −1 to decrease the data rate on its subcarrier. If the decision of the subcarrier is not to change the data rate, then the receiver sets the value in the subcarrier to a different value from the one used in the same subcarrier of the previous CTS, which is used in the previous data transmission. When the multicast source has received the CTS frames from all of its members, it finds the members' indications as to their preferred data rate based on Table 2. If all of the members want to increase the data rate, the source increases the data rate by one level compared to that found in the "*Subtype*" subfield of the RTS frame. If any one of the members wants to decrease the data rate level compared to that embedded in the previous RTS frame, the source decreases the data rate by one level and forms a multicast data frame by using this data rate.

3.5.2 Case Where Three Bits are Used

Compared to the case where one bit is used, that where three bits (or three subcarriers) are used is much simpler. After choosing the best data rate from Step 2 in Sect. 3.4, each member STA finds the three-bit representation from Table 1 for the chosen data rate, and sets the three-bit value on its assigned three subcarriers in "*CSI Indication*". If three OFDM symbols are used, the member uses the subcarriers with the same S_{ID} from all three OFDM symbols. Then, it attaches the "*CSI Indication*" OFDM symbols at the end of the CTS frame. Finally, all of the member STAs send their CTS frame to the multicast source. When receiving the CTS frames, the source finds all of the data rates preferred by the members. By adopting the philosophy of the minimum Modulation and Coding Scheme (MCS) algorithm in Kim and Cho [9], it chooses the lowest data rate among the preferred data rates as the one to use for the subsequent data packet.

4 Performance Evaluation

The performances of the one and three bit feedback methods are compared with the legacy multicast method (no feedback). We consider an OFDM-based physical layer as in IEEE 802.11a [28] operating in the 5 GHz frequency band. The wireless channel characteristics are modeled as three components: the path loss, shadowing and multipath fading. The path loss and shadowing are modeled as

$$PL(d) = PL(d_0) + 10\alpha \left(\frac{d}{d_0}\right) + X_\sigma, \tag{4}$$

where d_0 is a reference distance, α is the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. We consider $d_0 = 1$m, $\alpha = 2.56$, and $\sigma = 7.67$ [29]. To represent fading, we consider the ETSI indoor channel A delay profile, which models a typical office environment with no line-of-sight [30]. The power delay profile has an RMS delay spread of 50 ns and a maximum delay spread of 390 ns. This delay profile results in frequency selective fading in the IEEE 802.11a 20 MHz band. In the computation of the signal-to-noise ratio (SNR), the noise is modeled as additive white Gaussian noise (AWGN). We consider a hard-decision Viterbi decoder in the receiver, and assume the perfect synchronization of the receiver to the transmitted signal [31].

The simulation results in this paper were generated by the event-driven simulator used in Kim et al. [32]. The simulator was extensively modified to accurately model the actions of the receiver. The IEEE 802.11a physical layer was added to the simulator including the proper representation of the timing parameters for various data rates. The PHY layer has eight PHY modes characterized by different modulation schemes and convolutional coding rates, as shown in Table 3. Although some rate adaptation protocols use varying thresholds depending on the packet size, these thresholds are not affected by the packet size in this paper. The various errors in the MAC representation were also added to the simulator. The clear channel assessment (CCA) is modeled as per the IEEE 802.11 standard, which defines an energy detect (ED) threshold. A node is blocked if either it is busy receiving a signal on the medium or the signal strength is greater than the ED threshold. The ED threshold is set to −85 dBm.

The system under consideration is an IEEE 802.11a-based basic service set (BSS) in which pairs of devices are communicating with multicast packets. A pair of devices represents a STA and an access point (AP). Communication between two devices experiences a particular fading realization which may be different from that experienced by another communicating pair in the BSS. All of the STAs except for the AP are randomly distributed in a 100 m × 100 m square area and move randomly at a speed of 1 m/s. The AP is located at the center of the square. The packet inter-arrival time is an exponential random variable with parameter λ. Those packets that wait for more than 20 ms are dropped from the queue. Each plot in the simulation results was obtained by running the model for 50 h. The initial transmission rate

Table 3 IEEE 802.11a PHY modes

Mode	Modulation	Code rate	Data rate (Mbps)	Minimum sensitivity (dBm)
1	BPSK	1/2	6	−82
2	BPSK	3/4	9	−81
3	QPSK	1/2	12	−79
4	QPSK	3/4	18	−77
5	16-QAM	1/2	24	−74
6	16-QAM	3/4	36	−70
7	64-QAM	2/3	48	−66
8	64-QAM	3/4	54	−65

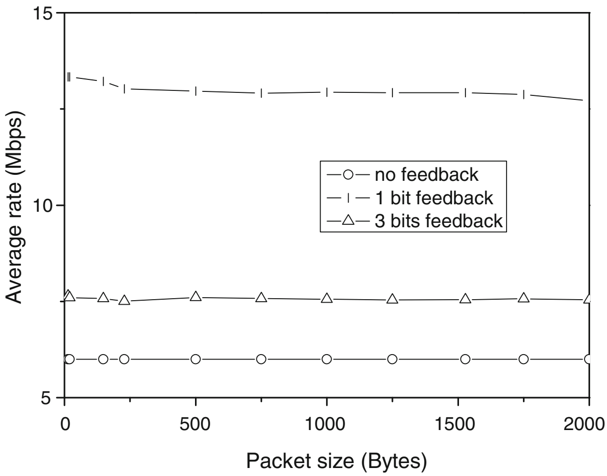


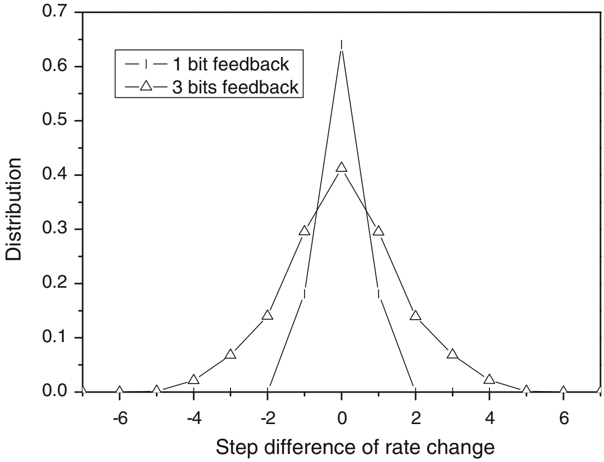
Fig. 7 Average transmission rate versus packet size

of each node in feedback method is set according to Table 3. The number of nodes is 25, λ is 500, and the packet size is 2,000 bytes except where otherwise specified.

Figure 7 shows the variation of the average transmission rate of the three methods as the packet size increases. The rate of the no feedback method, which is the legacy method, is maintained at 6 Mbps, because it has to use the lowest rate for the sake of reliability. The rates of the one-bit and three-bit feedback methods are not changed because there is not change in the average SNR environment. Thus, the rate is maintained at a constant value even though there are feedbacks for rate variation. However, the rates of the one-bit and three-bit feedback methods are higher than that of the no feedback method, because the feedbacks in the proposed method make rate adaptation feasible. The average rate of the one-bit feedback method is higher than that of the three-bit feedback method, because the rate change in the former is limited in one step, as shown in Table 2. That is, while the next rate in the three-bit feedback method can be changed to any rate in Table 3, that of the one-bit feedback method can be changed to only one level lower or higher from the current rate. Thus, the three-bit feedback method follows the optimal rate, while the one-bit feedback method follows the over-estimated rate.

The rate adaptation steps are compared in Fig. 8. The distribution of rate changes compared with the previous rate are shown in this figure. For example, if the previous rate was

Fig. 8 Distribution of rate adaptation steps



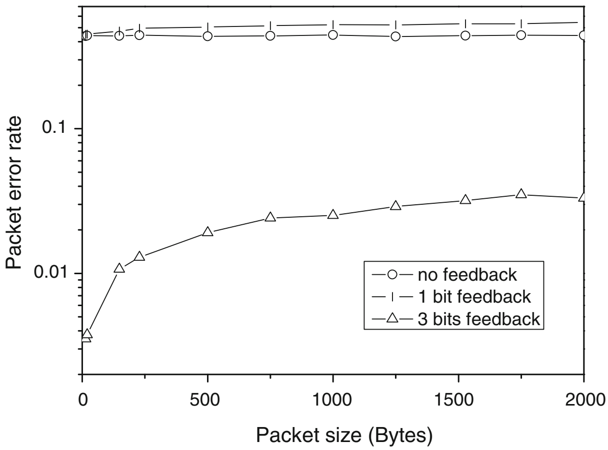


Fig. 9 Packet size versus packet error rate

24 Mbps and the current rate is 12 Mbps, the rate change is −2 steps in Table 3. In the one-bit feedback method, the step difference is either −1, 0, or 1, because it allows only a one step rate increase or decrease. On the other hand, the three-bit feedback method can change the rate more quickly, which results in a more accurate rate for the channel conditions, as shown in Fig. 7. The no feedback method has no rate change and is not shown in the figure.

Figure 9 shows the packet error rates (PERs) of the three methods caused by changing the packet size. A packet error means that the transmitted packet is not correctly received by the receiver because of the channel errors. The no feedback method always maintains a transmission rate of 6 Mbps even when the channel condition does not allow it. This causes it to have a higher PER. The PER of the one-bit feedback method is higher than that of the three-bit feedback method, because the former uses an over-estimated rate, as shown in Fig. 7.

Figure 10 shows the throughput of the three methods afforded by changing the packet size. The throughput in this figure is the average amount of data packets that are successfully transmitted during 1 s. Since the arrival rate is fixed, the increase of the packet size leads to

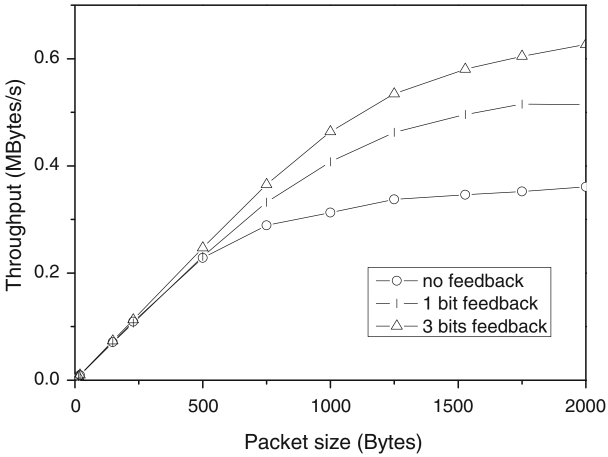


Fig. 10 Throughput versus packet size

an increase of the traffic load over the wireless channel. Thus, as the traffic load increases (the packet size increases), the throughput also increases. For small packet size, the throughputs of three methods are similar with each other even though their PERs are different in Fig. 9. This is because the error packets are retransmitted during the backoff period and the retransmission time does not deteriorate the throughput because of the low traffic load. In other words, there are much idle time when the packet size is small and this idle time is used for the retransmission of error packets. When the packet size is large, this idle time is reduced and the retransmission deteriorates the throughput. Thus, the throughputs of the no feedback and one-bit feedback method are less than that of the three-bit feedback method because of higher PER. When the packet size is large, the throughput of the no feedback method is less than that of the one-bit feedback method. This is because the transmission rate of the no feedback method is fixed at 6 Mbps while those of the other methods are higher than 6 Mbps because of their dynamic rate adaptation.

This low throughput of the no feedback method incurs a long delay and more packet loss rate, as shown in Figs. 11 and 12. The packet delay is the time from the arrival of the packet to its departure from the queue. Packet loss happens when the packet waits more than the threshold value, 20 ms, in the queue. Thus, as the average packet delay increases, there may be more packet loss in the queue. Because of the low transmission rate of the no feedback method, the packet delay increases as the packet size increases. The maximum delay that a packet can wait in the queue is set to 20 ms. Thus, as the packet delay increases, more packets are dropped from the queue. the three-bit feedback method shows the least packet delay and loss because of its higher rate and lower PER.

5 Conclusion

In this paper, we propose a rate-adaptive wireless multicast scheme over OFDM-based ad hoc networks. By adopting the OFDMA method in the feedback channel, a multicast source is able to obtain the channel status information of all of the member STAs. After estimating the channel status from the received RTS packet, each member STA decides its preferred data rate and sends it back to the source by using the new CTS packet format, which has one or

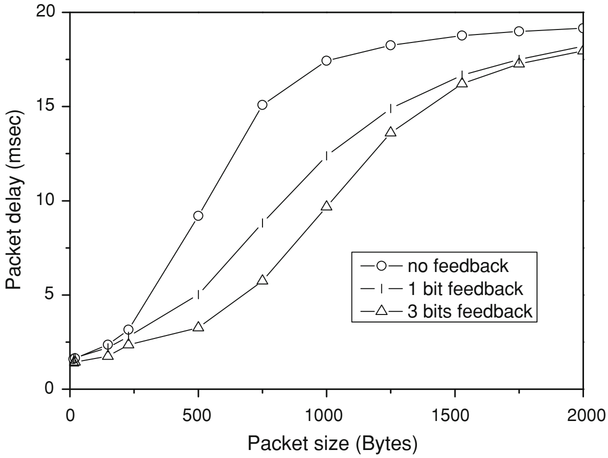


Fig. 11 Packet delay versus packet size

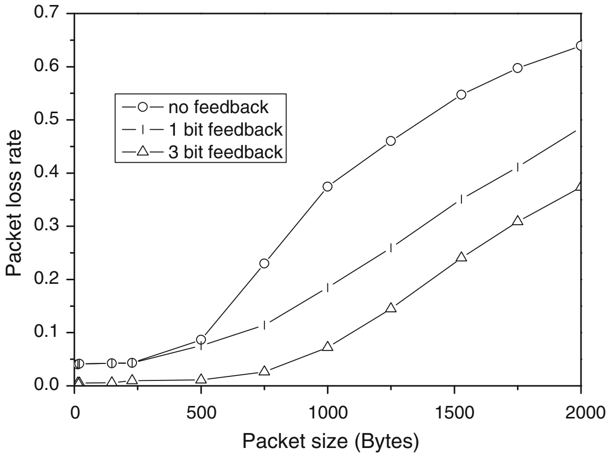


Fig. 12 Packet loss rate versus packet size

three more OFDM symbols compared to the conventional CTS packet. Since the multicast members use their pre-assigned and orthogonal subcarrier to indicate the data rate, the source can distinguish the data rate information from all of the members, even though they send the CTS at the same time. As a result, the data rate for multicast transmission is dynamically adapted according to the link condition without increasing the overhead. Through extensive evaluations, it is proven that the proposed method increases the network performance. We propose two types of indication methods of the rate preference, using one bit or three bits. Using three bits gives better performances than using one bit, because the former gives more information than the latter.

Currently, the performance of the proposed method with imperfect synchronization is being investigated even though some studies to deal with synchronization issue have been done as shown in [22–25]. According to the investigation results, some efforts to solve the issue will be made. Furthermore, retransmission algorithm for the multicast transmission will be studied.

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