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PAPER

Performance Evaluation of Video Transmission with the PCF of the IEEE 802.11 Standard MAC Protocol*

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SUMMARY This paper focuses on a single BSA (Basic Service Area) in an infrastructure network and studies the performance of the IEEE 802.11 standard MAC protocol by means of simulation. The MAC protocol supports DCF (Distributed Coordination Function) and PCF (Point Coordination Function). The simulation model includes both data transmission with the DCF and H.263 video transmission with the PCF. In the simulation we assume that the channel transmission rate is 2 Mbps and use the system parameters specified in the standard for the DSSS (Direct Sequence Spread Spectrum) physical layer. We evaluate the performance of this protocol in terms of throughput and MPDU (MAC Protocol Data Unit) delay for various values of the CFP (Contention Free Period) repetition interval and the CFP maximum duration. Numerical results show that if the CFP repetition interval is set too long, video MPDU delay becomes very large periodically; therefore, average video MPDU delay deteriorates. We also find that as the CFP maximum duration decreases, the number of video terminals that can be accommodated in the system decreases. Furthermore, how channel transmission errors affect the performance of the protocol is examined. A two-state continuous-time Markov model is used as a burst error model. As a result, we see that for a small number of video terminals, the average video-MPDU-delay performance does not deteriorate drastically for larger values of bit error rate.

key words: *wireless LAN, media access control, IEEE 802.11, H.263 video, performance evaluation*

1. Introduction

Wireless local area networks (LANs) can meet an increasing demand that mobile users access wired networks from their portable computers. The IEEE 802.11 committee has developed a wireless LAN standard to satisfy the needs of wireless access [1]. The scope of the standard is MAC (Media Access Control) and physical layers. The standard allows data rates of up to 2 Mbps in the 2.4 GHz band [1]. Future wireless LANs will be required to transmit multimedia traffic at higher data rates. To meet this demand, the IEEE 802.11a and IEEE 802.11b committees have been working for extensions of this standard for higher data rates of up to 54 Mbps in the 5 GHz band and 11 Mbps in the 2.4 GHz band, respectively [2].

The IEEE 802.11 standard MAC protocol supports two kinds of access methods: *DCF (Distributed Coordination Function)* and *PCF (Point Coordination Function)* [1]–[3]. The DCF is designed for asynchronous data transmission by using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) and must be implemented in all stations. On the other hand, the PCF is intended for transmission of real-time traffic as well as that of asynchronous data traffic. This access method is optional and is based on polling controlled by an *AP (Access Point)*.

The performance of the DCF has already been studied by many researchers [3]–[6]. Furthermore, the combined performance of data transmission with the DCF and voice transmission with the PCF has also been evaluated in [3]. However, performance evaluation taking into account video transmission with the PCF can be found only in [7], though some important physical parameters are not based on the standard; in particular, the channel transmission rate is set to 10 Mbps. In addition, the channel is assumed to be error-free [7].

On the other hand, many studies about video transmission over wireless LANs in general have been reported [8]–[15]. In the great majority of these studies, reservation-based MAC protocols are selected, and the wireless channel is centrally controlled by the base station. In [8], TDD ALOHA-Reservation for integrated video and data transmission is studied. BRMA (Bandwidth Reservation Multiple Access) for MPEG video transmission is treated in [9]. The performance of DPRMA (Dynamic Packet Reservation Multiple Access) and that of EC-MAC (Energy Conserving Medium Access Control Protocol) are evaluated considering a modified version of H.261 video in [10] and [11], respectively. MASCARA (Mobile Access Scheme Based on Contention and Reservation for ATM) and DQRUMA (Distributed Queueing Request Update Multiple Access) is studied in [12] and [13], respectively. These papers evaluate the performance of each protocol taking into account real-time VBR traffic. The studies in [9]–[13] are aimed at multimedia communication over wireless ATM (Asynchronous Transfer Mode) LANs. Furthermore, prototype wireless ATM systems have been developed for high-speed wireless multimedia transmission including MPEG video [14], [15]; as the MAC protocol, dynamic TDD-TDMA [14] and RS-ISMA (Slotted Idle Signal Multiple Access with Reservation) [15] are proposed.

The IEEE 802.11 standard MAC is a hybrid protocol of random access and polling when both DCF and PCF are used. That is, in this protocol, a wireless channel is divided into superframes; each superframe consists of a *CFP (Contention Free Period)* for the PCF and a *CP (Contention Period)*

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for the DCF. This means a CP for data transmission is located between two CFPs, which can be used for video transmission. Since the operational principle of this protocol is rather complicated, the performance of this protocol depends on many system parameters. In particular, the performance of video transmission with the PCF is very sensitive to system parameters about channel structure such as the CFP repetition interval and the CFP maximum duration. Therefore, performance evaluation of this protocol taking into consideration channel structure is needed to know how the system parameters should be selected to realize efficient video transmission.

This paper focuses on a single *BSA (Basic Service Area)* in an infrastructure network and studies the performance of the IEEE 802.11 standard MAC protocol taking into account both data transmission with the DCF and H.263 [16] video transmission with the PCF. In this paper we assume that the channel transmission rate is 2 Mbps and use the system parameters specified in the standard for the DSSS (Direct Sequence Spread Spectrum) physical layer. By simulation, we evaluate the performance of this protocol in terms of throughput and average *MPDU (Mac Protocol Data Unit)* delay for various values of the CFP repetition interval and the CFP maximum duration. We also assess video MPDU delay. In the simulation, video traffic obtained from a real video sequence is used. We also study how channel transmission errors affect the performance of the protocol. A two-state continuous-time Markov model is used as a burst error model.

This paper is organized as follows. Section 2 describes the system configuration we study here. Section 3 explains data transmission with the DCF and video transmission with the PCF. Section 4 specifies the polling scheme used by the PCF. Section 5 makes simulation assumptions. Section 6 gives numerical results from simulation and studies the performance of the protocol.

2. System Configuration

Figure 1 illustrates an example of a single BSA in an infrastructure network. In this paper we focus on a single BSA as shown in this figure and evaluate the performance of the IEEE 802.11 standard MAC protocol by simulation. We assume in this paper that the BSA includes an AP connected to a *DS (Distribution System)*, data terminals and video terminals. Data terminals send data messages to other data terminals within the BSA using the DCF. Each video terminal exchanges video messages with the AP in both uplink (terminal-to-AP) and downlink (AP-to-terminal) directions using the PCF.

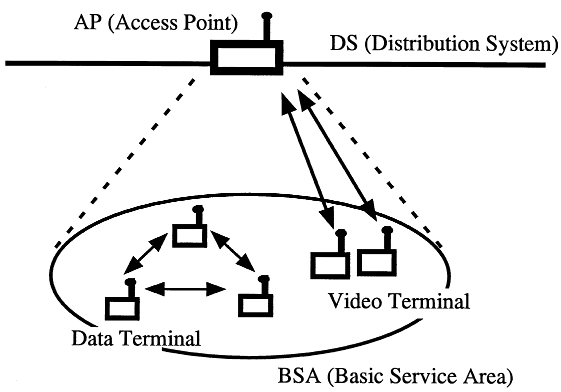

Fig. 1 System configuration.

3. MPDU Transmission with the IEEE 802.11 Standard MAC Protocol

In this section we describe the transmission procedures for data MPDU with the DCF and video MPDU with the PCF. In this paper, a data MPDU means an MPDU which contains data information in its payload. Similarly, a video MPDU means an MPDU with video information.

3.1 Data MPDU Transmission with the DCF

The DCF employs CSMA/CA. Figure 2 illustrates a data MPDU transmission with the DCF. When a terminal generates a data MPDU, it senses the state of the channel to determine if another terminal is transmitting.

If the medium is determined to be idle for a *DIFS (Distributed Coordination Function InterFrame Space)* period, the terminal transmits the data MPDU to a destination terminal. If the destination terminal receives the data MPDU correctly, it sends an *acknowledgment frame (ACK)* back to the source terminal after an *SIFS (Short InterFrame Space)* period. Since the SIFS period is shorter than the DIFS period, transmission of an ACK has priority over that of a data MPDU.

If the medium is determined to be busy, the terminal waits until the channel becomes idle for a DIFS period, and then it selects a random backoff period. During the idle period, the terminal decreases its backoff timer. If another terminal starts to send a frame, the terminal freezes the timer; then, the terminal decreases the backoff timer again after it judges the channel to be idle for a DIFS period. When the backoff timer finally becomes 0, the terminal begins to transmit a data MPDU.

The backoff period is a multiple of the duration of a slot-time and is selected uniformly in the range of 0—*CW (Contention Window)* slot-times. The initial value of CW is CW_{min}; then, for the n-th retransmission, CW is set to $2n(CW_{min}+1)-1$. When CW becomes the maximum value CW_{max}, it remains at CW_{max} for later retransmissions.

If two or more terminals begin to transmit data MPDUs

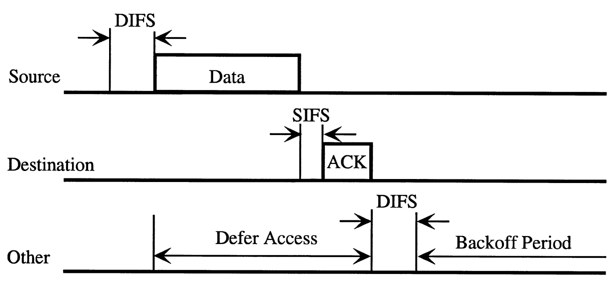

Fig. 2 Data MPDU transmission with the DCF.

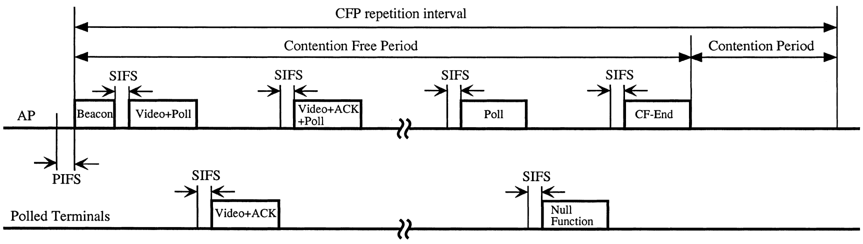

Fig. 3 Video MPDU transmission with the PCF.

almost simultaneously or select the same backoff period, a collision occurs. In this case, the terminals must retransmit the data MPDUs.

In the standard, the *RTS (Request To Send)* frame and the *CTS (Clear To Send)* frame can optionally be exchanged before transmission of a data MPDU in order to decrease the overhead due to collisions in hidden terminal environments. When a terminal receives an RTS or a CTS frame, it sets its *NAV (Network Allocation Vector)* until the time at which the corresponding data MPDU and ACK exchange is finished, and does not try to send any MPDU. In the simulation of this study, however, we assume no hidden terminals, and the RTS/CTS handshaking is not addressed.

3.2 Video MPDU Transmission with the PCF

In the PCF, the AP polls the video terminals on its polling list and enables them to transmit video MPDUs without collisions. When PCF is performed, a wireless channel has a superframe structure as shown in Fig. 3; each frame consists of a CFP and a CP. The CFP repetition interval determines the frequency with which the PCF starts.

As shown in Fig. 3, at the beginning of every CFP the AP sends a beacon frame to all terminals in the BSA after the AP confirms that the medium is idle for a *PIFS (Point Coordination Function InterFrame Space)* period. Note that a PIFS period is smaller than a DIFS period but larger than a SIFS period. The beacon frame has information on the maximum duration of the CFP, and the terminals set their NAV not to send any data MPDU in the CFP.

During the CFP, the AP polls each terminal in its polling list by sending either a Video+CF-Poll frame or a CF-Poll (no video) frame. If a terminal receives a Video+CF-Poll frame from the AP as shown in Fig. 3, it can respond to the AP after an SIFS period with either a Video+CF-ACK frame or a CF-ACK (no video) frame. If the AP receives a Video+CF-ACK frame, it can send either a Video+CF-ACK+CF-Poll frame (like Fig. 3) or a CF-ACK+CF-Poll frame. On the other hand, in the case that a terminal receives a CF-Poll (no video) frame from the AP, it can respond to the AP with either a Video frame or a Null Function (no video) frame. When the AP fails to receive an ACK, it waits for a PIFS period and polls the next terminal. The AP basically continues to poll each terminal until the time reaches the maximum duration of the CFP. However, the AP can immediately terminate the CFP by sending a CF-End frame if the AP judges that terminals in the BSA have no MPDUs to transmit.

4. The Polling Scheme

In this paper we adopt the following polling scheme for the PCF. The polling scheme used in this paper is based on a cyclical scheduling algorithm as in [3].

At the beginning of each CFP, the AP adds all video terminals into its polling list. Then, the AP polls each video terminal sequentially by sending a CF-Poll frame in the order in which it is placed in the polling list. When the AP polls a video terminal, it can also send a Video+CF-Poll frame if it has video information directed to the terminal. In the polling scheme used in this paper, the AP provides a counter for each video terminal that is added in the polling list. The counters for all terminals are set to zero at the beginning of every CFP. During a CFP, the AP increases the counter-value by one for a terminal if the AP sends a CF-Poll frame to the terminal and the polled terminal sends a Null Function frame back to the AP. Then, if the counter reaches a predetermined value (say K), the AP drops the video terminal from the polling list. When all video terminals are dropped from the polling list or the time reaches the maximum duration of the CFP, the AP preserves the information about the last polled terminal and it ends the CFP. Then, in the next CFP, the AP adds all video terminals into its polling list again and resumes polling from the next video terminal in the list.

5. Assumptions for Simulation

In our simulation, we make the following assumptions.

1): The channel propagation delay is negligible.

2): A two-state continuous-time Markov model in [3] is used as a burst error model. The model has state G and state B. State G represents that the channel is operating with a low bit error rate denoted by BER_{good}, and state B corresponds to a higher bit error rate denoted by BER_{bad}. The transition rate from state G to state B is denoted by $\alpha\ s^{-1}$, while the transition rate from state B to state G is denoted by $\beta\ s^{-1}$.

3): Each data terminal generates data MPDUs. The interarrival time between data MPDUs for a data terminal is exponentially distributed with a mean of a msec.

4): The length of the frame body of a data MPDU is geometrically distributed with a mean of h octets, provided that the frame body does not exceed the maximum length speci-

fied by the standard (i.e., 2312 octets).
5): The RTS/CTS handshaking mechanism is not used when a data terminal transmits a data MPDU.
6): Each video terminal generates a video sequence directed to the AP. On the other hand, the AP also generates a video sequence for each video terminal. When a video terminal / the AP generates a video frame, it forms a video MPDU and sends it to the AP / a video terminal using the PCF.

We use video traffic obtained from a real video sequence, where a person is talking in front of a camera. The sequence is encoded with an H.263 software encoder under the condition that the target encoding rate is 32 kbps, the reference frame rate is 15 fps and the coding format is sub-QCIF (128*96 pixels).
7): Each data terminal has a finite capacity of data buffer that can accommodate a maximum of B_d kbits. The capacity of video buffer at each video terminal is B_v kbits. If a data or video terminal generates a new MPDU and if its buffer does not have enough space to accommodate the MPDU, the terminal discards the MPDU.
8): When a data terminal sends a data MPDU, it cannot receive a corresponding ACK if a collision or a channel transmission error occurs with the data MPDU or ACK. In this case, the data terminal retransmits the same data MPDU according to the backoff procedure specified by the standard. Similarly, if a video terminal or the AP fails in sending a video MPDU due to channel transmission error, it also retransmits the same video MPDU in a subsequent polling cycle. The maximum allowable number of retransmissions of a data MPDU and that of a video MPDU are R_d and R_v, respectively. If a terminal cannot succeed in sending a MPDU within the maximum allowable number of retransmissions, it gives up sending the MPDU and drops it.

Table 1 lists system parameters and their values used in the simulation. In addition, we use system parameter values specified in the standard for the DSSS physical layer; namely, the duration of a slot is equal to 20 msec, $DIFS$=50 msec, $PIFS$=30 msec, $SIFS$=10 msec, CW_{min}=31 and CW_{max}=1023 [1].

Table 1 System parameters used in the simulation.

parameter	meaning	value
C	Channel transmission rate	2 Mbps
CFP_{rep}	CFP repetition interval	variable
CFP_{max}	CFP maximum duration	variable
M_d	The number of data terminals	20
M_v	The number of video terminals	variable
h	Average data MSDU length	1000 octets
a	Average interarrival time between data MPDUs	valuable
L_d	data load	valuable
B_d	data terminal buffer size	100 kbits
B_v	video terminal buffer size	100 kbits
R_d	The maximum number of retransmissions of a data MPDU	4
R_v	The maximum number of retransmissions of a video MPDU	4

6. Numerical Results

In this section we evaluate the combined performance of data transmission with the DCF and H.263 video transmission with the PCF.

In the following numerical results, we set K=1. In the case of K=1, if the AP and a video terminal exchange a CF-Poll frame and a Null Function frame only once, the AP drops the video terminal from the polling list. In this case, the duration of CFP can be shortened by the AP if the traffic load is not heavy.

The performance measures used in this paper are the data throughput, video throughput, average data MPDU delay and average video MPDU delay. The average data MPDU delay and average video MPDU delay are shown in units of millisecond. We also show the CFP_{ratio} to discuss the performance. The CFP_{ratio} is defined as the ratio of the average duration of a CFP to the duration of a CFP_{rep}.

The simulation results are represented by symbols such as circle, triangle and square. The results depicted by the closed symbols indicate data throughput or average data MPDU delay, while the ones depicted by open symbols indicate video throughput, average video MPDU delay or CFP_{ratio}. We will plot the video throughput and average video MPDU delay only for uplink video transmission. We have confirmed through simulation that the performance of downlink video transmission exhibits similar characteristics to that of uplink video transmission. In addition, we have also confirmed that with B_d=B_v=100 and R_d=R_v=4, buffer overflow and MPDU dropping do not occur unless the channel traffic load is very heavy or the channel bit error rate is very high.

The duration of each simulation run was taken to be 99 sec. We calculated the 95-percent confidence intervals of the simulation results. However, if the interval is smaller than the size of the corresponding simulation symbol in the figure, we do not show it there.

6.1 The Effect of CFP Repetition Interval

Figures 4 and 5 show the throughput and average MPDU delay as a function of CFP_{rep} for the data load L_d=0.1 and L_d=0.3, respectively. Note that L_d=8$M_d h/(aC)$=80000/a when M_d=20, h=1000 and C=2. These figures present the case in which CFP_{max}=0.8CFP_{rep} and the channel bit error rate BER is equal to 0. In order to study the effect of the number of video terminals M_v on the data performance, in these figures we show the performance for three values of M_v; namely, M_v=6, 10 and 18.

First, we examine the effect of CFP_{rep} on the video performance using these figures. Note that the video performance for L_d=0.1 is almost the same as that for L_d=0.3 because channel capacity is allocated first to the CFP in a superframe.

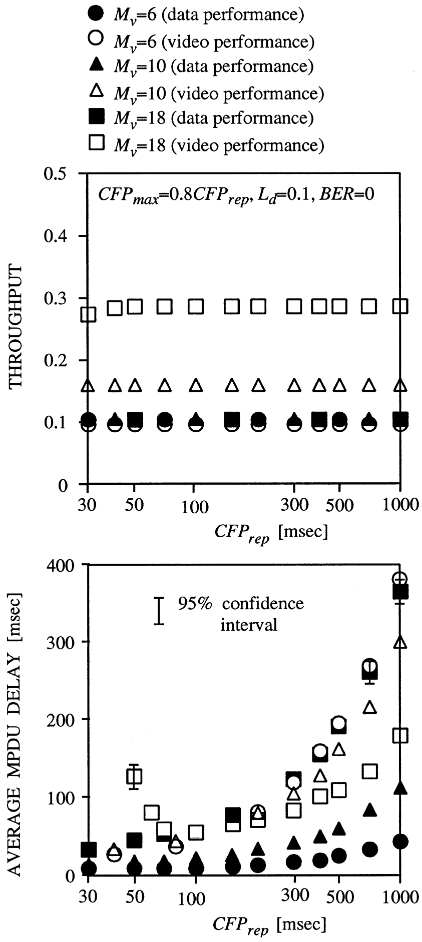

Fig. 4 Throughput and average MPDU delay versus CFP repetition interval for L_d=0.1.

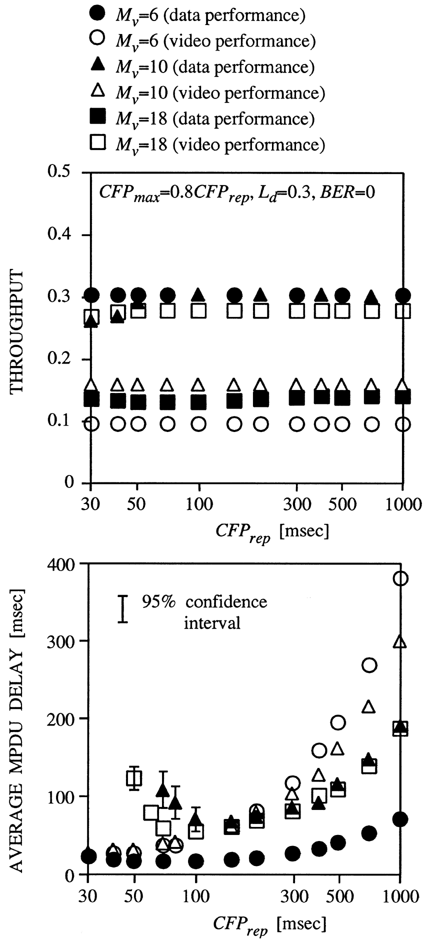

Fig. 5 Throughput and average MPDU delay versus CFP repetition interval for L_d=0.3.

We find in Figs. 4 and 5 that as the value of CFP_{rep} becomes smaller, the average video MPDU delay decreases for the cases of M_v=6 and 10. The reason why we have this result is as follows. When CFP_{rep} is set to be a small value, the AP resets its polling list in a short interval and polls each video terminal frequently; therefore, the average video MPDU delay becomes small. On the contrary, when CFP_{rep} is large, the average video MPDU delay is also large because a long CP can be inserted between two successive CFPs. In the case of M_v=18 the average video MPDU delay increases as CFP_{rep} decreases if CFP_{rep} is smaller than 100 msec. This is because the influence of control overhead on the video performance cannot be negligible.

Let us discuss the effect of CFP_{rep} on the video-MPDU-delay performance in more details using Figs. 6 and 7. Figure 6 depicts the video MPDU delay of each video frame generated by a video terminal for the first 100 frames. Figure 7 shows the video MPDU generation time and the video MPDU receiving time of each video MPDU generated by a terminal from 1000 msec to 2000 msec of simulation. In Fig. 7 the video MPDU generation time means the instant a terminal generates a video MPDU and the video MPDU receiving time means the instant the AP finishes receiving a video MPDU. This figure also shows intervals of the CFP by thick lines drawn just below the time axis for the video MPDU receiving time. In Figs. 6 and 7 we set M_v=10 and show the cases of CFP_{rep}=500 and 100. Other system parameters used in these figures are the same as those used in Fig. 4.

Figure 6 illustrates that the video MPDU delay fluctuates and becomes very large periodically in the case for CFP_{rep}=500 msec. The reason for this result can be made clearer by Fig. 7. That is, if CFP_{rep} is set to CFP_{rep}=500 msec, the video MPDU delay becomes very large if a terminal generates a video MPDU just after the end of a CFP. In the case of CFP_{rep}=100 msec, video MPDU delay does not become so large because the next CFP comes soon. We have also made subjective assessment of the video quality based on simulation results in Fig. 6. As a result, we have found that if CFP_{rep}=500 msec, the fluctuation of the video MPDU delay degrades the video quality.

Next let us discuss the effects of the CFP repetetion interval CFP_{rep} and the data load L_d on the data performance using Figs. 4, 5 and 8. Figure 8 plots CFP_{ratio} as a function of CFP_{rep}. System parameters used in this figure are the same as those used in Fig. 5.

We first find in Fig. 4 that as CFP_{rep} decreases, the average data MPDU delay becomes smaller. As CFP_{rep} decreases, the CFP and CP alternate in a shorter interval; therefore, even

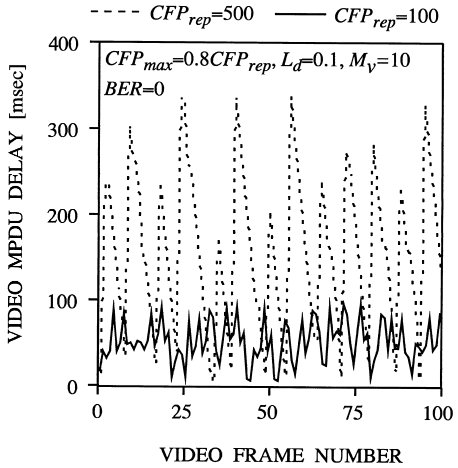

Fig. 6 Video MPDU delay of each video frame.

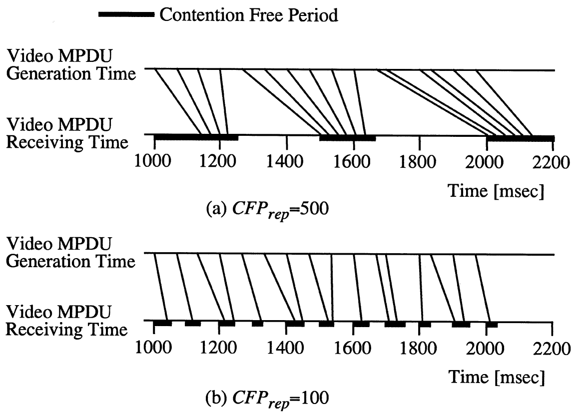

Fig. 7 Video MPDU generation time and video MPDU receiving time of each video frame.

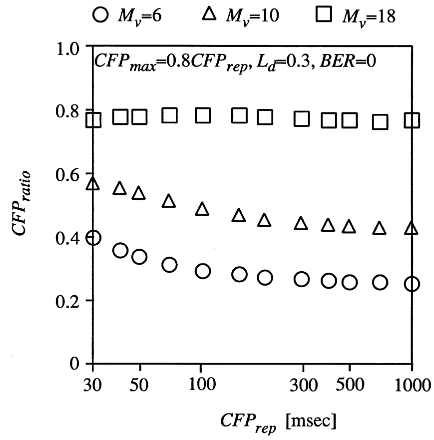

Fig. 8 CFP_{ratio} versus CFP repetition interval.

if each data terminal generates a data MPDU in a CFP, it does not wait for a long time until the next CP. This leads the average data MPDU delay to a small value if the traffic load of CP is not heavy: Note that in this figure CFP_{max} =0.8CFP_{rep} (i.e., the minimum capacity of CP is 20 percent of the channel capacity), and the data load L_d=0.1.

We then discuss the average data MPDU delay in the case of L_d=0.3 using Figs. 5 and 8. Figure 5 shows that as CFP_{rep} decreases, the average data MPDU delay for M_v=10 becomes smaller when CFP_{rep} is larger than 200 msec. However, if CFP_{rep} is smaller than this value, the average data MPDU delay increases as CFP_{rep} decreases. The reason why we have this result is as follows. When CFP_{rep} is larger than 200 msec, the traffic load of CP is light. In this case, as CFP_{rep} becomes smaller, average data MPDU delay also decreases because the CP starts more frequently. We find in Fig. 8, however, that as CFP_{rep} decreases, CFP_{ratio} increases. This is because control frames such as CF-Poll frame and Null Function frame are transmitted more frequently. Since an increase of CFP_{ratio} means an decrease of the capacity of CP, the traffic load of CP becomes heavier as CFP_{rep} decreases. Therefore, the average data MPDU delay increases if CFP_{rep} decreases below 200 msec. We also make a similar observation in the case of M_v=6; that is, as CFP_{rep} decreases, the average data MPDU delay decreases for CFP_{rep} > 70 msec while it slightly increases for CFP_{rep} < 70 msec.

Furthermore, We can observe in Fig. 5 that if M_v=10 and CFP_{rep} < 50 msec, or if M_v=18, the data performance deteriorates drastically. In these cases, we can find from Fig. 8 that the CFP_{ratio} is beyond about 0.55; that is, the capacity of CP is less than 45 percent of the channel capacity. This causes CP to become saturated in the case of L_d=0.3 owing to the control overhead.

6.2 The Effect of CFP Maximum Duration

Now, we examine the effect of the CFP maximum duration on the performance. Figure 9 depicts the throughput and average MPDU delay as a function of the number of video terminals M_v. Figure 10 plots CFP_{ratio} as a function of M_v. These figures present the case in which CFP_{rep}=100, the data load L_d=0.1 and BER=0.

We here focus on the maximum number of video terminals M_{vmax} that can share the channel under the condition that the average video MPDU delay is limited to a reasonable value (say 70 msec). From Fig. 9, we see that the value of M_{vmax} is 8, 13 and 18 for CFP_{max}=0.4CFP_{rep}, 0.6CFP_{rep} and 0.8CFP_{rep}, respectively. Consequently, we can say that as CFP_{max} increases, M_{vmax} also becomes larger; that is, the system can accommodate a larger number of video terminals. It should be noted in Fig. 10 that as CFP_{max} increases, the maximum value of CFP_{ratio} also increases; this means the minimum capacity of CP becomes smaller.

We also find in Fig. 9 that the average video MPDU delay does not change drastically as the number of video terminals M_v increases if M_v does not exceed the value of M_{vmax}. This is because an increasing number of video terminals only leads to an increase of CFP_{ratio} (see Fig. 10). If the number of video terminals is beyond M_{vmax}, the average video MPDU delay increases rapidly because the CFP cannot be extended any more and goes into a congested state.

In the following figures to be shown, we set CFP_{rep} =100 msec and CFP_{max}=0.8CFP_{rep} (i.e., CFP_{max}=80 msec) as de-

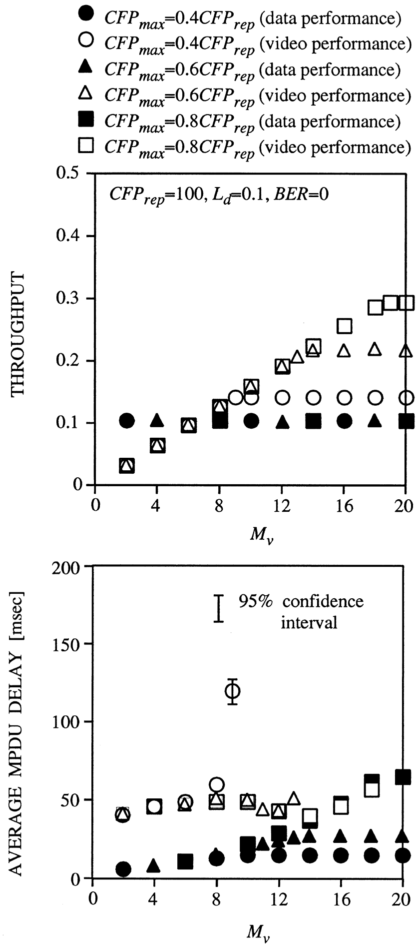

Fig. 9 Throughput and average MPDU delay versus the number of video terminals.

fault values. Under these system parameters, the system can accommodate 18 video terminals with tens msec of average video MPDU delay. In addition, at least one data MPDU can be transmitted in a CP†.

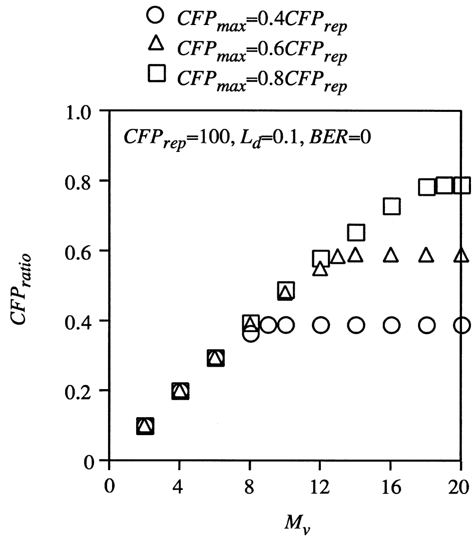

Fig. 10 CFP_{ratio} versus the number of video terminals.

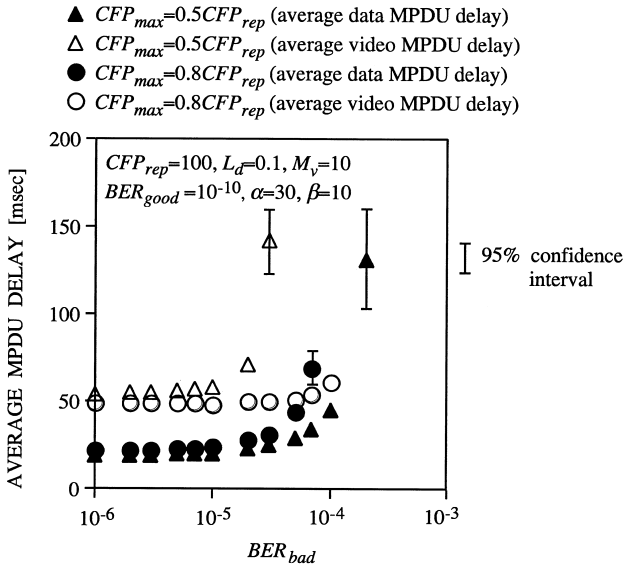

Fig. 11 Average MPDU delay versus BER_{bad} for M_v=10.

6.3 The Effect of Channel Transmission Error

Figures 11 and 12 reveal the average MPDU delay versus BER_{bad}. In Fig. 11 we set M_v=10 and show the cases of CFP_{max}=0.5CFP_{rep} and CFP_{max}=0.8CFP_{rep}. In Fig. 12 we set CFP_{max}=0.8CFP_{rep} and indicates three cases of M_v : namely, M_v=10, 15 and 18. Furthermore, Fig. 13 plots CFP_{ratio} versus BER_{bad}. In these figures, we set CFP_{rep}=100 and L_d=0.1. We also set BER_{good}=10^{-10}, α=30 and β=10 as in [3].

We first examine the effect of BER_{bad} on the values of CFP_{ratio} and average video MPDU delay. Figure 11 shows that in the case of CFP_{max}=0.8CFP_{rep}, the average video MPDU delay is almost constant (50 msec) when BER_{bad} is smaller than 10^{-4}. If BER_{bad} exceeds around this value, the average video MPDU delay increases rapidly.

Let us discuss the results in more detail using Figs. 11 and 13. We observe in Fig. 13 that when BER_{bad} exceeds around 10^{-5}, CFP_{ratio} begins to increase owing to retransmissions of video MPDUs. However, as seen from Fig. 11 the average video MPDU delay still remains about the same because the video terminals can retransmit almost all video MPDUs during the same CFP owing to the extended duration of the CFP. Then, if BER_{bad} is greater than 10^{-4}, almost all CFPs are ended at the CFP maximum duration because of many retransmissions; therefore, the average video MPDU delay begins to increase. We also observe in Fig. 11 that the average video MPDU delay begins to increase around 10^{-5} if

† According to the standard, the time needed to send a maximum-size data MPDU using the RTS/CTS handshaking must be allotted for each CP. In the case of the DSSS physical layer at the 2 Mbps channel rate, it takes about 11 msec to transmit a maximum-size data MPDU. If CFP_{rep}=100 msec and CFP_{max} =0.8CFP_{rep}, the minimum duration of a CP becomes 20 msec. This duration is longer than that needed to send a maximum-size data MPDU.

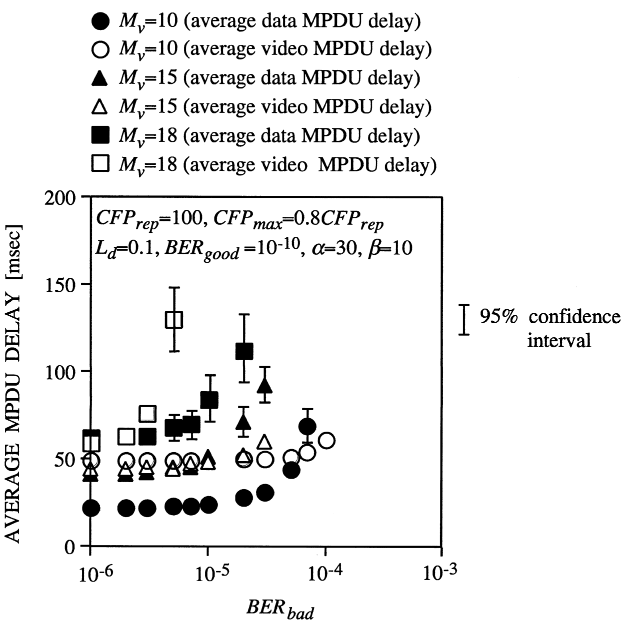

Fig. 12 Average MPDU delay versus BER_{bad} for CFP_{max}=0.8CFP_{rep}.

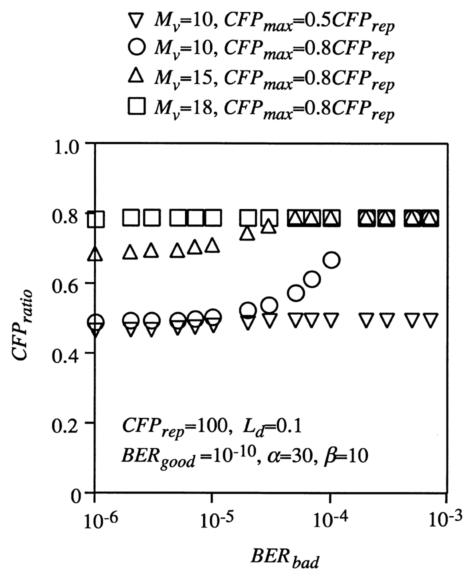

Fig. 13 CFP_{ratio} versus BER_{bad}.

CFP_{max}=0.5CFP_{rep}. Under this condition, the CFP cannot be extended for retransmissions of video MPDUs.

We then examine how the number of video terminals affects the video performance. Figure 12 shows that the average video MPDU delay for M_v=15 begins to increase around BER_{bad}=3*10^{-5}. Notice that this value of BER_{bad} is smaller than that in the case of M_v=10 (i.e., 10^{-4}). Furthermore, when M_v=18, the average video MPDU delay begins to deteriorate even around BER_{bad}=10^{-6}. Therefore, we can say that the average video MPDU delay begins to deteriorate at a larger value of BER_{bad} as the number of the video terminals decreases. This is because channel capacity for retransmissions of video MPDUs increases as the number of video terminals becomes smaller. Figure 13 shows that CFP_{ratio} reaches CFP_{max} at a larger value of BER_{bad} as M_v is smaller. If the system accomodates M_{vmax} terminals (M_{vmax}=18 in this case), the video-MPDU-delay performance deteriorates drastically owing to a small number of allowable retransmissions because CFP_{ratio} is nearly equal to CFP_{max}/CFP_{rep} even if BER=0.

7. Conclusions

This paper has evaluated the performance of the IEEE 802.11 standard MAC protocol by means of simulation. The simulation model included both data transmission with the DCF and H.263 video transmission with the PCF.

First, we evaluated the performance of the protocol for various values of the CFP repetition interval and CFP maximum duration. Numerical results showed that if the CFP repetition interval is set too long, the video-delay performance deteriorates drastically, though the capacity of the CP becomes slightly larger. We also found that as the CFP maximum duration decreases, the number of video terminals that can be accommodated in the system also becomes smaller. Furthermore, we studied how the channel transmission error affects the performance of the protocol. As a result, we observed that as the CFP maximum duration becomes larger and the number of video terminals becomes smaller, the video-MPDU-delay performance does not deteriorate drastically for larger values of bit error rate.

Our future work includes the performance evaluation when using polling schemes different from that studied in this paper and handover schemes for mobile terminals.

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