An Analytical Model of Multi-rate Channel for IEEE 802.11e EDCAF

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Abstract

IEEE 802.11e provides the guaranteed quality of service (QoS) by providing different transmission priorities. IEEE 802.11e improves the media access control layer of IEEE 802.11 to satisfy the different QoS requirements by introducing two channel access functions: the enhanced distributed channel access (EDCA) and HCF controlled channel access (HCCA). Therefore, most devices support different transmission rates in wireless network. Generally a station using a lower transmission rate will occupy communication channel for a longer time and degrade system performance, which causes bandwidth waste and unfairness and cannot provide the guaranteed QoS for the stations with higher transmission rates. This paper proposes an multi-rate discrete Markov chain model to analyze the performance of EDCAF.

1. INTRODUCTION

In recent years, wireless transmission technology is widely applied for the applications of multimedia. Quality of service (QoS) must be considered while priority issues are applied in different kinds of traffics. According to the characteristic of wireless local area network (WLAN), IEEE 802.11e standard is proposed to achieve the guaranteed QoS requirements [1]. In the legacy IEEE 802.11 standard [2], different transmission rates for stations can co-exist in a WLAN infrastructure, while the transmission rate is selected according to the signal to noise ratio (SNR) and bit error rate (BER). In general, both receiver and transmitter need a faster modulation scheme with higher SNR to achieve a higher transmission rate. On the other hand, only a simpler modulation scheme and lower SNR are needed for a lower transmission rate. Several rate selection schemes have been proposed, such as the auto rate fallback (ARF) scheme [3] and the receiver-based auto rate (RBAR) [4] scheme.

Different stations may obtain channels with the same probability in the EDCAF of IEEE 802.11e, if the stations have the same contention parameters regarding different physical rates, where the contention parameters include arbitration interframe space (AIFS), the size of contention window (CW) and persistence factor (PF). However, EDCAF ignores that the station with lower transmission rate occupies a channel longer than the others with higher transmission rates under multiple transmission rates. The waiting interval may seriously affect system performance and QoS in wireless networks [5].

According to the IEEE 802.11 specification, a packet may be sent by using two different rates. A basic transmission rate may be used by the physical layer convergence protocol (PLCP), while the payload of the medium access control (MAC) may dynamically be sent at highest transmission rate depending on SNR. Receiver knows the transmission rate of the MAC payload by verifying the PLCP header; the frame format of the IEEE 802.11b physical layer is shown as Fig. 1. We assume that all frames have the same MAC payload size hence the higher transmission rate yields the shorter transmission time. Fig. 2 shows the timing to transmit frames by different transmission rates at different locations.

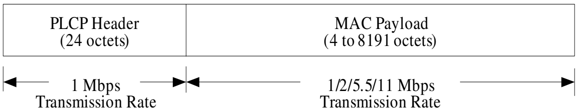

Fig. 1: IEEE 802.11b physical layer frame format

Some researches use discrete Markov chain model [6]-[8] or mean value analysis [9] to analyze the performance of IEEE 802.11 or IEEE 802.11e but only considering one physical rate. This paper proposes a multi-rate discrete Markov chain model to analyze the character of the multi-rate channel in the real wireless infrastructure.

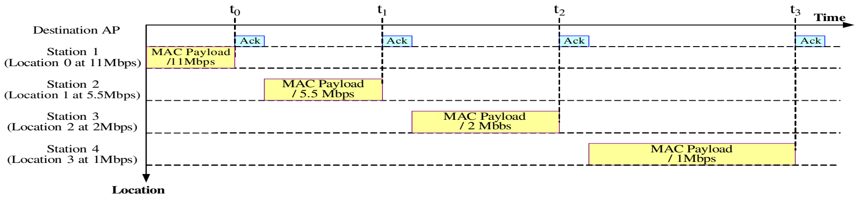

Fig. 2 : The transmission timing by different transmission rates at different locations

2. Multi-rate System Model and Analysis

In this section, the analytical model for multi-rate EDCAF is established and analyzed. The wireless channel is assumed to be ideal without considering the issues of path loss, propagation delay, bit error rate and hidden nodes; each category transmits packets under saturation mode. The analytical model is obtained by extending the discrete Markov chain model of EDCAF [8], called the multi-rate discrete Markov chain model, whose state transition diagram is shown as Fig. 3.

2.1 *Analysis of transition probabilities*

In Fig. 3, each state represents a category with *AC(i)* in a slot time and a state transits at the end of a slot time. Each state contains five parameters (*L, i, j, k, d*), where *L and i* indicate the location and physical rate of a station, the type of access category, respectively; *j* denotes the current backoff stage for the *j*th retry; *k* denotes the current value of backoff counter after taking the value from [$0, W_{L,i,j}-1$]; and *d* denotes the remaining frozen time (AIFSN slots) before the deferred access finished. The transition probabilities of the multi-rate discrete Markov chain model are described as follows:

a. The state (*L, -1, -1, -1, d*) for $1\leq d\leq T_{succ,L,i}$ as shown in the part A of Fig. 3 represents the successful transmission period, where $T_{succ,L,i}$ is the successful transmission times in a slot time unit given the most approximate integer value.

b. The state *(L ,i , -1, -1, d)* for $1\leq d\leq A_{L,i}$ as shown in the part B of Fig. 3 represents the deferring period of AIFS[AC*(i)*] before transmitting a new scheduled packet, where $A_{L,i}$ is the frozen time of AIFS[*AC(i)*] in a slot time unit.

c. The state *(L, i, j, k, 0)* for $0\leq j\leq m$ *and* $0\leq k\leq (W_{L,i,j}-1)$ as shown in the part C of Fig. 3 represents the backoff period. A category with *AC(i)* will take a random value in [$0,W_{L,i,j}$] for CW after each collision detection procedure, then enters the next backoff stage.

d. The state *(L, i, j, 0, 0)* for $0\leq j\leq m$ as shown in the part D of Fig. 3 represents the states of successful transmissions.

e. The state *(L, i, j, k, d)* for $0\leq j\leq m$, $1\leq k\leq (W_{L,i,j}-1)$ and $0\leq d\leq A_{L,i}$ as shown in the part E of Fig. 3 represents the state that a category with *AC(i)* enters AIFS[*AC(i)*] deferring period if the channel is sensed to be busy during the backoff period; the category with *AC(i)* will reset AIFS[*AC(i)*] counter to the original value and defer again.

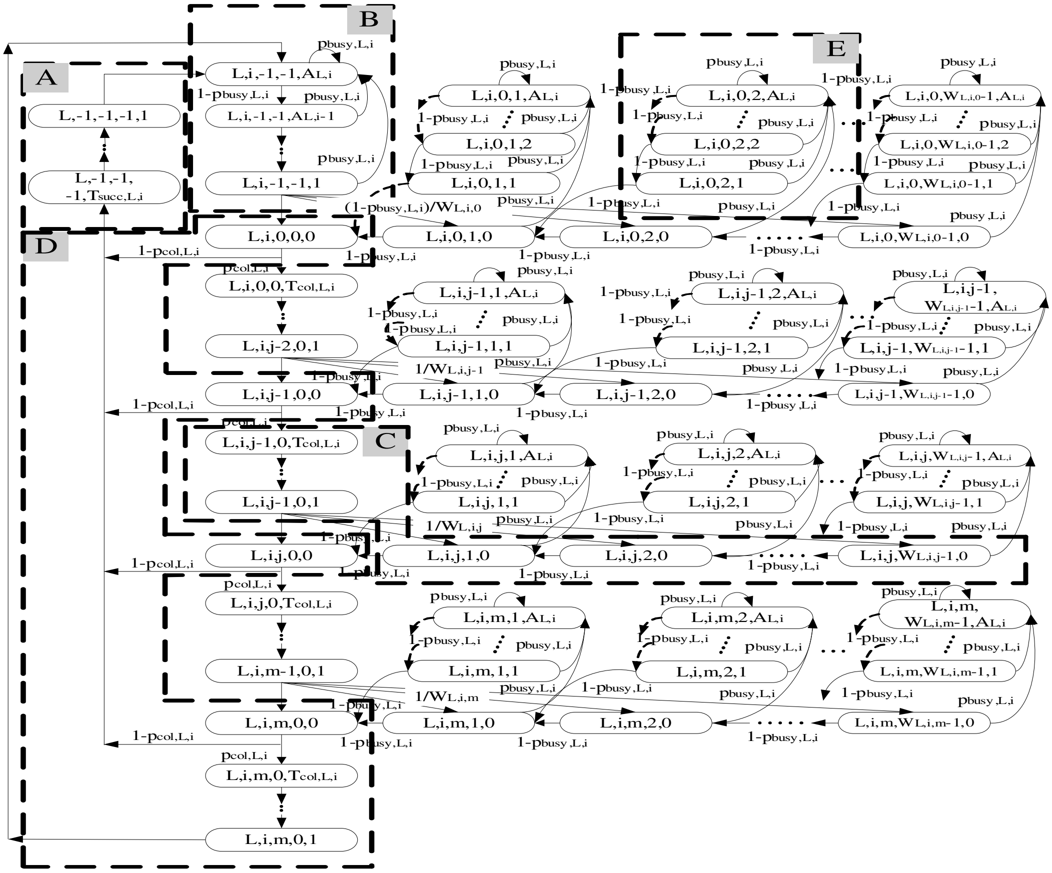

Fig. 3 : The state transition diagram of multi-rate discrete Markov chain model

2.2 *Analysis of multi-rate discrete Markov chain model*

In this section, the multi-rate discrete Markov chain model is analyzed to obtain the stationary probabilities. Let $b_{L,i,j,k,d}$ be the stationary probability at the stochastic state (L,i,j,k,d), which is the probability of each AIFS value d at AIFS deferring period as Eq. (1). $b_{L,i,j,k,0}$ is denoted as the probability of each backoff value k at backoff stage j as Eq. (2). $b_{L,i,j,0,0}$ is denoted as the probability of attempt transmission at each backoff stage j as Eq. (3), where the probability of the initial state, $b_{L,i,0,0,0}$, can be obtained by calculating the transition probabilities of a category with $AC(i)$ at location L. Eqs. (4) and (5) show for the probabilities of all successful transmissions and collision detections, respectively. $b_{L,i,-1,-1,d}$ is denoted as the probability that the first AIFS defers access when a new packet is scheduled for transmission as Eq. (6). In summary from Eq. (1) to Eq. (6), $b_{L,i,j,k,d}$ can be expressed in terms of $b_{L,i,0,0,0}$, $p_{col,L,i}$ and $p_{busy,L,i}$. Because the sum of all stationary probabilities of Markov chain is equal to 1, $b_{L,i,0,0,0}$ can be finally determined by Eq. (7).

$$b_{L,i,j,k,d} = \frac{p_{busy,L,i}}{\left(1-p_{busy,L,i}\right)^{d}} \cdot b_{L,i,j,k,0} \quad 0\le j\le m,\ 1\le k\le W_{L,i,j}-1,\ 1\le d\le A_{L,i} \tag{1}$$

$$b_{L,i,j,k,0} = \frac{W_{L,i,j}-k}{W_{L,i,j}} \cdot b_{L,i,j,0,0} \quad 0\le j\le m, 1\le k\le W_{L,i,j}-1 \tag{2}$$

$$b_{L,i,j,0,0} = p_{col,L,i}^{j} \cdot b_{L,i,0,0,0} \quad 0\le j\le m \tag{3}$$

$$b_{L,-1,-1,-1,d} = \left(1-p_{col,L,i}\right)\cdot \sum_{j=0}^{m} b_{L,i,j,0,0} = b_{L,i,0,0,0}\cdot\left(1-p_{col,L,i}^{m+1}\right) \quad 1\le d\le T_{succ,L,i} \tag{4}$$

$$b_{L,i,j,0,d} = p_{col,L,i}\cdot b_{L,i,j,0,0} = p_{col,L,i}^{j+1}\cdot b_{L,i,0,0,0} \quad 0\le j\le m,\ 1\le d\le T_{col,L,i} \tag{5}$$

$$b_{L,i,-1,-1,d} = \frac{1}{\left(1-p_{busy,L,i}\right)^{d}}\cdot b_{L,i,0,0,0} \quad 1\le d\le A_{L,i} \tag{6}$$

$$b_{L,i,0,0,0} = \left[\begin{array}{l} T_{succ,L,i}\cdot\left(1-p_{col,L,i}^{m+1}\right)+\dfrac{1-\left(1-p_{busy,L,i}\right)^{A_{L,i}}}{p_{busy,L,i}\cdot\left(1-p_{busy,L,i}\right)^{A_{L,i}}} \\ +\left(1+p_{col,L,i}\cdot T_{col,L,i}\right)\cdot\dfrac{1-p_{col,L,i}^{m+1}}{1-p_{col,L,i}} \\ +\dfrac{1}{2}\cdot\dfrac{1}{\left(1-p_{busy,L,i}\right)^{A_{L,i}}}\cdot\sum_{j=0}^{m}p_{col,L,i}^{j}\cdot\left(W_{L,i,j}-1\right) \end{array}\right]^{-1} \tag{7}$$

$\tau_{L,i}$ is denoted as the probability that a category with $AC(i)$ attempts to transmit a packet at location L when the backoff counter reaches zero, which can be obtained by summing $b_{L,i,j,0,0}$ *for* $j=0,1,\ldots m$ as shown in Eq. (8). Let τ_L be the probability that a station accesses channel at location L, which is the sum of transmission probabilities of all categories $AC(i)$ in one station as shown in Eq. (9).

$$\tau_{L,i} = \sum_{j=0}^{m} b_{L,i,j,0,0} = \sum_{j=0}^{m} b_{col,L,i}^{j}\cdot b_{L,i,0,0,0} = \frac{\left(1-p_{col,L,i}^{m+1}\right)}{\left(1-p_{col,L,i}\right)}\cdot b_{L,i,0,0,0} \tag{8}$$

$$\tau_L = 1-\sum_{i=0}^{M-1}\left(1-\tau_{L,i}\right) \tag{9}$$

$v_{L,i}$ is denoted as the probability that a channel is occupied by the given category with $AC(i)$ at location L as shown in Eq. (10), because a channel may be occupied for successful transmission or collision detection. Let v_L be the probability that a station occupies the channel at location L, which can be obtained by summing the probabilities that all categories with $AC(i)$ occupy the channel in one station as shown in Eq. (11).

$$v_{L,i} = \sum_{d=1}^{T_{succ,L,i}} b_{L,-1,-1,-1,d} + \sum_{j=0}^{m}\sum_{d=1}^{T_{col,L,i}} b_{L,i,j,0,d} = b_{L,i,0,0,0}\cdot\left(1-p_{col,L,i}^{m+1}\right)\cdot\left(T_{succ,L,i}+p_{col,L,i}\cdot T_{col,L,i}\cdot\frac{1}{1-p_{col,L,i}}\right) \tag{10}$$

$$v_L = 1-\sum_{i=0}^{M-1}\left(1-v_{L,i}\right) \tag{11}$$

In the IEEE 802.11e standard, there exists two levels of channel access contentions. The first contention is so called internal contention which occurs among the traffics of different priorities inside the same station. The winner of the first contention will enter the second contention called external contention which occurs among the traffics at different stations by CSMA/CA scheme. Finally, the highest priority traffic will be permitted to transmit packets.

For the priorities that $(L',i)>(L,i)$, the probabilities of $v_{L',i}$ and $\tau_{L',i}$ have the higher priority than $v_{L,i}$ and $\tau_{L,i}$, respectively, at the internal contention. The probability of $p_{col,L,i}$ can be obtained by considering a transmitted frame encountering a collision in a time slot, where n_L and n_h are the number of stations at location L and h, respectively, as shown in Eq.(12). Similarly, $p_{busy,L,i}$ can be obtained and shown as Eq. (13). Let p_{busy} be the probability of the channel busy, shown as Eq. (14). Consequently, $p_{col,L,i}$, $p_{busy,L,i}$, and $b_{L,i,0,0,0}$ can be solved from Eqs. (7)-(14) by numerical methods.

$$p_{col,L,i} = 1-\prod_{(L',i)>(L,i)}\left(1-\tau_{L',i}\right)\cdot\left(1-\tau_L\right)^{n_L-1}\cdot\prod_{\substack{h=0\\h\neq L}}^{K-1}\left(1-\tau_h\right)^{n_h} \tag{12}$$

$$p_{busy,L,i} = 1-\prod_{(L',i)>(L,i)}\left(1-v_{L',i}\right)\cdot\left(1-v_L\right)^{n_L-1}\cdot\prod_{\substack{h=0\\h\neq L}}^{K-1}\left(1-v_h\right)^{n_h} \tag{13}$$

$$p_{busy} = 1-\prod_{h=0}^{K-1}\left(1-v_h\right)^{n_h} \tag{14}$$

2.3 *Throughput analysis*

Let $p_{tr,L,i}$ and $p_{trcol,L,i}$ be the probabilities of successful transmission and collision detection of the category *AC(i)* at location *L*, which are given by Eqs. (15) and (16), respectively. A category with *AC(i)* can be successfully transmitted only if no internal higher priority categories with *AC(i)* and no other external station is occupying the channel. The probability of successful transmission $p_{s,L,i}$ is given by Eq. (17).

$$p_{tr,L,i} = \sum_{d=1}^{T_{succ,L,i}} b_{L,-1,-1,-1,d} = b_{L,i,0,0,0} \cdot T_{succ,L,i} \cdot \left(1 - p_{col,L,i}^{m+1}\right) \quad (15)$$

$$p_{trcol,L,i} = \sum_{j=0}^{m} \sum_{d=1}^{T_{col,L,i}} b_{L,i,j,0,d} = b_{L,i,0,0,0} \cdot p_{col,L,i} \cdot T_{col,L,i} \cdot \frac{1-p_{col,L,i}^{m+1}}{1-p_{col,L,i}} \quad (16)$$

$$p_{s,L,i} = C(n_L,1) \cdot p_{tr,L,i} \cdot \prod_{(L',i)>(L,i)} \left(1-v_{L',i}\right) \cdot \left(1-v_L\right)^{n_L-1} \cdot \prod_{\substack{h=0 \\ h\neq L}}^{K-1} \left(1-v_h\right)^{n_h}$$

$$= n_L \cdot p_{tr,L,i} \cdot \prod_{(L',i)>(L,i)} \left(1-v_{L',i}\right) \cdot \left(1-v_L\right)^{n_L-1} \cdot \prod_{\substack{h=0 \\ h\neq L}}^{K-1} \left(1-v_h\right)^{n_h} \quad (17)$$

Based on the above-mentioned assumption that all packets in a category with *AC(i)* have the same size, the collision duration is dominated by the lowest rate station, because the collision is caused by multi-rate stations at all locations. Let $p_{col,L,i}^{sameL}$ and $p_{col,L,i}^{diffL}$ be the collision probabilities caused by the stations at the same and different locations as shown in Eqs. (18) and (19), respectively. Let $p_{col,L,i}^{L}$ be the collision probability for the category with *AC(i)* at locations *L*, which is obtained by summing $p_{col,L,i}^{sameL}$ and $p_{col,L,i}^{diffL}$ shown as Eq. (20). The probability that the channel is idle for a slot time, p_{Idle}, is shown as Eq. (21). Finally, the normalized saturation throughput of the category with *AC(i)* at location *L* and total system throughput, $S_{L,i}$ and S_{Total}, can be obtained by Eqs. (22) and (23), respectively.

$$p_{col,L,i}^{sameL} = p_{trcol,L,i} \prod_{(L',i)>(L,i)} \left(1-v_{L',i}\right) \cdot \left[1-\left(1-v_L\right)^{n_L} - n_L \cdot \left(1-v_L\right)^{n_L-1} \cdot v_L\right] \prod_{\substack{h=0 \\ h\neq L}}^{K-1} \left(1-v_h\right)^{n_h}$$

$$0 \le L \le (K-1);\ 2 \le n_L \quad (18)$$

$$p_{col,L,i}^{diffL} = p_{trcol,L,i} \prod_{(L',i)>(L,i)} \left(1-v_{L',i}\right) \left[1-\left(1-v_L\right)^{n_L}\right] \left[1-\prod_{h=0}^{L-1}\left(1-v_h\right)^{n_h}\right] \prod_{h=L+1}^{K-1} \left(1-v_h\right)^{n_h}$$

$$1 \le L \le (K-1);\ 1 \le n_L \quad (19)$$

$$p_{col,L,i}^{L} = p_{col,L,i}^{sameL} + p_{col,L,i}^{diffL} \quad ; \quad 0 \le L \le (K-1) \quad (20)$$

$$p_{Idle} = 1 - p_{busy} \quad (21)$$

$$S_{L,i} = \frac{p_{s,L,i} \cdot T_{Payload,L,i}}{p_{Idle} \cdot T_{Slot} + \sum_{h=0}^{K-1}\left[\sum_{i=0}^{M-1}\left(p_{s,h,i} \cdot T_{succ,h,i}\right)\right] + \sum_{h=0}^{K-1}\left[\sum_{i=0}^{M-1}\left(p_{col,h,i}^{h} \cdot T_{col,h,i}\right)\right]} \quad (22)$$

$$S_{Total} = \sum_{L=0}^{K-1}\left(\sum_{i=0}^{M-1} S_{L,i}\right) \cdot rate_L \quad (23)$$

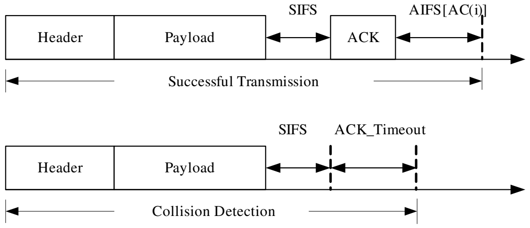

Fig. 4 : $T_{succ,L,i}$ and $T_{col,L,i}$ for the basic access timing of IEEE 802.11b

Note that T_{Slot} is the average time of empty slot; $rate_L$ is the physical layer rate of the station at location *L*; $T_{Payload,L,i}$ is the average packet payload size for a category with *AC(i)* at location *L* as shown in Eq. (24); $T_{succ,L,i}$, and $T_{col,L,i}$ are the average time of successful transmission and collision detection for a category with *AC(i)* at location *L*, respectively. According to the basic access timing of IEEE 802.11b as shown in Fig. 4, $T_{succ,L,i}$ and $T_{col,L,i}$ can be obtained by Eqs. (25) and (26), respectively, where T_{ACK} and $T_{H,L,i}$ are the time to transmit an ACK frame and the header at location *L* by assuming the transmission rate of 1 Mbps in IEEE 802.11b, as shown in Eqs. (27) and (28). Finally, the time of *AIFS*[*AC(i)*] is shown as Eq. (29).

$T_{Payload,L,i}$=*Average Payload(Bytes)*8/rate*$_L$*(Mbps)* (24)

$T_{succ,L,i}=T_{H,L,i}+T_{Payload,L,i}+SIFS+T_{ACK}+AIFS[AC(i)]$ (25)

$T_{col,L,i}=T_{H,L,i}+T_{Payload,L,i}+SIFS+ACK\_Timeout$ (26)

T_{ACK} = *PLCP preamble(144bits) + PLCP Header(48bits) + ACK Header(112bits)*
*=192(bits)/1Mbps+14(Bytes)*8/1Mbps* (27)

$T_{H,L,i}$ = *PLCP preamble(144bits) +PLCP Header(48bits) +MAC Header(272bits)*
*=192(bits)/1Mbps+34(Bytes)*8/rate*$_L$*(Mbps)* (28)

AIFS[*AC(i)*]=*AIFSN*[*AC(i)*]* T_{Slot} + SIFS (29)

3. EVALUATING THE THEORETICAL MODEL

To validate the multi-rate Markov chain model, we compare the results obtained by simulation and numerical method to investigate how the performance is affected by the different physical rates and contention parameters. We assume that all stations operate in the basic access mode under the IEEE 802.11e protocol and there are two types of stations: fixed and mobile. Each station has one active AC with the same packet size and operates at the saturation mode. The fixed station always connects to AP at the range of 11Mbps; the mobile station (MS) is far away from AP and selects a suitable rate (11/5.5/2/1 Mbps) according to the received signal strength. We evaluate throughputs for two cases depending on different contention parameters under different physical rates, where the related parameters are listed in Table 1. Figs. 5 and 6 compare the throughputs obtained by simulation and numerical under different physical rates in case 1 and case

2. It is obvious that these results obtained by simulation and numerical are very close under the acceptable errors.

TABLE 1 : PARAMETERS USED IN THE ANALYSIS

Parameters	Case 1		Case 2	
	Fixed STA	MS STA	Fixed STA	MS STA
CW_{min}	3		3	
CW_{max}	15		15	15/31/63/127
AIFSN	2		2	2/2/3/3
PF	2		2	
Packet Size	8184 bits		8184 bits	
Physical Rate	11 Mbps	11/5.5/2/1 Mbps	11 Mbps	11/5.5/2/1 Mbps

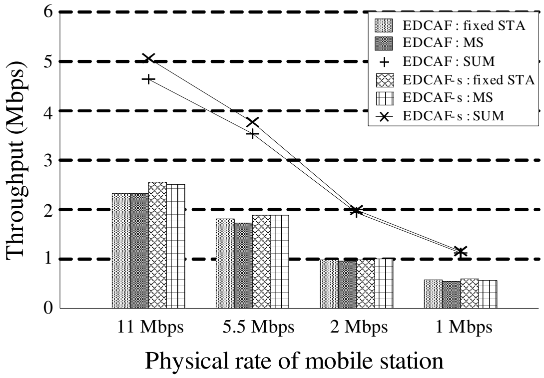

Fig. 5 : The throughput comparison for case 1

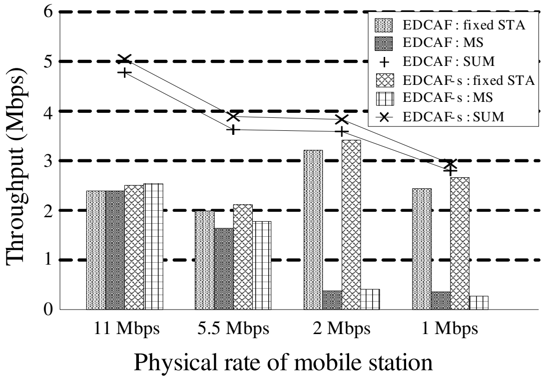

Fig. 6 : The throughput comparison for case 2

According to the previous results, we simply made a summary as follows. In case 1 with the same contention parameters, a lower rate station needs a longer transmission time to transmit the same size packet, which increases the channel occupied probabilities. In addition, it reduces the probability of transmission attempt and increases the probabilities of occupying channel and backoff stage in higher rate station. In case 2, the different values of AIFSN, CW_{min}, and CW_{max} will impact the frozen probability, the idle probability of backoff stage, the transmission probability, the collision probability, and even the normalized throughput. Therefore the lower rate station will cause the unfairness of bandwidth usage and dominate the system throughput. In order to guarantee the QoS requirements, the multi-rate stations must be dynamically allocated different contention parameters and priorities.

4. CONCLUSION

In this paper we introduced a multi-rate Markov chain model for wireless channel and studied the throughput for IEEE 802.11e EDCAF. This model and results are validated via numerical method and simulation. The effect of multi-rate Station on the QoS has also been investigated. This analysis provides a helpful understanding for future EDCAF QoS research.

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