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RESEARCH ARTICLE

A fragment-based retransmission scheme with quality-of-service considerations for wireless networks

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ABSTRACT

In order to satisfy quality-of-service requirements for real-time multimedia applications over wireless networks, IEEE 802.11e has been proposed to enhance wireless-access functionalities. In IEEE 802.11e, collisions occur frequently as the system load becomes heavy, and then, the latency for successfully transmitting data is lengthened seriously because of contention, handshaking, and backoff overheads for collision avoidance. In this paper, we propose a fragment-based retransmission (FBR) scheme with quality-of-service considerations for IEEE 802.11e-based wireless local area networks. Our FBR can be used in all proposed fragmentation-based schemes and greatly decrease redundant transmission overheads. By utilizing FBR, the retransmission delay will be significantly improved to conform strict time requirements for real-time multimedia applications. We develop an analytical model and a simulation model to investigate the performance of FBR. The capability of the proposed scheme is evaluated by a series of simulations, for which we have encouraging results. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
IEEE 802.11; wireless networks; fragment-based retransmission scheme

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1. INTRODUCTION

High-speed physical (PHY) layers (i.e., IEEE 802.11a, g(54 Mbps), and IEEE 802.11n (up to 600 Mbps)) and a quality-of-service (QoS)-based medium access control (MAC) layer (i.e., IEEE 802.11e) derive the next wireless local area network (WLAN) generation. These high-speed WLAN techniques bring various multimedia services for mobile and fixed users. However, contention-based transmission protocol will cause large and unnecessary transmission overheads including contention, handshaking, and long backoff processes for collision avoidance (CA). Hence, reducing the transmission overheads can significantly increase system transmission efficiency and improve the performance of these multimedia applications.

The IEEE 802.11 MAC protocol defines two access methods: distributed coordination function (DCF) and point coordination function (PCF) [7]. DCF employs a carrier sense multiple access/collision avoidance (CSMA/CA) mechanism for asynchronous data transmission. PCF supports QoS-guaranteed polling-based access, but the current products hardly provide the PCF mechanism because of its high implementation cost. The DCF mechanism is used to determine whether a station (STA) has authority for channel occupancy. If the STA occupies the channel, a proper data rate (if WLAN supports multi-rate transmission) is selected. Intuitively, all STAs shall use the highest-level modulation scheme with the highest data rate all the time to achieve the maximum network throughput. However, maximum data transmission might not be obtained because the maximum transmission rates depend on the link quality determined by the PHY factors such as distance and the number of obstructions between the sender and the receiver.

In IEEE 802.11 MAC, a successful data transmission is recognized by an acknowledgement (ACK) control frame sent by the receiver of the data frame. If any error on the transmitted data frame occurs (i.e., an ACK frame is not received by the sender), the sender would contend for channel occupancy again and retransmit the data frame. In this case, the contention procedure would be re-activated for data retransmission with an accordingly doubled contention window (CW). With the binary exponential backoff procedure, the backoff time may increase tremendously for each retransmission. The aforementioned procedure repeats until the data frame is successfully transmitted or until the maximal retry count is reached. Based on the aforementioned discussions, the sender needs to repeatedly execute the contention procedure for data retransmission especially when the bit error rate (BER) is high or the traffic load is heavy. This could result in extra bandwidth and power consumption and longer frame delay.

The emerging of QoS demands pushes the amendment of IEEE 802.11e QoS enhancement standard [8] for multimedia applications over WLANs. The IEEE 802.11e specification introduces the hybrid coordination function (HCF), which is backward compatible with DCF and PCF. By using parameterized QoS information, the HCF makes STAs to access wireless medium with different priority levels. In HCF, the contention-based channel access operation (similar to DCF) is named as the enhanced distributed channel access (EDCA), and the contention-free channel access operation (similar to PCF) is named as the HCF-controlled channel access. The EDCA controls the arbitration inter-frame space (AIFS) and the CW size to provide higher channel access probability for high-priority data frames. However, with a random process of selecting backoff window, QoS of a high-priority multimedia stream could be temporarily unsatisfactory, especially when the system load is heavy [3,25].

Among the works related to QoS considerations for WLANs, Engelstad *et al.* derived delay and throughput analysis of IEEE 802.11e EDCA model [5]. Xiao evaluated the performance analysis of priority schemes for IEEE 802.11 and IEEE 802.11e WLANs [27]. In addition to performance analysis and evaluation for the existing IEEE 802.11e specification, Hwang *et al.* modified the IEEE 802.11e MAC retransmission scheme to efficiently resend voice-of-IP (VoIP) frames when the frame transmission fails [10]. However, the modified retransmission scheme maintains the original channel contention function of IEEE 802.11e for the retransmitted VoIP frames, which incurs significant overheads for channel access. Through the modification of original backoff mechanism and dynamic adjustment of CW values, the failure of frame transmissions/retransmissions can be reduced in [14,25]. Although the modification of CW values improves the retransmission efficiency, the overheads of frame retransmissions cannot be completely avoided if some random error frequently occurs during frame deliveries. The negative impact of the random error on performance degradation of retransmissions would be more serious for long frames. In the long frames, any error(s) occurring at a small part of the transmitted data will result in the retransmission of the whole frame, which significantly increases the frame delay and wastes the network resource.

Some related works proposed fragmentation-based approaches to improve the performance of wireless networks [1,4,13,15,17,26]. The approaches are logical link control-layer based. Djama *et al.* proposed adaptive cross-layer fragmentation to guarantee the QoS of real-time frames [4]. It uses the real-time protocol/real-time control protocol reports on the application layer to decide a FragmentationThreshold[†] and enhances the QoS of real-time frames. In [13], the authors proposed a dynamic fragmentation to enhance throughput in WLANs. This scheme uses different data rates according to the channel conditions and then selects different aFragmentationThreshold for different data rates. Xi *et al.* [26] proposed the adaptive fragmentation (ADF) scheme to adjust fragments based on channel conditions. When the transmission frame fails, this scheme can distinguish the failure reasons, which are channel collision or channel interference. If the frame transmission fails due to channel interference, the ADF adjusts fragment size according to the channel environment. Olteanu *et al.* [17] studied the overhead introduced by the advanced encryption standard cipher in the context of WLANs and computed the optimal frame and fragment sizes to render the maximum throughput. The aggregation with a fragment retransmission scheme was proposed by Li *et al.* [15]. In the scheme, multiple packets received from the upper layer are aggregated into a big frame before transmission. The performance of the aggregation with fragment retransmission was studied when VoIP and video traffics are transmitted over WLANs [1].

In this paper, we propose a fragment-based retransmission (FBR) scheme to divide each original data frame into two fragmental data blocks. In FBR, the original 32-bit cyclic redundancy check (CRC) is divided into two 16-bit CRC. The corresponding CRC-16 field is appended to each fragmental data block. The two data blocks are independent, and only the failed fragmental block(s) needs to be retransmitted. Furthermore, a failed fragmental block is given a secondary chance to retransmit without contention. The retransmission procedure is executed in the coming time slot without exercising the backoff operation so that the contention overhead is greatly decreased. Therefore, the proposed scheme can improve the transmission performance and decrease the delay for soft real-time applications (e.g., multimedia applications). By the simulations, we observe that compared with other schemes, the proposed scheme can improve goodput, MAC delay, queuing delay, and dropping rate of frame transmission. Although the discussions in the next sections are based on IEEE 802.11e networks, the proposed FBR scheme also can be applied to any contention-based network with CRC, such as IEEE 802.15.4 networks. Note that the proposed scheme is not applicable for multicast and broadcast traffic

[†]The standards of IEEE 802.11 networks define a FragmentationThreshold as the threshold of fragmentation. A packet will be fragmented into frames when the length of a packet is longer than aFragmentationThreshold.

in 802.11 networks. The rest of this paper is organized as follows: Section 2 describes our FBR scheme. In Section 3, an analytical model is proposed to investigate the performance of FBR. In Section 4, a simulation model for FBR scheme is presented. With the simulations, we compare the performance of FBR with that of IEEE 802.11e standard. Finally, the conclusion is given in Section 5.

2. FRAGMENT-BASED RETRANSMISSION SCHEME

This section briefly describes CRC for wireless networks, and then presents our FBR scheme.

2.1. Cyclic redundancy check

In wireless networks, an error-detection technique is necessary to provide a reliable communication between a sender and its corresponding receiver. One of the widely used techniques is CRC. CRC adopts a kind of hash functions to produce a checksum (i.e., redundant information) against a block of data. Before the sender transmits data to its corresponding receiver, the checksum will be generated based on the original data, appended to the original data, and packed in a frame. The generated redundant information is also known as frame check sequence (FCS) in some contexts. When the receiver receives the entire frame, it can determine the correctness of the frame by checking the FCS. CRC has been shown to be easily implemented with strong error detection [20].

Let $P_B(x,n)$ denote the probability that under some BER, a burst error with length x occurs when a frame of size n (in bits) is transmitted. By [20], $P_B(x,n)$ can be expressed as

$$P_B(x,n) = \Sigma_{i=0}^{x-2}\left[\varepsilon^{x-i}(1-\varepsilon)^{n-x}(n-x+1)\binom{x-2}{i}\right] \quad (1)$$

where ε is the BER. Although CRC can effectively detect frame errors, the 'mis-detection' of the errors by using CRC probably occurs. Let $P_{ue}(k,n)$ be the probability that the k-bit CRC code fails to detect any error in a frame of length n. From [20], $P_{ue}(k,n)$ will be

$$P_{ue}(k,n)=2^{-(k-1)}P_B(k+1,n)+2^{-k}\Sigma_{x=k+2}^{n}P_B(x,n) \quad (2)$$

With Equation (2), when $\varepsilon = 10^{-5}$ (noisy transmission media), $k = 32$ (CRC-32) and $n = 9600$ (i.e., 1200 bytes), the value of $P_{ue}(32, 9600)$ is about $6.456 * 10^{-9}$ and considerably small. If we divide the data frame into two blocks (i.e., 4800 bits) and utilize CRC-16 to check errors, we can obtain a similar error-detection rate (i.e., $P_{ue}(16, 4800)$ = $6.456 * 10^{-9}$). This indicates that for a short frame, CRC-16 is robustly enough for error detection. In 802.11, the maximal frame length of MAC layer is 2312 bytes [7]. CRC-e can almost detect all errors when the data frame with $2^{e-1} - 1$ bits has no more than e errors [16]. However, when the number of errors is larger than e, CRC-e has a higher probability that some error(s) in the data cannot be detected. The maximum length of data that CRC-16 can protect is equal to $32\,767 (= 2^{15} - 1)$ bits (about 4096 bytes) [20]. CRC-16 can almost detect the errors when the length of frames is less or equal $2^{15}-1$ bits and the number of errors is not more than 16. Hence, CRC-16 can provide a sufficient capability to detect errors in IEEE 802.11 networks. Note that even if there is just an error in the data, the data must be retransmitted.

The maximum length of data that CRC-8 or CRC-4 can protect is much shorter than 2312 bytes. If CRC-8 or CRC-4 is utilized to protect IEEE 802.11 data, the probability of error mis-detection is much high. Thus, CRC-4 or CRC-8 is not considered in this paper.

2.2. Our fragment-based retransmission scheme

In this subsection, we propose an FBR scheme to improve the performance for wireless networks. Before describing our FBR, we use an example to illustrate the standard IEEE 802.11 MAC transmission procedure shown in Figure 1(a). In this example, the STAs that intend to transmit data frames exercises backoff to contend for channel occupancy after waiting for the period of DCF inter-frame space (DIFS). The backoff time for each STA is uniformly distributed in the range of [0,CW], where CW is the length of the contention window. The STA with the minimum backoff time occupies the channel. Then request-to-send/clear-to-send (RTS/CTS) four-way handshaking is utilized to reserve the coming time slots for data transmission [21]. In the handshaking process, a minimum gap between two successive transmitted frames is reserved and defined as short inter-frame space (SIFS). If RTS is successfully transmitted to the receiver, the receiver responds with CTS. Otherwise, the backoff operation with a doubled CW would be re-executed. Suppose that RTS/CTS handshaking is successfully performed (i.e., no collision occurs). Then, the data frame is delivered from the sender to the receiver, and the receiver sends ACK to the sender if data transmission is successfully received. If data transmission fails, the receiver does not reply ACK that the sender waits for. In IEEE 802.11, CRC is used to detect errors on data transmission, and a 32-bit FCS field is included in the design of an MAC protocol for error detection. If errors occur during data transmission and are detected, the contention procedure would be re-activated for data retransmission with a doubled CW.

3. ANALYTICAL MODEL

In RTS/CTS control frames, the 'Duration' field is utilized to represent how long the channel will be occupied for the coming frame transmission (including ACK frame), which are denoted as $RTS_{Duration}$ and $CTS_{Duration}$. In Figure 1(a), $RTS_{Duration} = 3SIFS + CTS + A_s + ACK$

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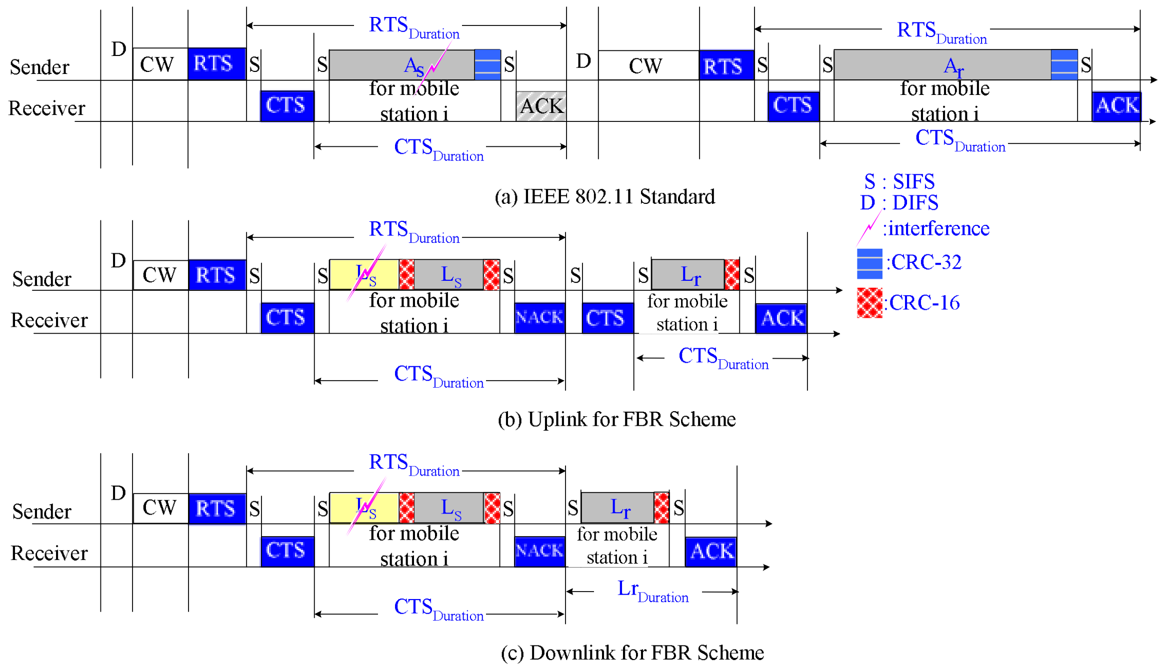

Figure 1. The transmission procedure in (a) IEEE 802.11, (b) uplink for fragment-based retransmission (FBR), and (c) downlink for FBR. We use the characters 'D' and 'S' to represent 'DIFS' and 'SIFS', respectively. ACK, acknowledgement; CRC, cyclic redundancy check; CTS, clear-to-send; CW, contention window; DIFS, distributed coordination function inter-frame space; RTS, request-to-send; SIFS, short inter-frame space.

and $\text{CTS}_{\text{Duration}} = 2\text{SIFS} + A_s + \text{ACK}$, where A_s denotes the transmission time of data and 32-bit CRC with a transmission rate of s Mbps. Note that if the transmission of the data frame fails, the sender will retransmit the data frame with the transmission rate r (where $r \leq s$). The r value for retransmission is set to a one-level lower rate than s. For example, in IEEE 802.11b, three different transmission rates (i.e., 11, 5.5, and 2 Mbps) are provided. For instance, if $s = 5.5$ Mbps, then $r = 2$ Mbps. As discussed in the previous subsection, CRC can provide a strong detection mechanism against noise, and it is not necessary to use CRC-32 for error detection when short frames are transmitted. Instead, CRC-16 could be used to save a 16-bit field that can be used for other purposes.

The basic idea of our proposed FBR is that we divide each original data frame into two fragmental data blocks and append a CRC-16 field to each fragmental data block in the MAC layer. The CRC-16 field of each fragmental data block is checked. The failed fragmental data blocks are given a secondary chance for retransmission without contention, and the retransmission rate is decreased to a lower level for reducing the error probability. FBR can decrease the length of retransmitted data and then increase the retransmission performance. Note that in the worst case, when both of the two fragmental data blocks fail, the length of data retransmission is equal to that in IEEE 802.11. The proposed FBR does not incur any extra contention overhead.

The transmission process is separated into two parts in infrastructure mode: uplink transmission (from an STA to the AP) and downlink transmission (from the AP to an STA). We focus on the discussion about uplink transmission. The downlink transmission has a similar procedure. As shown in Figure 1(b), if there are errors in the first fragmental data block, the receiver (i.e., AP) informs the sender of transmission failure by using a new NACK control frame.[‡] The frame length of the NACK control frame is the same as that of ACK. In this case of Figure 1(b), the transmission of the first fragmental data block fails, and the duration for retransmission is specified and reserved. The duration equals to $\text{CTS} + 3\text{SIFS} + L_r + \text{ACK}$, where L_r is the time for retransmitting a fragmental data block plus CRC-16 with the transmission rate r. Then, the sender (i.e., STA) retransmits the failed data block with the transmission rate r after the SIFS period. Note that, in WLAN, it is difficult to determine whether hidden-node problems exist. However, the proposed FBR can be used for uplink transmission to solve the hidden-node problems among STAs. In FBR, an additional CTS frame announces the duration (i.e., $\text{CTS}_{\text{duration}}$)

[‡]One flag bit in the ACK frame is used in our FBR to distinguish NACK from the standard ACK. We use the reserve bit of frame control field of NACK frame to decide which the fragmental block is a failure.

of frame retransmission to other STAs. With the additional CTS frame, extra bandwidth consumption resulting from the hidden-node problems in infrastructure WLAN power-save mode can be avoided. Our FBR can be also applied to downlink data delivery from AP to STAs. Compared with uplink transmission, the additional CTS frame is omitted because AP is not a hidden node for these STAs, as shown in Figure 1(c). The duration for retransmission (i.e., Lr_{Duration}) is specified and reserved by utilizing retransmission fragmental data block.

In order to implement our proposed scheme, an additional control frame type, NACK, is needed to notify the sender which data block has failed in the transmission. Moreover, the sender must compute CRC-16 checksum for two individual fragmental data blocks and appends the CRC-16 field to the corresponding fragmental data block. The receiver must check the CRC-16 field for two times.

In this section, we will propose an analytical model to investigate the MAC delay of FBR. For simplicity, a frame length is normalized as a time unit (slot). In order to derive the average MAC delay, we first describe the state transition of an STA under the FBR scheme and then model the probabilities that the STA transmits from one state to another one. Finally, we present the procedure of the MAC delay derivation.

3.1. State transition for fragment-based retransmission

Figure 2 illustrates the state transition diagram of a mobile STA for FBR. The diagram of FBR consists of six states: IDLE, ARRIVE, BACKOFF, ATTEMPT, RETRY_1, and RETRY_2.

Initially, the STA stays in IDLE state. When a data frame arrives, the state transits from IDLE state to ARRIVE state. In this subsection, we just analyze the MAC delay. Therefore, we assume that the arrival frame will be served immediately, and have no waiting time. When the frame

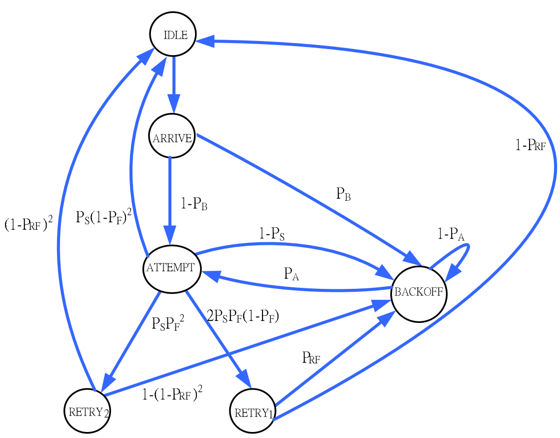

Figure 2. The state transition diagram for fragment-based retransmission.

is served by the STA, the channel sensing procedure is executed. If the channel is idle, the STA selects a random backoff time to countdown. If the STA counts to zero and senses that the channel is still idle, the state transit from ARRIVE state to ATTEMPT state. Otherwise, the STA enters into BACKOFF state. Note that the STA will transit from ARRIVE state to BACKOFF state and suspends the backoff countdown if the channel is used during the STA countdowns.

If RTS/CTS control frames and the two fragmental data blocks are successfully transmitted, the state transmits from ATTEMPT state to IDLE state. Otherwise, if the collision of RTS/CTS transmission occurs, the state transits from ATTEMPT state to BACKOFF state. When residing in BACKOFF state, the STA selects a random backoff time according to the backoff rule. The state for the STA transits from BACKOFF state to ATTEMPT state after the end of backoff countdown. In ATTEMPT state, if there are errors in data block transmission, the state transmits from ATTEMPT state to RETRY_1 or RETRY_2 state depending on the number of failed data blocks. State RETRY_i represents that i data blocks fail in the first transmission and will be retransmitted.

In RETRY_1 and RETRY_2 states, the STA retransmits fragmental data blocks at a lower data transmission rate. If retransmission with a lower transmission rate fails, the state transmits from RETRY_1 or RETRY_2 state to BACKOFF state. Otherwise, the state transits from RETRY_1 or RETRY_2 state to IDLE state.

3.2. Transition probabilities of fragment-based retransmission

In this subsection, we will model the probabilities among the states. We will just derive the MAC delay. Therefore, we assume that the probability that the STA transits from IDLE state to ARRIVE state is 1. Assume that the state transition probability from ARRIVE state to BACKOFF state is P_B, and the state transition probability from ARRIVE state to ATTEMPT state is $1 - P_B$. In FBR, the renewal interval is defined as the time between successive renewal points. A renewal interval consists of an idle period and a busy period. In the idle period, the transmission medium remains idle because of backoff, DIFS interval, or no frame arrival. In the busy period, the medium is used to perform data/control frame transmission or fragmental data block retransmission. With the aforementioned discussions, the transition probability P_B from ARRIVE state to BACKOFF state is expressed as

$$P_B = \frac{B}{I + B} \tag{3}$$

where I and B are the average lengths of idle and busy periods in each renewal interval, respectively. B will be defined in the next section. The average length I of the idle period is derived by the following equation: $I = 1/\Lambda + \text{DIFS}$.

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Assume that P_S is the probability for successful RTS/CTS transmission when the STA is in ATTEMPT state. In ATTEMPT state, if the collision of RTS/CTS transmission occurs, the state transits from ATTEMPT state to BACKOFF state with the probability of $1 - P_S$. Note that because of the short length of RTS/CTS frames, frame error for RTS/CTS can be ignored. The derivation of P_S is described as follows. We assume that the arrival process of frames at an STA forms the Poisson distribution with arrival rate λ. The probability P_S that RTS/CTS frame is successfully transmitted is given by

$$P_S(\Delta t) = \exp^{-\Lambda \Delta t} \quad (4)$$

where Δt is a slot time and Λ is the total frame arrival rate in the system. For the number N of mobile STAs with arrival rate λ, the total arrival rate Λ is qual to $N\lambda$.

When residing in BACKOFF state, the STA selects a random backoff time according to the backoff rule. The state for the STA transits from BACKOFF state to ATTEMPT state after the end of backoff countdown. The state transition probability is P_A. Otherwise, the STA suspends the backoff countdown and waits for next contention with the probability $1 - P_A$. P_A can be derived as $P_A = \exp^{-\Lambda(\text{DIFS}+T_B)}$, where T_B is the mean backoff time for a frame transmission, and from [22], we have $T_B = \sum_{i=0}^{4}[P_S(\Delta t)(1 - P_S(\Delta t))^i 2^{i-1} W] + (1 - P_S(\Delta t))^5 2^4 W$, where W is the minimum CW size.

Let $(1 - P_F)$ denote the probability for successfully transmitting a fragmental data block, where $P_F = 1 - (1 - P_b)^{\text{PHY+MAC}+L+\text{ACK}}$ is the probability that a fragmental data block fails to transmit [24]. P_b denotes the BER. L is the data length (in bits). PHY, MAC, and ACK are represented the lengths of the PHY layer head, MAC layer head, and the ACK frame, respectively. Note that due to the short length of the PHY layer head, MAC layer head, and the ACK frame, errors for PHY/MAC/ACK can be ignored. If RTS/CTS and the two fragmental data blocks are successfully transmitted, the probability from ATTEMPT state to IDLE state is $P_S(1 - P_F)^2$. Otherwise, if there are errors in data block transmission, the state transmits from ATTEMPT state to RETRY_1 or RETRY_2 state depending on the number of failed data blocks. State RETRY_i represents that i data blocks fail in the first transmission and will be retransmitted. The probabilities from ATTEMPT state to RETRY_1 and RETRY_2 states are equal to $\binom{2}{1} P_S P_F (1 - P_F)$ and $\binom{2}{2} P_S P_F^2$, respectively.

In RETRY_1 and RETRY_2 states, the STA retransmits fragmental data blocks at a lower data transmission rate. The lower data transmission rate can resist the noise interference and reduce the probability that there errors occur during the retransmission of the fragmental data block(s). If retransmission with a lower transmission rate fails, the state transmits from RETRY_1 or RETRY_2 state to BACKOFF state. Otherwise, the state transits from RETRY_1 or RETRY_2 state to IDLE state. Let P_{RF} be the probability that a fragmental data block fails in retransmission and $P_{RF} = 1 - (1 - P_{rb})^{\text{PHY+MAC}+L+\text{ACK}}$, where P_{rb} and L denote the BER under a lower retransmission rate and the data length, respectively [11,13]. The probabilities from RETRY_1 and RETRY_2 states to IDLE state are $1 - P_{RF}$ and $(1 - P_{RF})^2$, respectively. The probabilities from RETRY_1 and RETRY_2 states to BACKOFF state are P_{RF} and $1-(1-P_{RF})^2$, respectively. In the next section, we will discuss the average MAC delay in FBR.

3.3. The medium access control delay derivation for fragment-based retransmission

We will derive the MAC delay for FBR. The average length B of the busy period for FBR is is derived as follows. Let T_S and T_C respectively denote the average times for four-way handshaking and RTS/CTS transmission. $T_R(i)$ is denoted as the interval of the retransmission for i fragmental data blocks. From Figure 1(b), we have

$$T_S = \text{RTS} + 4\tau + 3\text{SIFS} + \text{CTS} + 2L_s + \text{ACK} \quad (5)$$

$$T_C = \text{RTS} + 2\tau + \text{SIFS} + \text{CTS} \quad (6)$$

$$T_R(i) = 2\tau + 3\text{SIFS} + iL_r + \text{ACK} + \text{CTS} \quad (7)$$

where τ is the propagation delay for frame transmission, and L_s and L_r are the transmission times of a fragmental data block plus the corresponding CRC with transmission rates of s and r Mbps, respectively. The propagation delay τ for the data block is omitted because τ is extremely small compared with the transmission time for the data frame [6].

Then, based on Equations (5), (6), and 7, the average length B of the busy period is derived as follows:

$$B = (1 - P_S)T_C + P_S \Bigg[\sum_{i=1}^{2} \binom{2}{i} (1 - P_F)^{2-i} P_F^i \times (1 - P_{RF})^i (T_R(i) + T_S) + (1 - P_F)^2 T_S \Bigg] \quad (8)$$

Let D_1 be the average MAC delay of a frame arrival for FBR. That is, D_1 is the interval between the time that the mobile STA serves the frame and the time that the frame is successfully transmitted. Thus, we have

$$D_1 = P_B(B + D_B) + (1 - P_B)\left(\text{DIFS} + \sum_{i=0}^{31} \frac{i}{32} + D_A\right) \quad (9)$$

where D_A and D_B are the average waiting times in ATTEMPT and BACKOFF states, respectively. DIFS + $\sum_{i=0}^{31} \frac{i}{32}$ is the average waiting time when the STA is in ARRIVE state. From Figure 2, D_A is given by

$$D_A = (1-P_S)(T_C + D_B) + P_S\left[\sum_{i=1}^{2}\binom{2}{i}(1-P_F)^{2-i}\left\{P_F^i(1-P_{RF})^i(T_R(i)+T_S)+(1-P_F)^2T_S\right\}\right] \quad (10)$$

Similarly, D_B is derived as

$$D_B = P_A(\text{DIFS}+T_B+D_A)+(1-P_A)(\text{RTS}+D_B) \quad (11)$$

Let

$$X = P_S\left[\sum_{i=1}^{2}\binom{2}{i}(1-P_F)^{2-i}P_F^i(1-P_{RF})^i \times(T_R(i)+T_S)+(1-P_F)^2T_S\right] \quad (12)$$

Let Y and Z denote (DIFS$+T_B$) and $\sum_{i=0}^{31}\frac{i}{32}$, respectively. D_A is re-written as $D_A=(1-P_S)(T_C+D_B)+X$, and D_B is re-written as $D_B = P_A(Y+D_A)+(1-P_A)(\text{RTS}+D_B)$. Hence, D_A and D_B are derived as shown in the following:

$$D_A=(1-P_S)\left(\frac{Y+T_C+X-\text{RTS}}{P_S}+\frac{\text{RTS}}{P_AP_S}+X\right) \quad (13)$$

and

$$D_B = \frac{Y+T_C+X-\text{RTS}}{P_S}+\frac{\text{RTS}}{P_AP_S}-T_C \quad (14)$$

Hence, by substitution, the average MAC delay D_1 for FBR could be derived on the basis of the results of D_A and D_B, as shown in the following:

$$D_1 = P_B\left(B+\frac{Y+T_C+X-\text{RTS}}{P_S}+\frac{\text{RTS}}{P_AP_S}-T_C\right) + (1-P_B)\left[\text{DIFS}+Z+(1-P_S)\times\left(\frac{Y+T_C+X-\text{RTS}}{P_S}+\frac{\text{RTS}}{P_AP_S}+X\right)\right] \quad (15)$$

Our analytical model has been validated against the simulations. For the simplicity of analysis, the analytical model and the simulation model utilized the parameters of IEEE 802.11b. Figure 3 shows the average MAC delay obtained from analysis and simulation for FBR, where the average length for data frame, data rate, and BER are assumed to be 1500 bytes, 11 Mbps, and 10^{-5}, respectively. From this figure, we observe that the analytical results are very close to the experimental results. When the traffic load is less than 0.5, the average performance difference between the analysis and simulation results is about 0.2 ms. On the other hand, when the traffic load is larger than 0.5, the average performance difference between the analysis and simulation results is about 0.36 ms. This phenomenon indicates that the accuracy of our analytical model slightly decreases as the traffic load increases. In heavy traffic load, the gap of the analytical results and the simulation results has widened. The reason is that in the simulation results, the arrival rates are underestimated because the decimal point of the arrival rate is omitted. Note that in the simulations, we do not consider the hidden-node problems so that the nodes can hear the radio range of each other.

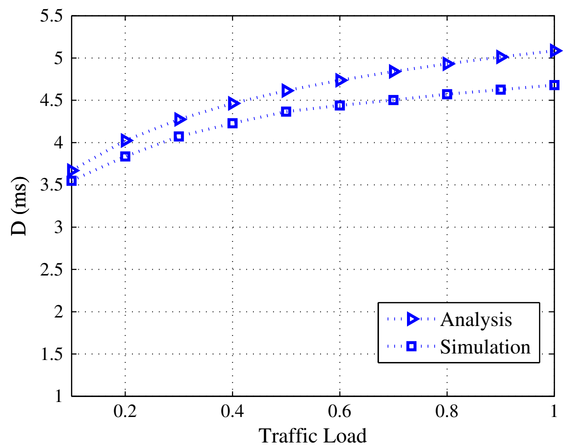

Figure 3. Comparison of the analysis and simulation results.

4. PERFORMANCE EVALUATION

The purpose of this section is to evaluate the performance of the proposed FBR scheme. We develop a simulation model for FBR and use some numerical examples to show the capabilities of our FBR.

Table I. System parameters.

Parameter	Normal value
Transmission rate	54 Mb/s
A slot time	9 µs
SIFS	10 µs
DIFS	28 µs
RTS frame length	160 bits (80 µs)
CTS frame length	112 bits (56 µs)
ACK frame length	112 bits (56 µs)
Preamble and PLCP header	20 µs
MAC header	34 octets
CWmin	16 slots
CWmax	1023 slots
BER	10^{-5} [24]

ACK, acknowledgement; BER, bit error rate; CTS, clear-to-send; CW, contention window; DIFS, distributed coordination function inter-frame space; MAC, medium access control; PLCP, physical layer convergence procedure; RTS, request-to-send; SIFS, short inter-frame space.

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Table II. Parameters for four traffic types: 1 denotes the highest priority, and 4 is the lowest priority [23].

Traffic types	Priority	Default relative deadline	Maximum PDU size (byte)	Application
Voice	1	150 ms	250 bytes	VoIP
Video	2	30 ms	2048 bytes	Video on demand
Multimedia	3	250 ms	2048 bytes	Video conference
Background	4	N/A	2312 bytes	FTP

VoIP, voice of IP; FTP, File Transfer Protocol; PDU, protocol data unit.

Table III. IEEE 802.11e parameters set [9].

AC	CWmin	CWmax	AIFSN
AC_VO	7	15	2
AC_VI	15	31	2
AC_BE	31	1023	3
AC_BK	31	1023	7

AIFSN, arbitration inter-frame space number; AC, access point; CW, contention window.

4.1. Simulation and analytical modeling

Our simulation model follows the IEEE 802.11g specification and simulates a hybrid multimedia applications environment, as shown in Table I. We compare the performance of IEEE 802.11e with FBR and IEEE 802.11e+g standard. We assume that the arrival process of frames at an STA forms a Poisson distribution with the arrival rate λ [12,18], and the length of data frames is exponentially distributed with a mean of $1/\mu$ time slots. Thus, the network traffic load can be defined as $N\lambda/\mu$, where N is thenumber of STAs in the network. From [2], the range of the arrival rates for each STA in our simulations is set from $0.227 * 10^{-3}$ to $2.227 * 10^{-3}$. When the arrival rate is less or equal to $0.681 * 10^{-3}$, we define the situation as 'small' arrival rate. On the other hand, when the arrival rate is higher than $1.589 * 10^{-3}$, the situation is defined as 'large' arrival rate. Each simulation runs at least 300 s, and each simulation result is obtained from averaging the results of 100 independent simulations. Without loss of generality, several assumptions are made to reduce the complexity of the simulation model and described as follows.

- There are 19 or 29 fixed STAs randomly located in the infrastructure environment.
- An AP is static and located at the center of simulated area. Note that our simulation model can be easily extended to accommodate ad hoc WLAN.
- All STAs support power-save mode.
- All control frames are sent at 2 Mbps transmission rate.
- Propagation delay between an STA and an AP is ignored.

In the simulations, we consider four kinds of QoS services in the Internet: voice, video, multimedia, and background traffic. The parameters are defined on the basis of the parameter setup in [23]. The first three traffic types are classified as real-time applications. The system needs a guarantee to transmit data generated by the applications before their relative deadlines. The background application is the best effort service. Every STA carries the same traffic for each traffic type under some network traffic load. When the network traffic load is U and the number of STAs is N, the traffic load of each traffic type in an STA is equal to $U/((N+1)*4)$. Note that we assume that the AP also provides the same traffic load as an STA. The number n_i of slots needed to transmit data for some traffic type i is derived on the basis of the corresponding maximum protocol data unit (PDU) size. Each STA has to use continuous

Table IV. Notations and abbreviations.

Symbol/term	Description	Symbol/term	Description
AIFS	Arbitration inter-frame space	FCS	Frame check sequence
AP	Access point	FEC	Forward error correction
BER	Bit error rate	GP	Goodput
CRC	Cyclic redundancy check	HCF	Hybrid coordination function
CSMA/CA	Carrier sense multiple access/collision avoidance	IWLAN	Infrastructure WLAN
CTS	Clear-to-send	MAC	Medium access control
CW	The length of the contention window	PCF	Point coordination function
D	MAC delay	PHY	Physical layer
DCF	Distributed coordination function	RTS	Request-to-send
DIFS	DCF inter-frame space	STA	Station
DP	Dropping rate	SIFS	Short inter-frame space
EDCA	Enhanced distributed channel access	WLAN	Wireless local area networks
FBR	Fragment-based retransmission		

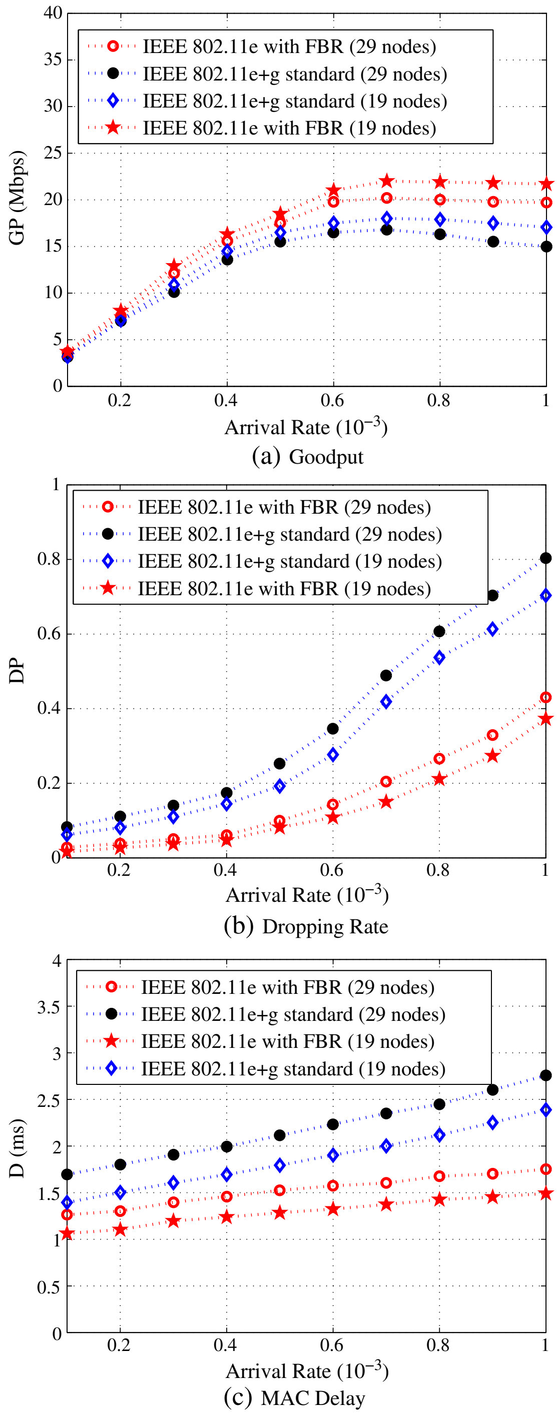

Figure 4. Effects of arrival rate on system goodput (*GP*), dropping rate (*DP*), and medium access control (MAC) delay (*D*). FBR, fragment-based retransmission.

n_i slots for data transmission per m_i slots. m_i could be derived by the following formula: $m_i = n_i / \frac{U}{(N+1)*4}$. In our simulation, each data frame of the three traffic types (i.e., voice, video, and multimedia) is given a default relative deadline. For real-time services, senders will drop the overdue data frames if they do not receive the ACK frames before the lifetimes expire. Contrarily, the senders will retransmit the data frames of the background traffic type. The parameters are summarized in Table II. The IEEE 802.11e EDCA parameter sets of the simulation is shown in Table III.[§]

The primary performance metrics are goodput (GP), dropping rate (DP), MAC delay (D), and queueing delay (QD). GP is defined as the ratio of the expected delivery period of data payload to the totally expected transmission period (excluding control frames, etc.) [19]. DP is defined as the ratio of the number of data frames dropped by the system divided by the total number of data frames. Note that a data frame will be dropped when its deadline has expired or the maximal retry count is reached. D is defined as the interval between the time that the mobile STA serves the frame and the time that the frame is successfully transmitted. QD is defined as the interval from when a data frame arrives until the frame is successfully transmitted, including the waiting in the buffer of the STA. The notations and abbreviations used in this paper are summarized in Table IV. .

4.2. Numerical examples

Figure 4(a) shows the effects of the arrival rate on GP for IEEE 802.11e with FBR and IEEE 802.11e+g standard schemes when the number N of STAs is equal to 19 or 29. With 802.11g 54 Mbps capacity, the arrival rates for each STA from $0.227 * 10^{-3}$ to $2.27 * 10^{-3}$ are simulated. This figure indicates that when $N = 19$, the GP values of the compared schemes increase until the arrival rate is equal to $1.589 * 10^{-3}$. Then, the GP values decrease. The reason is that the system is overloaded when the arrival rate is equal to $1.589 * 10^{-3}$. From the results, we can observe that IEEE 802.11e with FBR outperforms IEEE 802.11e+g standard under $N = 19$. The reason is that IEEE 802.11e with FBR utilizes extra transmission opportunity to retransmit erroneous fragmental blocks when the frames have noise inference. IEEE 802.11e with FBR decreases extra contention steps and collisions. The performance difference between IEEE 802.11e with FBR and IEEE 802.11e+g standard gradually increases when the arrival rate is from $0.227 * 10^{-3}$ to $2.27 * 10^{-3}$. The reason is

[§]IEEE 802.11e networks have four traffic types, and we can use the analytical model in Section 3.3 to derive the MAC delay of four traffic types in Table II by the following procedures. For each traffic type, the corresponding CWmin value in Table III is used to derive the mean backoff time T_B for a frame transmission. The CWmin value is the minimum CW size W of the equation for T_B. The length of an AIFS for each traffic type in IEEE 802.11e networks can be computed on the basis of the AIFSN values in Table III. The AIFS for some traffic type in IEEE 802.11e network is defined as AIFS $=$ AIFSN $*$ a_slot_time $+$ SIFS and is similar to the DIFS of IEEE 802.11b. For example, the AIFS value for the voice traffic type is equal to 28 $(= 2 * 9 + 10)$ μs.

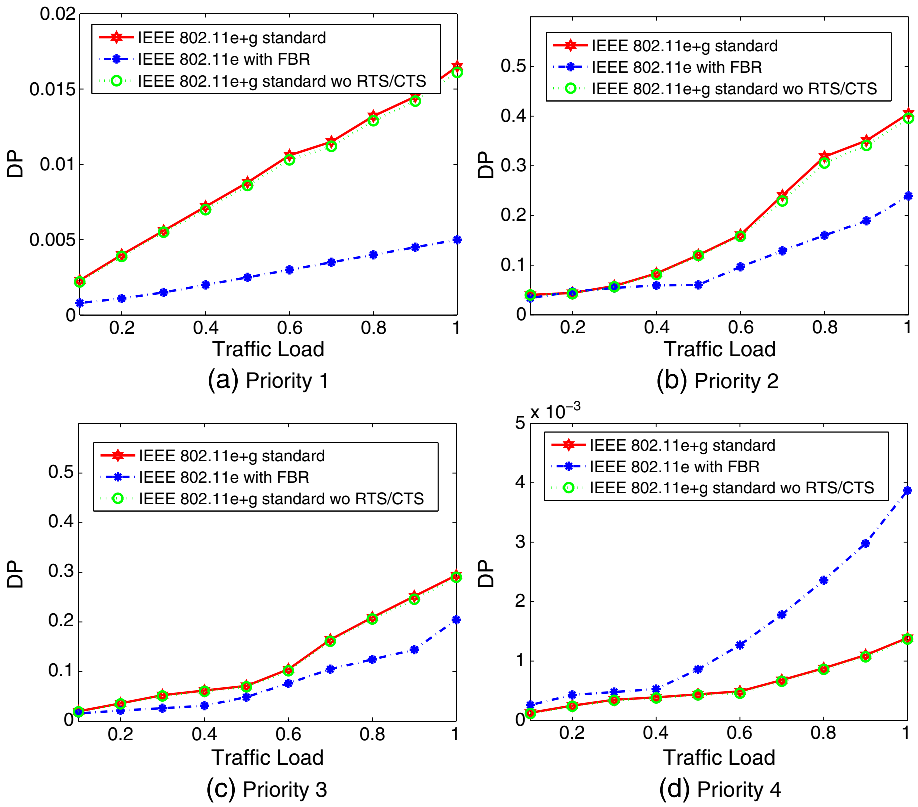

Figure 5. Effects of traffic load on dropping rate (*DP*) for different traffic types. FBR, fragment-based retransmission; RTS; request-to-send; CTS, clear-to-send.

that when the arrival rate is high, the number of collisions will become large. Note that the results under $N = 29$ are similar to those under $N = 19$. The difference is that when $N = 19$, the GP values under IEEE 802.11e with FBR and IEEE 802.11e+g standard are larger than the corresponding ones when $N = 29$. This is because under the same arrival rate, the total traffic load is heavier when there are more STAs in the network. Hence, the number of collisions will become large.

Figure 4(b) shows the effect of arrival rates on DP for IEEE 802.11e with FBR and IEEE 802.11e+g standard schemes when N is equal to 19 or 29. First, we discuss the experimental results under $N = 19$. For all schemes under investigation, DP increases as the arrival rate increases. When the arrival rate is less or equal to $1.135 * 10^{-3}$ and N is equal to 19 or 29, the performance difference between IEEE 802.11e with FBR and IEEE 802.11e+g standard is similar. However, when the arrival rate is greater than $1.135 * 10^{-3}$, the difference increases progressively. The reason is that in IEEE 802.11, the contention for channel occupancy under heavier traffic loads becomes severe, which significantly results in DP rise. We observe that the experimental results under $N = 29$ are similar to those under $N = 19$. Because of the heavier traffic load, the contention for channel becomes serious. Therefore, DP values for IEEE 802.11e with FBR and IEEE 802.11e+g standard schemes under $N = 29$ are larger than the corresponding ones under $N = 19$.

Figure 4(c) shows the MAC delay D of IEEE 802.11e with FBR and IEEE 802.11e+g standard when N is equal to 19 or 29. This figure intuitively shows that for all schemes under investigation, under $N = 19$, D increases as the arrival rate increases. This figure also indicates that when the arrival rate is low, the curves for all schemes are insensitive to the arrival rate and their values are smaller than 2 ms. On the other hand, when the arrival rate is high, D significantly increases as the arrival rate increases. In IEEE 802.11e+g standard, the retransmission process for a specific frame may be repeatedly activated because of severe BER. Each retransmission incurs additional contention overheads and degrades the system performance. Therefore, the frames of IEEE 802.11e with FBR standard could be successfully delivered with extra retransmission opportunity, which implicitly decreases the contention/collision overhead for a frame transmission. We also observe that the experimental results under $N = 29$ are similar to those under $N = 19$. Because of the heavier traffic load, the retransmission process for a specific frame may be serverely activated. D values for IEEE 802.11e with FBR and IEEE 802.11e+g standard schemes under $N = 29$ are larger than the corresponding ones under $N = 19$.

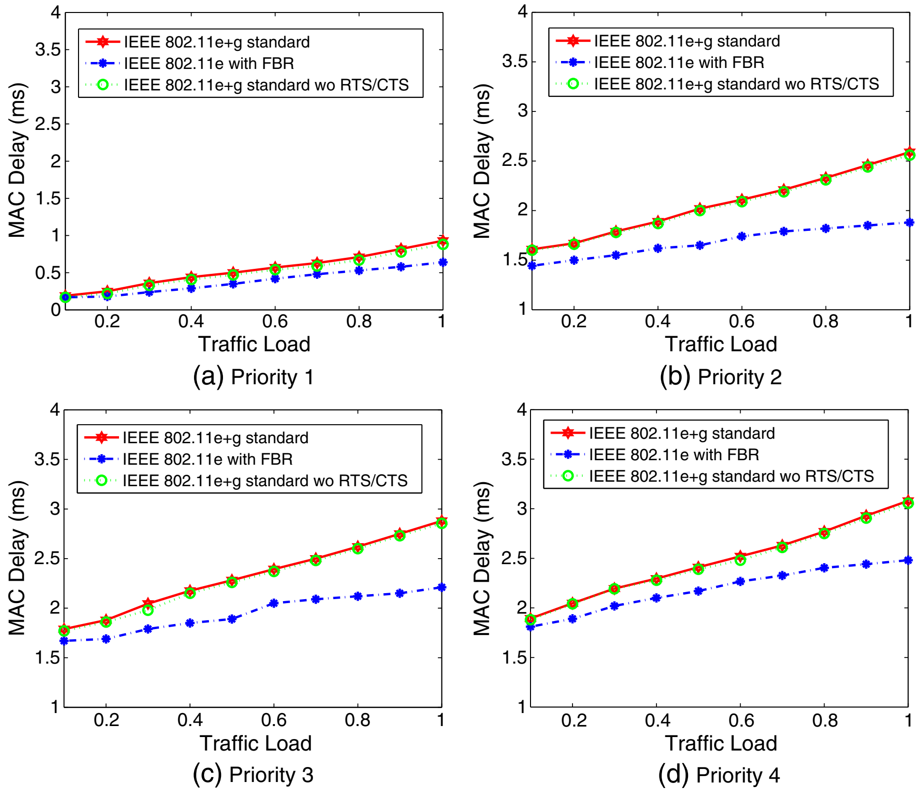

Figure 6. Effects of traffic load on medium access control (MAC) delay for different traffic types. FBR, fragment-based retransmission; RTS; request-to-send; CTS, clear-to-send.

In the following figures, we show the experimental results when the number N of STAs in the network is equal to 19. Note that the results are similar to that when N is equal to 29. When the traffic load is less or equal to 0.3, we define the situation is 'light' traffic load. On the other hand, when the traffic load is higher than 0.7, the situation is defined as 'heavy' traffic load.

Figure 5 shows the DP values of different traffic types under IEEE 802.11e with FBR, IEEE 802.11g+e standard, and IEEE 802.11g+e standard without RTS/CTS. The DP values for different applications increase as the traffic load increases. Based on the numerical results shown in Figure 5(a)–(c), we observe that real-time traffic (i.e., with priorities 1, 2, and 3) in IEEE 802.11e with FBR have smaller DP values than the corresponding ones in IEEE 802.11e+g standard and IEEE 802.11g+e standard without RTS/CTS. The reason is that the large retransmission delay is not suitable for multimedia applications with real-time requirements. Note that the DP values of traffic of priority 2 are greatly higher than that of priorities 1 and 3. This is because the traffic type of priority 2 have a longer maximum PDU size and a shorter default relative deadline. Figure 5(d) shows the DP values of background traffic type under the compared schemes. Note that in IEEE 802.11e+g standard and and IEEE 802.11g+e standard without RTS/CTS, the DP value is lower than that in IEEE 802.11e with FBR. The reason is that under IEEE 802.11e with FBR, the channel is used for real-time applications in most times. Therefore, most data frames of traffic with priority 4 are not sent successfully when the maximal retry count is reached. The lengths of RTS/CTS frames are much smaller than those of data frames of four traffic types. Thus, the performance difference between IEEE 802.11e+g standard and IEEE 802.11g+e standard without RTS/CTS is very small.

Figure 6(a)–(d) shows the MAC delay D of different traffic types under IEEE 802.11e with FBR, IEEE 802.11e+g standard, and IEEE 802.11g+e standard without RTS/CTS. The D values for different applications increase as the traffic load increases. The simulation results show that the IEEE 802.11e with FBR have smaller D values than those of IEEE 802.11e+g and IEEE 802.11g+e standard without RTS/CTS under all traffic types. Although IEEE 802.11e+g has been enhanced in the contention mechanism of different traffic types to support different QoS requirements, its channel access method still produces largely redundant transmission overheads for CA (e.g., contention, handshaking, and long backoff processes). Because of the small lengths of RTS/CTS frames, IEEE 802.11g+e standard without RTS/CTS has similar performances compared with IEEE 802.11g+e standard. Contrarily, IEEE 802.11e with FBR utilizes an extra

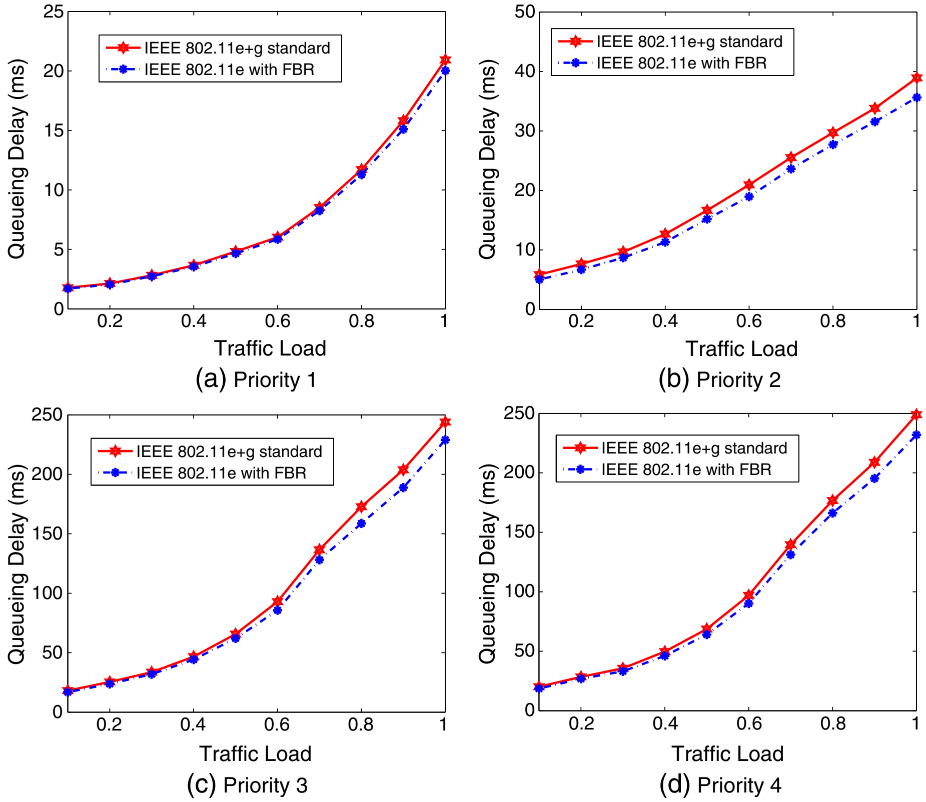

Figure 7. Effects of traffic load on queueing delay for different traffic types. F-3cmBR, fragment-based retransmission.

transmission opportunity to successively transmit data frames. A data frame is divided into two blocks. If the data frame transmission is a failure, we just retransmit the erroneous fragmental block(s). It can effectively decrease the overheads of channel contention and retransmission. Therefore, by utilizing IEEE 802.11e with FBR, the D value will be improved to conform to strict time bound for real-time data.

Figure 7(a)–(d) shows the queueing delay of different traffic types under IEEE 802.11e with FBR and IEEE 802.11e+g standard when a sender must transmit data frames through the AP to the corresponding receiver. The QD values for different traffic types increase as the traffic load increases. The simulation results show that the IEEE 802.11e standard with FBR have smaller QD values than those of IEEE 802.11e+g under all traffic types when the traffic load is larger than 0.5. From Figure 6, we observe that it needs more time to transmit a data frame when the traffic load is heavy. A data frame arrives and then is queued in the buffer of the STA. If the traffic load is heavy, the number of data frames in the buffer will be large. The data frame cannot be served until the previous data frames in the buffer are transmitted. Therefore, the difference between the QD values of IEEE 802.11e with FBR and IEEE 802.11e+g standard becomes larger when the traffic load is heavier. By utilizing IEEE 802.11e with FBR, the QD value will be improved to conform to strict time bound for real-time data.

5. CONCLUSION

This paper proposed an FBR scheme with QoS considerations for IEEE 802.11-based wireless networks. With our FBR scheme, each data frame is given a secondary chance for retransmission without contention, and the transmission efficiency is greatly improved, which provides QoS for real-time applications in WLAN. Our FBR could cooperate with IEEE 802.11e to decrease the retransmission overheads resulting from channel access. An analytical and a simulation models were developed to investigate the performance of FBR. The capability of the proposed scheme was evaluated by a series of simulations, compared with standard IEEE 802.11e+g wireless networks. From the numerical results, our FBR significantly outperforms the standard MAC of IEEE 802.11e+g.

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