Transactions Letters

On Throughput Performance of Channel Inequality in IEEE 802.11 WLANs

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***Abstract*—In this paper we investigate the throughput performance of IEEE 802.11 Distributed Coordination Function (DCF) in the presence of physical-layer (PHY) inequality, i.e. varied channel conditions and/or unequal data rates determined by the Link Adaptation (LA) scheme. We present a theoretical model for DCF protocol with the LA scheme of AutoRate Fallback (ARF). The analysis results show that the system throughput of DCF-based WLANs is determined by the lowest data rate used with stations; throughput sharing among stations depends on the variation of link qualities rather than the difference of data rates. The simulation results validate the accuracy of our analytical model.**

***Index Terms*—IEEE 802.11 WLAN, DCF, performance analysis.**

I. Introduction

IEEE 802.11 Wireless Local Area Networks (WLANs) become increasingly popular in the recent years with the wide deployment of infrastructure and the prevalence of mobile/handheld devices. The IEEE 802.11 standards [1] on the physical layer (PHY) support multiple transmission rates with different Modulation and Coding Schemes (MCS). According to the experienced channel condition, one data rate will be selected from multiple rates available to achieve both a reliable link quality and the highest throughput as possible. In such a varying-channel and multi-rate WLAN environment, the throughput performance essentially depends on not only the Medium Access Control (MAC) protocol, but also the PHY inequality among 802.11 stations, i.e. different channel conditions and/or unequal data rates determined by the Link Adaptation (LA) scheme. The authors in [2] [3] conducted experiments and simulations to study throughput of the 802.11 MAC protocol, Distributed Coordination Function (DCF) in the presence of PHY inequality. However, they did not offer complete theoretical analyses which can be the most important base for understanding the impact of PHY inequality on the performance of DCF. In [4] [5] the authors presented theoretical analyses for DCF protocol in error-prone fading channels. Nevertheless, they consider only identical non-perfect channel conditions and equal data rates for all stations, which may be insufficient for thoroughly investigate the performance of DCF with PHY inequality.

In this paper we study the throughput performance of DCF protocol when 802.11 stations can be with unequal data rates and/or in different channel conditions. The analysis should be more practical to realistic WLAN environments since the sender stations can adopt unequal data rates with a LA mechanism, and also can experience different link qualities in transmission at most of the time due to limited MCSs available. We develop an analytical model for DCF protocol with the LA scheme of AutoRate Fallback (ARF) [6] which has been adopted by most commercial 802.11 WLAN products. The numerical results show that: the throughput performance of DCF-based WLANs is greatly affected by both the experienced channel conditions and used data rates of 802.11 stations, while system throughput is determined by the lowest used data rate, and individual-station throughput depends on the variation of link qualities among stations rather than the difference of data rates. We validate our analytical model via simulations and the results demonstrate its accuracy.

II. Analytical Model for 802.11 DCF with PHY Inequality

In this section we present the theoretical model for DCF protocol with the LA scheme of ARF. Our DCF model is developed based on previous work [7], while we further take into account the finite retransmission limit, the probability that the backoff counter is frozen when the channel is sensed busy, error-prone channels and multiple data rates.

Consider K IEEE 802.11 stations in error-prone channel conditions with multiple data rates. The non-perfect 802.11 channels is modeled with the Gilbert-Elliott two-state discrete Markov chain which is commonly adopted for modeling fading channels such as the Rayleigh channel [8]. From the model, we can obtain the level of Received Signal Strength (RSS) and Signal to Noise Ratio (SNR) associated with each transmitted packet in a given time period. Assume each station

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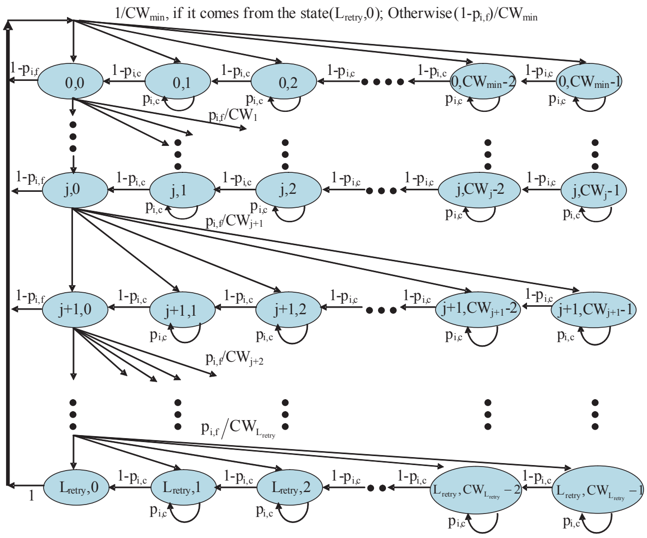

Fig. 1. The state transition diagram of station i.

always has a packet to send (i.e. operating in a saturated traffic condition). To station i ($i = 0 \sim K-1$), let $p_{i,c}$ denote the probability of a transmitting packet collided with other ones. That is:

$$p_{i,c} = 1 - \prod_{h=0,h\neq i}^{K-1} (1-\tau_h) \tag{1}$$

where τ_h is the probability for station h ($h \neq i$) transmitting a packet in a given slotted time. It is noted that even in the presence of packet collisions, the packet with the strongest RSS has an opportunity to be correctly decoded at the receiver. This is referred as the capture effect [9]. Here we use a simplified capture model: when multiple packets collide at the receiver, only the packet can be successfully received if its RSS is larger than anyone of others by at least a threshold. Thus to station i the probability of transmission error due to packet collisions with the capture effect, $p_{i,cap}$, can be expressed as:

$$p_{i,cap} = 1 - \prod_{h=0,h\neq i}^{K-1} (1-\tau_h \cdot cap_{i,h}) \tag{2}$$

where $cap_{i,h}$ represents the capture effect on station i associated with station h:

$$cap_{i,h} = \begin{cases} 0, \text{if} 10\log(RSS_i/RSS_h) \geq z_0 \\ 1, else \end{cases} \tag{3}$$

where RSS_x is RSS associated with station x; z_0 is the relative RSS threshold with a typical value of 10 dB adopted in ns2 simulator [10].

To station i, let $p_{i,e}$ denote the probability of a packet transmission corrupted in non-perfect channels due to fading or noise. $p_{i,e}$ basically depends on the frame size, the used MCS, and SNR at the receiver site. Consider that the error can occur in both the transmissions of data packets and Acknowledgement (ACK) frames and assume error-free transmissions of Request-To-Send / Clear-To-Send (RTS/CTS) packets for the four-way handshaking scheme. Assume that the channels between the sender and the receiver are symmetric (i.e. SNR of data packet observed at the receiver is very similar to that of ACK packet received at the sender). Assume that SNR is unchanged inside the duration of a packet transmission and consider uncoded modulations like what are adopted from 802.11b standards. Thus the transmission-error probability, $p_{i,e}$ can be derived as shown in (4), where PHY_i is the used PHY mode and Γ_i is the experienced SNR of station i; FS_i is the frame size in bytes; PHY_{basic} is the PHY mode for ACK frame; $ACKS$ is the ACK frame size in bytes; $BER(PHY_i, \Gamma_i)$ is the BER of mode PHY_i with SNR Γ_i, which can be provided empirically with experiments or theoretically with analyses.

As a result, a failure of transmission can be caused by the packet collision with other stations, and/or packet corruption in error-prone channels. Since the two events are independent, the probability of transmission failure for station i, pi,f can be expressed as:

$$p_{i,f} = p_{i,cap} + (1 - p_{i,cap}) \cdot p_{i,e} \tag{5}$$

According to 802.11 standards, a station needs to wait for a random backoff time before the next transmission to avoid a collision with other stations. The random backoff timer is uniformly chosen in the interval (0, CW-1), where CW is the contention window size. After each retransmission due to collision or corruption, CW will be doubled until the number of retries comes to a certain limit, L_{retry}. Let CW_{min} denote the initial CW, and CW_j denote the CW in the j^{th} backoff stage. Once CW reaches a maximum value CW_{max}, it will remain at the value until it is reset. Therefore, the relationships among CW_j, CW_{min}, CW_{max}, and L_{retry} can be as shown in (6).

For station i, let $s(i,t)$ and $c(i,t)$ be the stochastic process representing the backoff stage and backoff time counter at time t respectively. The two-dimensional process $s(i,t), c(i,t)$ can be modeled with the discrete-time Markov chain shown in Fig. 1. We adopt the following notation:

$$\begin{aligned} &P_i\left\{j_1, l_1 | j_0, l_0\right\} \\ &= \Pr\left\{s(i,t+1) = j_1, c(i,t+1) = l_1 | s(i,t) = j_0, c(i,t) = l_0\right\}. \end{aligned}$$

Thus from the two-dimensional Markov chain we can obtain the following equations shown in (7). The first equation in (7) represents the fact that the backoff counter is decremented when the channel is sensed idle with the probability of (1-$p_{i,c}$) or frozen otherwise. It is noticed that $p_{i,c}$, the collision probability defined in Equation (1), can also represent the counter-frozen probability here since both the counter-frozen and packet-collided events are caused by one more other stations transmitting packets in a given slotted time. The second equation accounts for that a successful packet transmission with the probability of (1- $p_{i,f}$) will returns to backoff stage 0 and the counter is uniformly chosen in the interval (0, CW_{min}-1). The third equation considers the case of unsuccessful packet transmission that a retransmission due to collision or corruption will enter into the next backoff stage. Finally the forth equation accounts for that if the number of retries reaches the maximum value L_{retry}, the backoff stage will be reset to 0 no matter the consequent transmission is successful or failed.

$$p_{i,e} = 1 - (1 - BER(PHY_i, \Gamma_i))^{FS_i*8} * (1 - BER(PHY_{basic}, \Gamma_i))^{ACKS*8} \tag{4}$$

$$CW_j = \begin{cases} 2^j CW_{\min}, \ for\ j = 0, 1, ..., m-1, \text{if} L_{retry} > m \\ 2^m CW_{\min} = CW_{\max}, \ for\ j = m, ..., L_{retry}, \text{if} L_{retry} > m \\ 2^j CW_{\min}, \ for\ j = 0, 1, ..., L_{retry}, \text{if} L_{retry} \le m \end{cases}$$
$$\text{where } m = \log_2(CW_{\max}/CW_{\min}) \tag{6}$$

$$\begin{cases} P_i \{j, l | j, l+1\} = 1 - p_{i,c}, l \in (0, CW_j - 2), j \in (0, L_{retry}) \\ P_i \{0, l | j, 0\} = (1 - p_{i,f})/CW_{\min}, l \in (0, CW_{\min} - 1), j \in (0, L_{retry} - 1) \\ P_i \{j, l | j-1, 0\} = p_{i,f}/CW_j, l \in (0, CW_j - 1), j \in (1, L_{retry}) \\ P_i \{0, l | L_{retry}, 0\} = 1/CW_{\min}, l \in (0, CW_{\min} - 1) \end{cases} \tag{7}$$

Let $b_{i,j,l} = \lim_{t\to\infty} \Pr\{s(i,t) = j,\ c(i,t) = l\}, j \in (0, L_{retry}), l \in (0, CW_j - 1)$ be the stationary state probabilities of the Markov chain. From the chain regularity and by means of a simple computation, $b_{i,0,0}$ is given by Equation (8):

$$b_{i,0,0} = \begin{cases} \frac{2(1-2p_{i,f})(1-p_{i,f})(1-p_{i,c})}{A+B}, L_{retry} \le \text{m} \\ \frac{2(1-2\cdot p_{i,f})(1-p_{i,f})(1-p_{i,c})}{C-D+E+F}, L_{retry} > \text{m} \end{cases},$$

where

$$\begin{aligned} A &= CW_{\min}(1 - (2p_{i,f})^{L_{retry}+1})(1 - p_{i,f}); \\ B &= (1 - p_{i,f}^{L_{retry}+1})(1 - 2p_{i,c} - 2p_{i,f} + 4p_{i,c}p_{i,f}); \\ C &= CW_{\min}(1 - (2p_{i,f})^{m+1})(1 - p_{i,f}); \\ D &= (1 - 2p_{i,f})(1 - p_{i,f}^{m+1}); \\ E &= (1 - 2p_{i,f})(2^m CW_{\min} - 1)(1 - p_{i,f}^{L_{retry}-m}); \\ F &= 2(1 - 2p_{i,f})(1 - p_{i,f}^{L_{retry}+1})(1 - p_{i,c}). \end{aligned} \tag{8}$$

Since a given station transmits when its backoff timer reaches 0, the probability that station i transmits a packet in a randomly chosen slotted time, τ_i, can be derived as:

$$\tau_i = \sum_{j=0}^{L_{retry}} b_{i,j,0} = \sum_{j=0}^{L_{retry}} p_{i,f}^j \cdot b_{i,0,0} = b_{i,0,0} \cdot \frac{1 - p_{i,f}^{L_{retry}+1}}{1 - p_{i,f}}. \tag{9}$$

From Equation (9) we can see that τ_i depends on the probability of transmission failure $p_{i,f}$, which is determined with the corruption probability $p_{i,e}$ and the error probability due to packet collision with the capture effect, $p_{i,cap}$. From Equation (1) to (9), we can solve unknown parameters τ_i and $p_{i,f}$ numerically with a given set of RSSs (RSS_1, ...RSS_K), SNRs (Γ_1, ...Γ_K), PHY modes (PHY_1, ...PHY_K), and frame sizes (FS_1, ...FS_K) associated with the K stations.

Let P_{tr} be the probability that at least one station transmits in the considered slotted time:

$$P_{tr} = 1 - \prod_{h=0}^{K-1} (1 - \tau_h) \tag{10}$$

Let $P_{i,single}$ denote the probability that only station i transmits and the remaining K-1 stations are idle on condition that at least one station transmits. Thus it is expressed as:

$$P_{i,single} = \tau_i \cdot \prod_{h=0,h\ne i}^{K-1} (1 - \tau_h)/(1 - \prod_{h=0}^{K-1} (1 - \tau_h)) \tag{11}$$

Considering a given slot, the channel idle probability is (1-P_{tr}). The channel busy probability is P_{tr}, which consists of the following parts: the probability of a successful transmission of station i, $P_{tr} \cdot P_{i,single} \cdot (1 - p_{i,e})$; the probability of a successful transmission of station h ($h \ne i$), $P_{tr} \cdot \sum_{h=0,h\ne i}^{K-1} P_{h,single} \cdot (1 - p_{h,e})$; the probability of a failed transmission due to non-perfect channel conditions, $P_{tr} \cdot \sum_{x=0}^{K-1} P_{x,single} \cdot p_{x,e}$; and the probability of a failed transmission due to collision, $P_{tr} \cdot (1 - \sum_{x=0}^{K-1} P_{x,single})$. Hence the saturated throughput of station i, thr_i can be expressed as Equation (12):

$$\begin{aligned} thr_i &= \frac{P_{tr} \cdot P_{i,\sin gle} \cdot (1 - p_{i,e}) \cdot 8(FS_i - H)}{W + X + Y + Z}, \\ where & \\ W &= (1 - P_{tr}) \cdot T_{slot}; \\ X &= P_{tr} \cdot \sum_{x=0}^{K-1} (P_{x,\sin gle} \cdot (1 - p_{x,e}) \cdot Ts_x); \\ Y &= P_{tr} \cdot \sum_{x=0}^{K-1} (P_{x,\sin gle} \cdot p_{x,e} \cdot Te_x); \\ Z &= P_{tr} \cdot (1 - \sum_{x=0}^{K-1} P_{x,\sin gle}) \cdot Tc. \end{aligned} \tag{12}$$

H is the total length of PHY and MAC headers in bytes; T_{slot} is the slotted time; Ts_x, Te_x are the time of station x ($x = 0 \sim K-1$) processing a successful transmission and experiencing a failed transmission due to a corruption respectively; Tc is the period of a collision; The values of Ts_x, Te_x and Tc depend on the channel access mechanism and the used data rate r_x of station x. For the basic Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) scheme and RTS/CTS scheme respectively, they can be expressed as:

$$Basic: \begin{cases} Ts_x^{bas} = DIFS + T_{header} + (FS_x - H) \cdot 8/r_x + \gamma \\ \quad +SIFS + ACK + \gamma \\ Tc^{bas} = DIFS + T_{header} + ((FS_z - H) \cdot 8/r_z)^* + \gamma \end{cases}$$

$$RTS/CTS: \begin{cases} Ts_x^{RTS} = DIFS + RTS + \gamma + SIFS + CTS + \gamma \\ \quad +SIFS + T_{header} + (FS_x - H) \cdot 8/r_x \\ \quad +\gamma + SIFS + ACK + \gamma \\ Tc^{RTS} = DIFS + RTS + \gamma + SIFS + CTS + \gamma \end{cases}$$

Te_x is equal to Ts_x in both of the basic and RTS/CTS scheme. $DIFS$, $SIFS$, T_{header}, ACK and γ denote DIFS time, SIFS time, the time to transmit the header, the time to transmit an ACK and the time of propagation delay, respectively;$((FS_z - H) \cdot 8/r_z)^*$ is the longest transmission time associated with station z in a collision.

The throughput thr_i in (12) is derived with given channel conditions and data rates. The expected value of thr_i given SNR γ with LA scheme x, $E_x(thr_i|\Gamma_i = \gamma)$, can be formulated as (13):

$$E_x(thr_i|\Gamma_i = \gamma) = \sum_{y=1}^{L} (thr_i|PHY_i = y,\Gamma_i = \gamma)P_x(PHY_i = y|\Gamma_i = \gamma) \tag{13}$$

where L is the number of PHY modes available; $thr_i|PHY_i = y,\Gamma_i = \gamma$ is the throughput of station i using PHY mode y with SNR γ in (12), which is determined by DCF protocol. $P_x(PHY_i = y|\Gamma_i = \gamma)$ is the conditional probability of selecting mode y given SNR γ, which is determined by the LA scheme x. By linearly combining the two values as shown in (13), we can thus obtain the expected value of thr_i given SNR γ with LA scheme x, $E_x(thr_i|\Gamma_i = \gamma)$. Given a SNR distribution with the probability density function $p_\gamma(\gamma)$, the average throughput of station i with LA scheme x, $E_x(thr_i)$ can be derived as:

$$E_x(thr_i) = \int_\gamma E_x(thr_i|\Gamma_i = \gamma)p_\gamma(\gamma)d\gamma = \int_\gamma \sum_{y=1}^{L} (thr_i|PHY_i = y,\Gamma_i = \gamma)P_x(PHY_i = y|\Gamma_i = \gamma)p_\gamma(\gamma)d\gamma. \tag{14}$$

Finally the system throughput, S can be obtained by summing up $E_x(thr_i)$ of the K stations:

$$\text{System throughput } S = \sum_{i=1}^{K} E(thr_i). \tag{15}$$

Now we analyze the LA scheme of AutoRate Fallback (ARF) [6] and consider IEEE 802.11b PHY for example. IEEE 802.11b PHY employs 4 uncoded modulations to provide the rate of 1, 2, 5.5, and 11 Mbps respectively at the 2.4GHz band. [11] presented BER vs. SNR of the 4 802.11b PHY modes provided empirically with Intersil WLAN product called HFA3861B in the AWGN environment. These curves will be used for the following numerical analysis and experimental simulations in the next section. With ARF, the PHY mode to be used basically is determined by monitoring the number of received and missed ACK frames. If m successive ACK frames cannot be received correctly, the transmission rate is then degraded to the lower rate. If the sender successfully receives n consecutive ACK frames, it will raise the current rate to the higher order for the subsequent transmissions. Fig. 2 shows the Markov chain model for ARF protocol with the typical values of m and n equal to 2 and 10 respectively. From this model we have the following equations:

$$(1 - p_{i,f}(1,\gamma))^{10} \cdot P_{ARF}(PHY_i = 1|\Gamma_i = \gamma) = (p_{i,f}(2,\gamma))^2 \cdot P_{ARF}(PHY_i = 2|\Gamma_i = \gamma) \tag{16}$$

$$\begin{aligned}((1 - p_{i,f}(2,\gamma))^{10} + (p_{i,f}(2,\gamma))^2) \cdot P_{ARF}(PHY_i = 2|\Gamma_i = \gamma) &= (1 - p_{i,f}(1,\gamma))^{10} \cdot P_{ARF}(PHY_i = 1|\Gamma_i = \gamma) \\ &+ (p_{i,f}(3,\gamma))^2 \cdot P_{ARF}(PHY_i = 3|\Gamma_i = \gamma)\end{aligned} \tag{17}$$

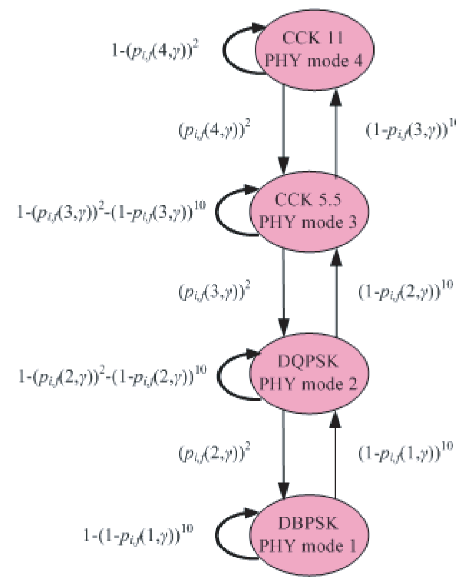

Fig. 2. The Markov chain model for the 4 IEEE 802.11b PHY modes with ARF protocol using parameters m = 2 and n = 10.

$$\begin{aligned}((1 - p_{i,f}(3,\gamma))^{10} + (p_{i,f}(3,\gamma))^2) \cdot P_{ARF}(PHY_i = 3|\Gamma_i = \gamma) &= (1 - p_{i,f}(2,\gamma))^{10} \cdot P_{ARF}(PHY_i = 2|\Gamma_i = \gamma) \\ &+ (p_{i,f}(4,\gamma))^2 \cdot P_{ARF}(PHY_i = 4|\Gamma_i = \gamma)\end{aligned} \tag{18}$$

$$(p_{i,f}(4,\gamma))^2 \cdot P_{ARF}(PHY_i = 4|\Gamma_i = \gamma) = (1 - p_{i,f}(3,\gamma))^{10} \cdot P_{ARF}(PHY_i = 3|\Gamma_i = \gamma) \tag{19}$$

where $p_{i,f}(y,\gamma)$ is the probability of transmission failure for station i using PHY mode y (y is from 1 to 4 for 1 to 11 Mbps in order) with SNR γ in (5). With the following normalization condition imposed,

$$\sum_{j=1}^{4} P_{ARF}(PHY_i = j|\Gamma_i = \gamma) = 1 \tag{20}$$

the conditional probability that PHY mode y is selected for station i given SNR γ with ARF, $P_{ARF}(PHY_i = y|\Gamma_i = \gamma)$ can be derived numerically.

III. The Results and Discussion

In this section we provide numerical results to explore the impact of PHY channel inequality on the throughput performance of IEEE 802.11b WLANs. We consider an IEEE 802.11b infrastructure WLAN in which each station transmits a saturated traffic flow of a fixed payload size of 1500 bytes with the basic CSMA/CA scheme to AP. The system parameters are adopted from IEEE 802.11b standard [1]. The first two scenarios are conducted for distinctly showing the effects of different channel conditions and/or unequal data rates on the throughput performance of 802.11 DCF. The third scenario is set up to investigate the impact of ARF on the system throughput. For all the scenarios we also conduct corresponding simulations based on C++ programming language to validate the accuracy our analytical model. Each result comes from the simulation of 100000 transmissions of packets.

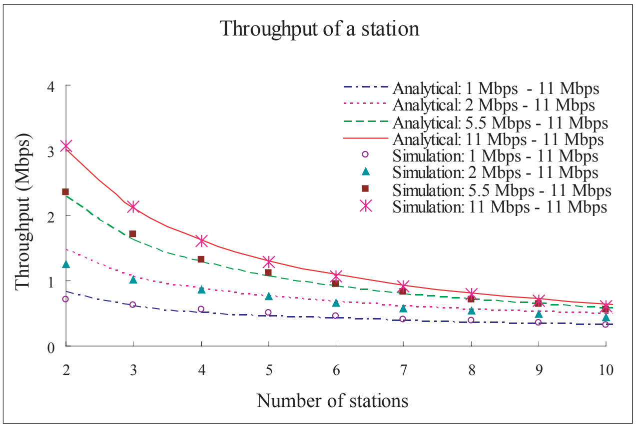

Fig. 3. In Scenario 1, the throughput of a station vs. the number of stations in case that one station transmits at a lower data rate (1, 2, 5.5, or 11 Mbps) whereas all the others transmit at the highest rate of 11 Mbps (all the stations are with the same BER of 1E-5).

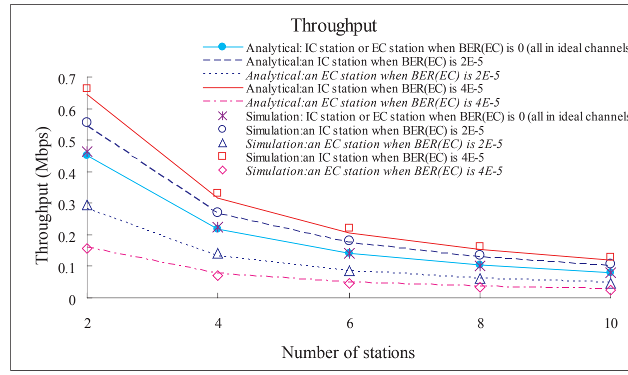

Fig. 4. In Scenario 2, the saturated throughput of an IC and EC station vs. the number of stations varying with the BER level of EC station, $BER(EC)$. For instance, in case of $BER(EC)$ equal to 2E-5, the simulation result of IC station is indexed as the circle mark, while that of EC station is indexed as the triangle mark.

A. Scenario 1: Stations with identical BER at unequal data rate

In this subsection we conduct the transmission scenario that all the stations are with equal BER however at different data rates. Assume that all the stations are with BER of 1E-5, while one station transmits at a lower data rate (1, 2, 5.5, or 11 Mbps) and all the others transmit at the highest rate of 11 Mbps. The throughput with the number of stations is derived from Equation (12) and shown in Fig. 3. It is observed that all the stations have equal throughputs regardless of their data rates. This phenomenon is so called ¨performance anomaly¨ [12] which means that when stations experience identical link qualities, i.e. the same BERs, the throughput of stations with high data rates will be limited within the lowest rate used among stations. For example let's consider 2 stations. When they both transmit at the rate of 11 Mbps, the throughput of each one is about 3.63 Mbps as shown in Fig. 3. However, if one station changes to use the lowest rate of 1 Mbps, the throughput of another one remaining at 11 Mbps will greatly degrade to 0.82 Mbps. The overall throughput is therefore decreased by as large as 80% ((7.26 Mbps - 1.64 Mbps) / 7.26 Mbps = 77.4%).

Performance anomaly arises from the fact that IEEE 802.11 DCF protocol substantially provides equal transmission opportunities for stations regardless of their transmission data rates, presenting throughput-based fairness. The analysis results demonstrate that the system throughput of 802.11 DCF is significantly affected by the cross-layer impact of the lowest PHY rate used among stations.

B. Scenario 2: Stations in different channel conditions with equal or unequal data rates

In this subsection we show the results when stations are in different channel conditions with equal or unequal data rates. The kind of analysis can be sensible because even with a LA mechanism, 802.11 stations still can experience different link qualities at most of the time due to limited MCSs available. First we have the scenario all the stations are with an equal data rate to clearly show a skewed sharing of throughput among stations due to different channel qualities. Consider all the stations use the same data rate of 1 Mbps. Assume half of the stations, named ideal-channel (IC) stations, are in ideal channel conditions with BER = 0, whereas the others, named error-prone-channel (EC) stations, suffer from channel degradation due to mobility with BER ranging from 0 to 4E-5.

Throughput of a station is derived from Equation (12) and presented in Fig. 4 with respect to the number of stations and BER of EC stations, $BER(EC)$. It is shown that when IC and EC stations are in the same channel condition, i.e. $BER(EC)$ = 0, their throughput performances are equal. When the difference of channel conditions increases, the performance variation is gradually enlarged. Now let's consider 2 stations. If they are both in an ideal condition, throughput of each one is about 450 Kbps as shown in Fig. 4. When one station's BER deteriorates to 2E-5, its throughput degrades to 281 Kbps, whereas the throughput of the other one with ideal conditions increases to 542 Kbps. The performance variation is as large as 58% ((542 Kbps -281 Kbps) / 450 Kbps = 57.96%).

The performance variation arises by the following facts. Due to its higher BER, EC station statistically experiences more retries to succeed a transmission than IC station does. When a retransmission is performed, according to CSMA/CA standards the backoff window will be increased exponentially until the retries come to a certain limit. Thus EC station would adopt a larger backoff timer on average and then has less chance to access the channel. Our analysis results show that the individual throughput performance (fairness of channel sharing among stations) of DCF is significantly affected by the cross-layer impact of PHY channel inequality.

Now we examine the scenario that stations are in different channel conditions with unequal data rates. The scenario is similar to that aforementioned except that EC stations use an unequal data rate of 11 Mbps. Fig. 5 presents the throughput of IC station with the rate of 1 Mbps and EC station with 11 Mbps. It is shown that when IC and EC stations are with the same channel condition, i.e. $BER(EC)$ = 0, their throughput performances are equal, presenting ”performance anomaly” similar to what are shown in Fig. 3. When $BER(EC)$ degrades to 2E-5 and 4E-5 successively, throughput of EC

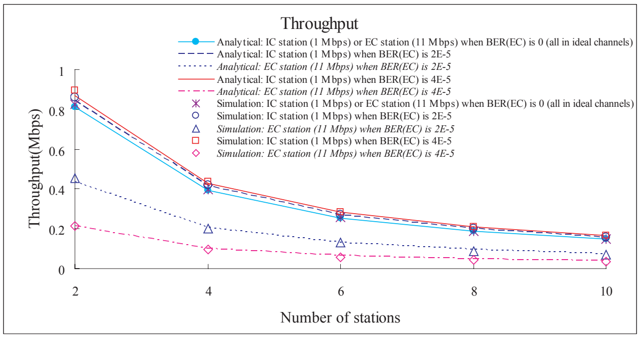

Fig. 5. In Scenario 2, the saturated throughput of an IC station with the data rate of 1 Mbps and an EC station with 11 Mbps vs. the number of stations varying with the BER level of EC station, $BER(EC)$. For instance, in case of $BER(EC)$ equal to 2E-5, the simulation result of IC station is indexed as the circle mark, while that of EC station is indexed as the triangle mark.

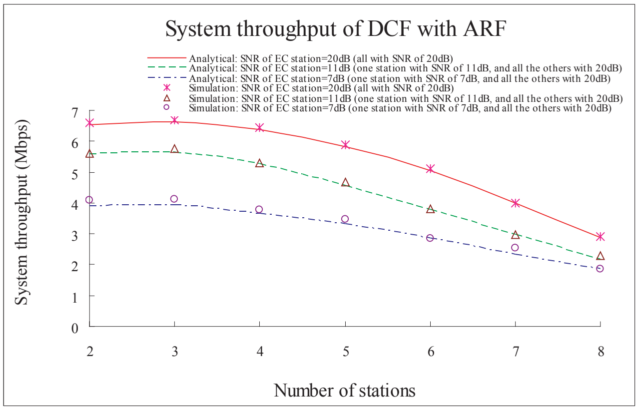

Fig. 6. In Scenario 3, the system throughput of DCF with ARF vs. the number of stations varying with SNR of EC station.

station suffers from more and more starvation whereas that of IC station remaining in a good condition is progressively increased. For example, consider the number of stations is 2. When both the two stations are in an ideal condition, their throughputs are equal as about 813 Kbps. When $BER(EC)$ degrades to 4E-5, throughput of EC station is extremely degraded to 212 Kbps whereas that of IC station is increased to 894 Kbps. The throughput variation between the two stations is as large as 84% ((894 Kbps -212 Kbps) / 813 Kbps = 83.89%). It is also shown that the throughput performance does not accord with the used data rates, i.e. throughput of EC station with the rate of 11 Mbps is even lower than that of IC station with 1 Mbps. The analysis results demonstrate that the skewed channel sharing is caused by different link qualities rather than unequal data rates; the presence of PHY channel inequality can cause significant throughput unfairness either at an equal rate or at different rates.

C. Scenario 3: Stations in unequal channel conditions with ARF

From the analysis results of Subsection 3.A and 3.B we show the impacts of different channel conditions and/or unequal data rates on the throughput performance of 802.11 DCF. In this subsection we analyze the effects of ARF on the system throughput. The typical values of m =2 and n = 10 are used for numerical analyses and simulations. Assume that one station, indexed as EC station, experiences variable SNR ranging from 20 dB to 7 dB; all the other stations, indexed as IC stations, are with stationary and ideal SNR of 20 dB. By linear combinations of $P_x(PHY_i = y|\Gamma_i = \gamma)$ derived in (20) and $thr_i|PHY_i = y,\Gamma_i = \gamma$ in (12), the individual throughput of each station with SNR γ can be derived from Equation (13). Thus the system throughput with respect to the number of stations can be obtained from Equation (15) and the results are shown in Fig. 6. It is shown that even when there is only one station with low SNR (i.e. EC station with SNR equal to 11 dB or 7 dB) in the network, the system throughput can be significantly reduced (e.g., throughput with three stations when SNR of EC station is 20, 11, and 7 dB is 6.626, 5.638, and 3.949 Mbps respectively). The reason is that with ARF, a station with deteriorated SNR can be likely to select low data rates, leading to degradation of system throughput due to performance anomaly [12]. It is also shown that the system throughput is degraded rather rapidly with the increase of stations (e.g., in case of EC station's SNR equal to 20 dB, throughput degrades sharply from 6.543 to 2.894 Mbps when the number of stations increases from 2 to 8). One reason is the growing collision probability caused by heavier traffic contentions. Another, most importantly, is that when the collision probability increases, ARF tends to downgrade the data rates and consequently decreases throughput. The results demonstrate that ARF which adjusts data rates by monitoring the counts of received ACK frames may not be suitable to a WLAN environment with high-density traffic.

IV. Conclusion

The system performance of 802.11 DCF-based WLANs is significantly impacted by PHY inequality, i.e. varied channel conditions and/or unequal data rates determined by the link adaptation scheme. In this paper we present a theoretical model for DCF protocol with the link adaptation scheme of ARF to analyze the throughput performance in the presence of PHY inequality. From the analysis results it is shown that: (i) System throughput is determined by the lowest data rate used with stations. (ii) Throughput sharing among stations depends on the variation of link qualities rather than the difference of data rates. We validate our analytical model via simulations and the results demonstrate its accuracy.

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