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數位家庭:網路、平台與應用--子計畫五：數位內容 P2P 串流平台之相關技術(2/3)

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行政院國家科學委員會專題研究計劃成果報告

數位家庭:網路、平台與應用-子計畫五

數位內容P2P串流平台之相關技術(2/3)

Technology for Streaming Digital Content over P2P Platforms

計畫編號：95-2219-E-002-018-
執行期限：95年8月1日至96年7月31日

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一、摘要

由於 IEEE 802.11 無線區域網路能夠提供寬頻接取上網，它在數位家庭的應用越來越受到矚目。在這樣一個以競爭為基礎的網路中，它的公平性效能是很重要的，尤其是當提供多媒體服務這些對於頻寬的改變會敏感反應的應用時(例如網路電話及影音串流)。這個計畫的目的是分析在 IEEE 802.11 無線區域網路中，當使用者的通道品質不同時，他們的傳輸效能會呈現什麼結果。我們利用 Bianchi [10] 所提出的二維陣列馬可夫鏈模型，並將其延伸以分析媒體存取控制層(MAC)在不同的通道品質及傳輸速率下的傳輸效能。從分析結果得知，當使用者的通道品質一致時，無論他們是不是有相同的傳送速率，都會呈現相同的傳輸效能；如果通道品質不同時，即使傳送速率能隨著通道品質改變，仍有可能造成傳輸效能的嚴重不公平。

關鍵詞：無線區域網路、性能分析、公平性

Abstract

IEEE 802.11 based WLAN (Wireless Local Area Networks) technology has gained tremendous popularities in digital home with its capability of providing broadband access for mobile users. In such a contention-based network, the fairness performance is of particular concern since the qualities of multimedia services like Internet phone and streaming video essentially depend on the allocation of channel access. The objective of this project is to analyze the fairness of IEEE 802.11 DCF in heterogeneous wireless LAN environments where users experience unequal channel conditions due to the mobility and fading effects. In this project, we exploit an analytical approach which extends a two dimensional Markov chain model of DCF proposed by Bianchi [10] to consider heterogeneous channel conditions. From the results our analyses, it is shown that 802.11 CSMA/CA can present fairness only on condition that the link qualities of all the hosts are equal in a statistical average sense. It is also observed that heterogeneous channel conditions can pose significant unfairness of channel sharing even with a link adaptation mechanism since MCSs (Modulation and Coding Schemes) available are limited.

Keywords: IEEE 802.11 WLAN, performance

analysis, fairness

二、研究目的及文獻探討

Most of the current IEEE 802.11 based WLANs (Wireless Local Area Networks) employ DCF (Distributed Coordination Function) [1], a random access MAC (Medium Access Control) protocol based on CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance), on account of its distributed nature for the simplicity of implementation. To such networks, fairness is of particular concern since the overall system performance essentially depends on the allocation of transmission mediums among users. The fairness of IEEE 802.11 DCF has been largely studied with theoretical analyses, simulations, or experiments in previous works [2]-[7]. It is considered over a short or long period of time separately for pertinently reflecting the performance of the specific applications or protocols. For example, the behavior of short-term fairness can make a significant impact on TCP transfers or delay-sensitive multimedia applications [2]. In general, short-term fairness means around an order of 10 ms scales while long-term fairness may involve a transmission of thousand packets [4]. Most of the previous works present the observation that DCF is fair over long time scales but can not provide short-term fairness. Koksal et al. [2] argued that short-term unfairness is due to a phenomenon posed by the backoff protocol in CSMA/CA: a host capturing the channel will likely keep it after a contention period, which is similar to the well-known "capture effect" shown in Ethernet [8]. However, Berger-Sabbatel et al. [4] provided a contrary perception that DCF indeed presents pretty fine short-term fairness and consequently provides long-term fairness while short-term fairness implies long-term fairness, but not vice versa [2]. They argued that the confusion of fairness problem in the previous works [2] is as a result of using the CSMA/CA protocol specific to Wavelan system [9] instead of that characterized in 802.11 standards. Indeed, there is an important difference between the two access methods: the Wavelan CSMA/CA protocol executes exponential backoff when the channel is sensed busy, whereas 802.11 protocol does that only when a collision is experienced. Although the analysis of Berger-Sabbatel et al. [4] is rather consistent with the behavior of the present 802.11 protocols, however, the conclusion is valid only under the assumption of homogeneous transmission qualities among the participating hosts, which may be unrealistic while hosts can experience unequal channel conditions due to mobility, fading, interference factors, and so on. Since an 802.11 exponential backoff performed is actually due to not only a transmission collision but also a packet corruption with bad signal qualities, the backoff behavior of hosts will be varied with their own link qualities, thereby leading to an unequal sharing of transmission channels.

The objective of this work is to evaluate the fairness of 802.11 DCF in heterogeneous WLAN environments. In this project, we exploit an analytical approach which extends a two dimensional Markov chain model of DCF proposed by Bianchi [10] to consider heterogeneous channel conditions. To better consist with the behavior of the present 802.11 protocols performing in realistic environments by

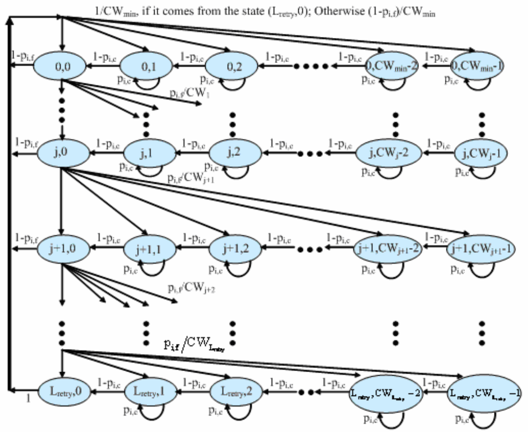

Fig. 1 The state transition diagram of host *i*

comparison with previous works [10] [11] [12], our analytical model takes into account more factors including the finite retransmission limit, the probability that the backoff counter is frozen when the channel is sensed busy, and error-prone channels. By our analyses, it is shown that 802.11 CSMA/CA can present fairness only on condition that the link qualities of all the hosts are equal in a statistical average sense. It is also observed that heterogeneous channel conditions can pose significant unfairness of channel sharing even with a link adaptation mechanism since MCSs (Modulation and Coding Schemes) available are limited.

The rest of this report is organized as follows. Section 2 presents our analytical model of 802.11 DCF. Section 3 shows analytical results which demonstrate the unfairness of 802.11 DCF due to heterogeneous channel conditions. Section 4 draws our conclusions.

三、研究方法

In this section we analyze IEEE 802.11 DCF protocols by extending a two dimensional Markov chain model first proposed by Bianchi [10]. Our analytical model can more truly evaluate the statistical performance of DCF in realistic WLAN environments since it takes more factors into account including the finite retransmission limit, the probability that the backoff counter is frozen when the channel is sensed busy, and error-prone channels.

Now we consider K IEEE 802.11 hosts in non-perfect channels. Assume that these hosts are within the transmission range of each other with each one always having a packet to send (i.e. operating in saturation conditions). To host i (i=0~K-1), let $p_{i,c}$ denote the probability of a packet collided with other hosts. That is:

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

where τ_h is the probability for host h ($h \neq i$) transmitting a packet in a given slotted time. To host i, let $p_{i,e}$ denote the probability of a packet corrupted due to error-prone channels. $p_{i,e}$ basically depends on SNR (signal to noise ratio), the used MCS, and the frame size. Consider uncoded modulations like what are adopted from 802.11b standards and assume that BER (Bit Error Rate) $p_{i,b}$ is unchanged inside each packet. Thus $p_{i,e}$ can be expressed as:

$$p_{i,e} = 1-(1-p_{i,b})^{FS_i*8} \qquad (2)$$

where FS_i is the frame size in bytes. To host i, the probability of a transmission failed, $p_{i,f}$, which consists of the probability of a packet collided and a collision-free packet corrupted can be expressed as:

$$p_{i,f} = p_{i,c} + (1-p_{i,c}) \cdot p_{i,e} \qquad (3)$$

In 802.11, a host needs to wait for a random backoff time before the next transmission to avoid a collision with other hosts. 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 a collision or a corruption, the *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 the *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} are shown as follows:

$$CW_j = \begin{cases} 2^j CW_{\min} & for\ j = 0,1,....,m\text{-}1, \text{if } L_{retry} > m \\ 2^m CW_{\min} = CW_{\max} & for\ j = m,....,L_{retry}, \text{ if } L_{retry} > m \\ 2^j CW_{\min} & for\ j = 0,1,....,L_{retry}, \text{if } L_{retry} \le m \\ \text{where } m = \log_2(CW_{\max}/CW_{\min}) \end{cases} \quad (4)$$

For host *i*, let *s(i,t)* and *b(i,t)* be the stochastic process representing the backoff stage and backoff time counter at time *t* respectively. Let

$$b_{i,j,l} = \lim_{t\to\infty} \Pr\{s(i,t) = j, b(i,t) = l\}, j \in (0, L_{retry}), l \in (0, CW_j - 1)$$

be the stationary distribution of the Markov chain as shown in Fig. 1. Using this Markov chain that describes the transition probabilities among states, All $b_{i,j,l}$ values can be expressed as a function of $p_{i,c}$, $p_{i,e}$ and $b_{i,0,0}$. With the following normalization condition imposed,

$$\sum_{j=0}^{L_{retry}} \sum_{l=0}^{CW_j-1} b_{i,j,l} = 1 \quad (5)$$

, $b_{i,0,0}$ is finally given by (6) and depends on the values of L_{retry} and *m*.

$$b_{i,0,0} = \begin{cases} \dfrac{2(1-2\cdot p_{i,f})(1-p_{i,f})(1-p_{i,c})}{CW_{\min}\cdot(1-(2\cdot p_{i,f})^{L_{retry}+1})\cdot(1-p_{i,f}) + (1-p_{i,f}{}^{L_{retry}+1})\cdot(1-2p_{i,c}-2\cdot p_{i,f}+4\cdot p_{i,c}\cdot p_{i,f})}, L_{retry} \le m \\ \dfrac{2(1-2\cdot p_{i,f})(1-p_{i,f})(1-p_{i,c})}{CW_{\min}\cdot(1-(2\cdot p_{i,f})^{m+1})\cdot(1-p_{i,f}) - (1-2\cdot p_{i,f})(1-p_{i,f}{}^{m+1}) + (1-2\cdot p_{i,f})(CW_{\min}\cdot 2^m - 1)(1-p_{i,f}{}^{L_{retry}-m}) + 2(1-2\cdot p_{i,f})(1-p_{i,f}{}^{L_{retry}+1})(1-p_{i,c})}, L_{retry} > m \end{cases} \quad (6)$$

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

$$\tau_i = \sum_{j=0}^{L_{retry}} b_{i,j,0} = \sum_{j=0}^{L_{retry}} p_{i,f}{}^j \cdot b_{i,0,0} = b_{i,0,0} \cdot \frac{1-p_{i,f}{}^{L_{retry}+1}}{1-p_{i,f}} \quad (7)$$

From equation (7) we can see that τ_i depends on the packet's failed probability $p_{i,f}$, which is determined with the collision probability $p_{i,c}$ and the corruption probability $p_{i,e}$. From equation (2), (3) and (4) to (7), we can solve unknown parameters τ_i and $p_{i,f}$ numerically with a given frame size FS_i and BER $p_{i,b}$.

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

$$P_{tr} = 1 - \prod_{h=0}^{K-1}(1-\tau_h) \quad (8)$$

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

$$P_{i,\sin gle} = \tau_i \cdot \prod_{h=0,h\ne i}^{K-1}(1-\tau_h)/P_{tr} \quad (9)$$

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 host *i*, $P_{tr}\cdot P_{i,\sin gle}\cdot(1-p_{i,e})$; the probability of a successful transmission of host *h* (*h*≠*i*), $P_{tr}\cdot \sum_{h=0,h\ne i}^{K-1} P_{h,\sin gle}\cdot(1-p_{h,e})$; the probability of a failed transmission due to non-perfect channel conditions, $P_{tr}\cdot\sum_{h=0}^{K-1} P_{h,\sin gle}\cdot p_{h,e}$; and the probability of a failed transmission due to collision, $P_{tr}\cdot(1-\sum_{h=0}^{K-1} P_{h,\sin gle})$. Hence the saturated throughput of host *i*, S_i can be expressed as

$$S_i = \frac{P_{tr}\cdot P_{i,\sin gle}\cdot(1-p_{i,e})\cdot PL_i * 8}{(1-P_{tr})\cdot T_{slot} + P_{tr}\cdot\sum_{h=0}^{K-1}P_{h,\sin gle}\cdot(1-p_{h,e})\cdot Ts_h + P_{tr}\cdot\sum_{h=0}^{K-1}P_{h,\sin gle}\cdot p_{h,e}\cdot Te_h + P_{tr}\cdot(1-\sum_{h=0}^{K-1}P_{h,\sin gle})\cdot T_C} \quad (10)$$

equation (10), in which PL_i is the payload length of host i in bytes; T_{slot} is the slotted time; Ts_h and Te_h are the time of host h 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_h and Tc depend on the channel access mechanism. In case of the basic scheme, they can be expressed as:

$$Ts_h^{bas} = DIFS + H + Tl_h + \gamma + SIFS + ACK + \gamma$$

$$Tc^{bas} = DIFS + H + Tl^* + \gamma$$

and for the four-way handshaking scheme, they are:

$$Ts_h^{RTS} = DIFS + RTS + \gamma + SIFS + CTS + \gamma + SIFS + H + Tl_h + \gamma + SIFS + ACK + \gamma$$

$$Tc^{RTS} = DIFS + RTS + \gamma + SIFS + CTS + \gamma$$

Te_h is equal to Ts_h in both of the basic and four-way handshaking scheme. $DIFS$, $SIFS$, H, 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. Tl^* is the time of the longest payload transmitted in a collision.

四、結果與討論

In this section we provide numerical results to demonstrate the unfairness of 802.11 DCF due to heterogeneous channel conditions. The transmission scenario is as follows. Consider an 802.11b WLAN environment in which each host transmits a saturated traffic flow of a fixed packet size with the basic CSMA/CA scheme. All the system parameters adopted are presented in Table 1. We provide performance analyses in both cases of hosts transmitting at an equal data rate and at different data rates with a link adaptation mechanism.

Payload = 1023 bytes	MAC header = 28 bytes	Propagation delay = 1us	Min. window size = 32
Slot time = 20us	PHY header = 24 bytes	DIFS = 50us	Max. window size = 1024
Data rate= 1(11) Mbps	ACK = 38 bytes	SIFS = 10us	Retry limit = 5

Table 1. System parameters

4.1 Heterogeneous link qualities with equal data rates

First we analyze the scenario the hosts transmit at an equal data rate to demonstrate the unfairness due to heterogeneous link qualities. Assume there are total K 802.11b contending hosts. Assume half of the hosts, named ideal-channel (IC) hosts, are always in a stationary and ideal channel condition (i.e. BER=0), whereas the others, named error-prone-channel (EC) hosts, are initially in an ideal condition and later suffer from channel degradation due to the mobility with an average BER of 2E-5 and 4E-5. The used data rates of IC and EC hosts are assumed the same as 1 Mbps.

The saturated throughput of a host is derived from equation (10) and presented in Fig. 2 with respect to K and the BER of EC hosts, *BER(EC)*. It is shown that when all the hosts are in an ideal condition initially, their performances are equal. When *BER(EC)* later deteriorates to 2E-5 and 4E-5 consecutively, the performance variation is gradually enlarged. Now let's consider 2 hosts.

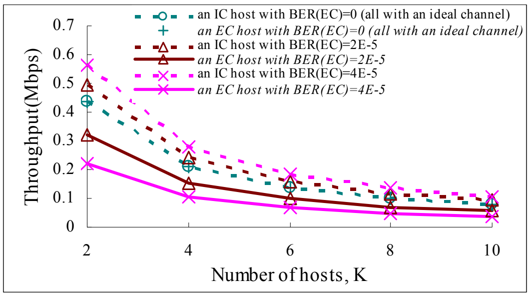

Fig. 2 Saturated throughput of an IC and EC host vs. the number of hosts varying with the BER level of EC hosts, *BER(EC)*. For instance, in case of *BER(EC)* equal to 2E-5, throughput of an IC host is indexed as the triangle-dotted line, while that of an EC host is indexed as the triangle-solid line

When they are both in an ideal channel, the achievable throughput of each one is about 436 Kbps as shown in Fig. 2. In case one host's BER deteriorates as 2E-5, its throughput degrades to 319 Kbps, whereas the throughput of the other one with ideal conditions increases to 494 Kbps. The performance variation is as large as 40.3% (176 Kbps/436 Kbps = 40.3%).

The performance variation arises by the following facts. Due to its higher BER, an EC host averagely experiences more retries to succeed a transmission than an IC host does. When a retransmission is performed, according to CSMA/CA standards, the backoff window size will be increased exponentially until the retries come to a certain limit. Thus an EC host would averagely adopt a larger backoff timer and then has less chance to access the channel. Such the unfair behavior is similar to the scenarios of asymmetric information among nodes [14]. Our analytical results also demonstrated that when all the hosts transmit at an equal data rate, 802.11 CSMA/CA can only present fairness on condition of homogeneous link qualities; the presence of heterogeneous link qualities can cause significant unfairness.

4.2 Heterogeneous link qualities with unequal data rates

Now we use the scenario which hosts transmit at unequal data rates with a link adaptation mechanism for demonstrating the unfairness due to heterogeneous link qualities. Assume that half of the hosts transmit at a data rate of 11Mbps in a stationary channel with an average BER of 5E-7, whereas the others transmit at 1Mbps with an equal BER of 5E-7 initially, and later with a deteriorated BER of 2E-5 and 4E-5 sequentially due to mobility. Fig. 3 presents the saturated throughput of an 11Mbps host and a 1Mbps host. It is shown that when all the hosts are initially with an equal BER 5E-7, they present identical performances, which is so called "performance anomaly" [3] meaning that if at least one host transmits at a lower data rate, the throughput of the others at higher rates will be degraded below the level of the lower rate. The analytical results demonstrate that 802.11 CSMA/CA can present fairness regardless of the same or different data rates under the condition of homogeneous link qualities.

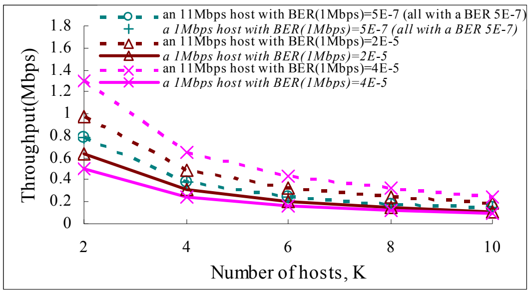

Fig. 3 Saturated throughput of an 11Mbps host and a 1Mbps host vs. the number of hosts varying with the BER level of 1Mbps hosts

However, it is shown that when *BER(1Mbps)* degrades to 2E-5 and 4E-5 successively, the throughput of a 1Mbps host in adverse channel conditions suffers from more and more starvation whereas that of an 11Mbps host in a better condition is progressively increased. It is also shown that the fairness gradually fades away. For example, in case that *K* is 2 and *BER(1Mbps)* is equal to 4E-5, the achievable throughput of an 11Mbps host is 1.295Mbps which exceeds the boundary of 1Mbps. From these results, we show that the unbalanced channel sharing is caused by heterogeneous link qualities rather than unequal data rates. The heterogeneous link qualities can cause the severe unfairness to hosts either at an equal rate or at different rates with a link adaptation mechanism.

五、結論

In this project we study the fairness of 802.11 DCF in the heterogeneous channel conditions. On condition of homogeneous link qualities, the analyses in past efforts [3] [4] show that 802.11 CSMA/CA presents both long-term and short-term fairness. In this project we exploit an analytical approach which extends a well-used two dimensional Markov chain model of DCF. With our analytical results, it is shown that 802.11 CSMA/CA can only present fairness provided that the link qualities of all the hosts are equal in a statistical average sense. It is also shown that the presence of heterogeneous channel conditions can cause severe unfairness of channel sharing even with a link adaptation mechanism.

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計畫成果自評

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On Fairness in Heterogeneous WLAN Environments*

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Abstract—**We analyze the fairness of IEEE 802.11 DCF in heterogeneous wireless LAN environments where users experience unequal channel conditions due to the mobility and fading effects. Previous works [3] [4] show that the 802.11 CSMA/CA can present fairness characteristics in both long-term and short-term. However, the conclusion is only valid under the condition of homogeneous link qualities, which may be impractical. In this paper, we consider heterogeneous channel conditions based on an analytical approach of extending a verified two dimensional Markov chain model of DCF proposed by Bianchi [10]. From our analytical results, it is shown that 802.11 CSMA/CA can present fairness among hosts with identical link qualities regardless of equal or different data rates applied, which is consistent with the observations of previous works. Our analytical results also demonstrate that the presence of heterogeneous channel conditions can pose significant unfairness of channel sharing even with a link adaptation mechanism since the MCSs (Modulation and Coding Schemes) available are limited.**

I. INTRODUCTION

Most of the current IEEE 802.11 based WLANs (Wireless Local Area Networks) employ DCF (Distributed Coordination Function) [1], a random access MAC (Medium Access Control) protocol based on CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance), on account of its distributed nature for the simplicity of implementation. To such networks, fairness is of particular concern since the overall system performance essentially depends on the allocation of transmission mediums among users. The fairness of IEEE 802.11 DCF has been largely studied with theoretical analyses, simulations, or experiments in previous works [2]-[7]. It is considered over a short or long period of time separately for pertinently reflecting the performance of the specific applications or protocols. For example, the behavior of short-term fairness can make a significant impact on TCP transfers or delay-sensitive multimedia applications [2]. In general, short-term fairness means around an order of 10 ms scales while long-term fairness may involve a transmission of thousand packets [4]. Most of the previous works present the observation that DCF is fair over long time scales but can not provide short-term fairness. Koksal et al. [2] argued that short-term unfairness is due to a phenomenon posed by the backoff protocol in CSMA/CA: a host capturing the channel will likely keep it after a contention period, which is similar to the well-known "capture effect" shown in Ethernet [8].

However, Berger-Sabbatel et al. [4] provided a contrary perception that DCF indeed presents pretty fine short-term fairness and consequently provides long-term fairness while short-term fairness implies long-term fairness, but not vice versa [2]. They argued that the confusion of fairness problem in the previous works [2] is as a result of using the CSMA/CA protocol specific to Wavelan system [9] instead of that characterized in 802.11 standards. Indeed, there is an important difference between the two access methods: the Wavelan CSMA/CA protocol executes exponential backoff when the channel is sensed busy, whereas 802.11 protocol does that only when a collision is experienced. Although the analysis of Berger-Sabbatel et al. [4] is rather consistent with the behavior of the present 802.11 protocols, however, the conclusion is valid only under the assumption of homogeneous transmission qualities among the participating hosts, which may be unrealistic while hosts can experience unequal channel conditions due to mobility, fading, interference factors, and so on. Since an 802.11 exponential backoff performed is actually due to not only a transmission collision but also a packet corruption with bad signal qualities, the backoff behavior of hosts will be varied with their own link qualities, thereby leading to an unequal sharing of transmission channels.

The objective of this work is to evaluate the fairness of 802.11 DCF in heterogeneous WLAN environments. In this paper, we exploit an analytical approach which extends a two dimensional Markov chain model of DCF proposed by Bianchi [10] to consider heterogeneous channel conditions. To better consist with the behavior of the present 802.11 protocols performing in realistic environments by

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comparison with previous works [10] [11] [12], our analytical model takes into account more factors including the finite retransmission limit, the probability that the backoff counter is frozen when the channel is sensed busy, and error-prone channels. Jain fairness index [2] is utilized to assess the fairness of IEEE 802.11 DCF in terms of saturated throughput. By our analyses, it is shown that 802.11 CSMA/CA can present fairness only on condition that the link qualities of all the hosts are equal in a statistical average sense. It is also observed that heterogeneous channel conditions can pose significant unfairness of channel sharing even with a link adaptation mechanism since MCSs (Modulation and Coding Schemes) available are limited. The remainder of this paper is organized as follows. Section 2 presents our analytical model of 802.11 DCF. Section 3 shows analytical results which demonstrate the unfairness of 802.11 DCF due to heterogeneous channel conditions. Section 4 draws our conclusions.

II. AN ANALYTICAL MODEL OF 802.11 DCF IN ERROR-PRONE CHANNELS

In this section, we analyze IEEE 802.11 DCF protocols by extending a two dimensional Markov chain model first proposed by Bianchi [10]. Our analytical model can more truly evaluate the statistical performance of DCF in realistic WLAN environments since it takes more factors into account including the finite retransmission limit, the probability that the backoff counter is frozen when the channel is sensed busy, and error-prone channels.

Now we consider K IEEE 802.11 hosts in non-perfect channels. Assume that these hosts are within the transmission range of each other with each one always having a packet to send (i.e. operating in saturation conditions). To host i (i=0~K-1), let $p_{i,c}$ denote the probability of a packet collided with other hosts. That is:

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

where τ_h is the probability for host h ($h \neq i$) transmitting a packet in a given slotted time. To host i, let $p_{i,e}$ denote the probability of a packet corrupted due to error-prone channels. $p_{i,e}$ basically depends on SNR (signal to noise ratio), the used MCS, and the frame size [13]. Consider uncoded modulations like what are adopted from 802.11b standards and assume that BER (Bit Error Rate) $p_{i,b}$ is unchanged inside each packet. Thus $p_{i,e}$ can be expressed as:

$$p_{i,e} = 1-(1-p_{i,b})^{FS_i*8} \qquad (2)$$

where FS_i is the frame size in bytes. To host i, the probability of a transmission failed, $p_{i,f}$, which consists of the probability of a packet collided and a collision-free packet corrupted can be expressed as:

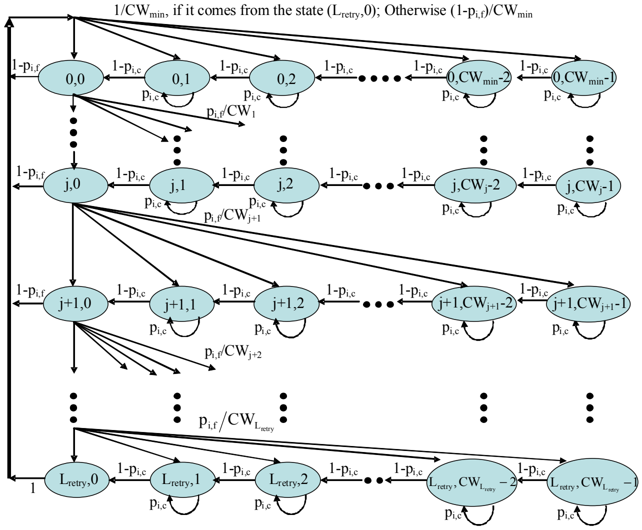

Fig. 1 The state transition diagram of host i

$$p_{i,f} = p_{i,c} + (1-p_{i,c}) \cdot p_{i,e} \qquad (3)$$

In 802.11, a host needs to wait for a random backoff time before the next transmission to avoid a collision with other hosts. 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 a collision or a corruption, the 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 the 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} are shown as follows:

$$CW_j = \begin{cases} 2^j CW_{\min} & for\ j = 0,1,....,m\text{-}1, \text{if } L_{retry} > m \\ 2^m CW_{\min} = CW_{\max} & for\ j = m,....,L_{retry},\ \text{if } L_{retry} > m \\ 2^j CW_{\min} & for\ j = 0,1,....,L_{retry}, \text{if } L_{retry} \le m \end{cases} \qquad (4)$$
$$\text{where } m = \log_2 (CW_{\max} / CW_{\min})$$

For host i, let $s(i,t)$ and $b(i,t)$ be the stochastic process representing the backoff stage and backoff time counter at time t respectively. Let

$$b_{i,j,l} = \lim_{t\to\infty} \Pr\{s(i,t)=j, b(i,t)=l\}, j \in (0, L_{retry}), l \in (0, CW_j - 1)$$

be the stationary distribution of the Markov chain as shown in Fig. 1. Using this Markov chain that describes the transition probabilities among states, All $b_{i,j,l}$ values can be expressed as a function of $p_{i,c}$, $p_{i,e}$ and $b_{i,0,0}$. With the following normalization condition imposed,

$$\sum_{j=0}^{L_{retry}} \sum_{l=0}^{CW_j - 1} b_{i,j,l} = 1 \qquad (5)$$

, $b_{i,0,0}$ is finally given by (6) and depends on the values of L_{retry} and m.

$$b_{i,0,0} = \begin{cases} \dfrac{2(1-2\cdot p_{i,f})(1-p_{i,f})(1-p_{i,c})}{CW_{\min}\cdot(1-(2\cdot p_{i,f})^{L_{retry}+1})\cdot(1-p_{i,f}) + (1-p_{i,f}{}^{L_{retry}+1})\cdot(1-2p_{i,c}-2\cdot p_{i,f}+4\cdot p_{i,c}\cdot p_{i,f})}, L_{retry} \le m \\ \dfrac{2(1-2\cdot p_{i,f})(1-p_{i,f})(1-p_{i,c})}{CW_{\min}\cdot(1-(2\cdot p_{i,f})^{m+1})\cdot(1-p_{i,f}) - (1-2\cdot p_{i,f})(1-p_{i,f}{}^{m+1}) + (1-2\cdot p_{i,f})(CW_{\min}\cdot 2^m - 1)(1-p_{i,f}{}^{L_{retry}-m}) + 2(1-2\cdot p_{i,f})(1-p_{i,f}{}^{L_{retry}+1})(1-p_{i,c})}, L_{retry} > m \end{cases} \qquad (6)$$

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

$$\tau_i = \sum_{j=0}^{L_{retry}} b_{i,j,0} = \sum_{j=0}^{L_{retry}} {p_{i,f}}^{j} \cdot b_{i,0,0} = b_{i,0,0} \cdot \frac{1 - {p_{i,f}}^{L_{retry}+1}}{1 - p_{i,f}} \qquad (7)$$

From equation (7) we can see that τ_i depends on the packet's failed probability $p_{i,f}$, which is determined with the collision probability $p_{i,c}$ and the corruption probability $p_{i,e}$. From equation (2), (3) and (4) to (7), we can solve unknown parameters τ_i and $p_{i,f}$ numerically with a given frame size FS_i and BER $p_{i,b}$.

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

$$P_{tr} = 1 - \prod_{h=0}^{K-1} (1 - \tau_h) \qquad (8)$$

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

$$P_{i,\sin gle} = \tau_i \cdot \prod_{h=0,h\neq i}^{K-1} (1 - \tau_h) / P_{tr} \qquad (9)$$

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 host i, $P_{tr} \cdot P_{i,\sin gle} \cdot p_{i,ps}$; the probability of a successful transmission of host h ($h \neq i$), $P_{tr} \cdot \sum_{h=0,h\neq i}^{K-1} P_{h,\sin gle} \cdot p_{h,ps}$; the probability of a failed transmission due to non-perfect channel conditions, $P_{tr} \cdot \sum_{h=0}^{K-1} P_{h,\sin gle} \cdot (1 - p_{h,ps})$; and the probability of a failed transmission due to collision, $P_{tr} \cdot (1 - \sum_{h=0}^{K-1} P_{h,\sin gle})$.

Hence the saturated throughput of host i, S_i can be expressed as equation (10), in which PL_i is the payload length of host i in bytes; T_{slot} is the slotted time; Ts_h and Te_h are the time of host h 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_h and Tc depend on the channel access mechanism. In case of the basic scheme, they can be expressed as:

$$Ts_h^{bas} = DIFS + H + Tl_h + \gamma + SIFS + ACK + \gamma$$

$$Tc^{bas} = DIFS + H + Tl^* + \gamma$$

and for the four-way handshaking scheme, they are:

$$Ts_h^{RTS} = DIFS + RTS + \gamma + SIFS + CTS + \gamma + SIFS + H + Tl_h + \gamma + SIFS + ACK + \gamma$$

$$Tc^{RTS} = DIFS + RTS + \gamma + SIFS + CTS + \gamma$$

Te_h is equal to Ts_h in both of the basic and four-way handshaking scheme. *DIFS*, *SIFS*, *H*, *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. Tl^* is the time of the longest payload transmitted in a collision.

III. NUMERICAL RESULTS AND DISCUSSION

In this section, we provide numerical results to demonstrate the unfairness of 802.11 DCF due to heterogeneous channel conditions. The transmission scenario is as follows. Consider an 802.11b WLAN environment in which each host transmits a saturated traffic flow of a fixed packet size with the basic CSMA/CA scheme. All the system parameters adopted are presented in Table 1. We provide performance analyses in both cases of hosts transmitting at an equal data rate and at different data rates with a link adaptation mechanism. Then we use the Jain fairness index [2] associated with the analytical results to assess the fairness of IEEE 802.11 DCF. This index is represented as:

$$\text{Jain fairness index} = \frac{(\sum_{i=1}^{K} x_i)^2}{K \sum_{i=1}^{K} {x_i}^2} \qquad (11)$$

where K is the number of the contending hosts. x_i can be the throughput or delay performed on host i. The index has a range of (0, 1] to evaluate fairness.

Payload = 1023 bytes	MAC header = 28 bytes	Propagation delay = 1us	Min. window size = 32
Slot time = 20us	PHY header = 24 bytes	DIFS = 50us	Max. window size = 1024
Data rate = 1(11) Mbps	ACK = 38 bytes	SIFS = 10us	Retry limit = 5

Table 1. System parameters

A. *Heterogeneous link qualities with equal data rates*

First we analyze the scenario the hosts transmit at an equal data rate to demonstrate the unfairness due to heterogeneous link qualities. Assume there are total K 802.11b contending hosts. Assume half of the hosts, named ideal-channel (IC) hosts, are always in a stationary and ideal channel condition (i.e. BER=0), whereas the others, named error-prone-channel (EC) hosts, are initially in an ideal condition and later suffer from channel degradation due to the mobility with an average BER of 2E-5 and 4E-5. The used data rates of IC and EC hosts are assumed the same as 1 Mbps.

The saturated throughput of a host is derived from equation (10) and presented in Fig. 2 with respect to K and the BER of EC hosts, *BER(EC)*. It is shown that when all the hosts are in an ideal condition initially, their performances are equal. When *BER(EC)* later deteriorates to 2E-5 and 4E-5 consecutively, the performance variation is gradually enlarged. The corresponding Jain fairness indices associated

$$S_i = \frac{P_{tr} \cdot P_{i,\sin gle} \cdot p_{i,ps} \cdot PL_i * 8}{(1 - P_{tr}) \cdot T_{slot} + P_{tr} \cdot \sum_{h=0}^{K-1} P_{h,\sin gle} \cdot p_{h,ps} \cdot Ts_h + P_{tr} \cdot \sum_{h=0}^{K-1} P_{h,\sin gle} \cdot (1 - p_{h,ps}) \cdot Te_h + P_{tr} \cdot (1 - \sum_{h=0}^{K-1} P_{h,\sin gle}) \cdot T_C} \qquad (10)$$

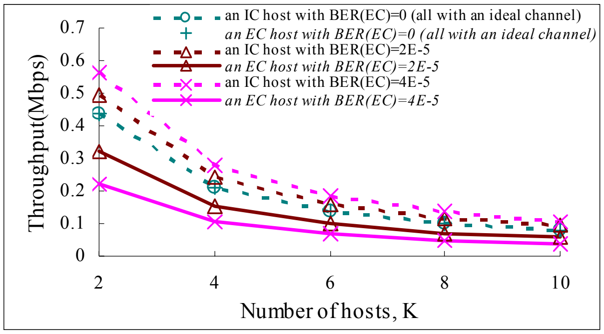

Fig. 2 Saturated throughput of an IC and EC host vs. the number of hosts varying with the BER level of EC hosts, *BER(EC)*. For instance, in case of *BER(EC)* equal to 2E-5, throughput of an IC host is indexed as the triangle-dotted line, while that of an EC host is indexed as the triangle-solid line

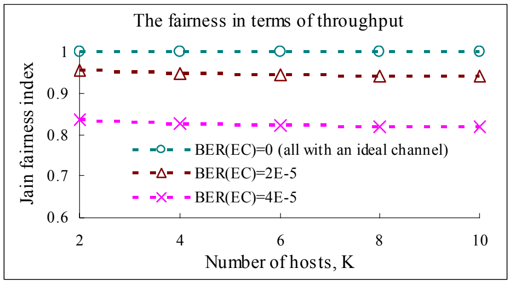

Fig. 3 The Jain fairness index associated with throughput vs. the number of hosts varying with the BER level of EC hosts

with throughput is derived from Eq. (11) and shown in Fig. 3. It is also indicated that with the increasing difference of link qualities, fairness degrades as the index decreases from 1 to about 0.83. Now let's consider 2 hosts. When they are both in an ideal channel, the achievable throughput of each one is about 436 Kbps as shown in Fig. 2. In case one host's BER deteriorates as 2E-5, its throughput degrades to 319 Kbps, whereas the throughput of the other one with ideal conditions increases to 494 Kbps. The performance variation is as large as 40.3% (176 Kbps/436 Kbps = 40.3%).

The performance variation arises by the following facts. Due to its higher BER, an EC host averagely experiences more retries to succeed a transmission than an IC host does. When a retransmission is performed, according to CSMA/CA standards, the backoff window size will be increased exponentially until the retries come to a certain limit. Thus an EC host would averagely adopt a larger backoff timer and then has less chance to access the channel. Such the unfair behavior is similar to the scenarios of asymmetric information among nodes [14]. Our analytical results also demonstrated that when all the hosts transmit at an equal data rate, 802.11 CSMA/CA can only present fairness on condition of homogeneous link qualities; the presence of heterogeneous link qualities can cause significant unfairness.

B. Heterogeneous link qualities with unequal data rates

Now we use the scenario which hosts transmit at unequal data rates with a link adaptation mechanism for demonstrating the unfairness due to heterogeneous link qualities. Assume that half of the hosts transmit at a data rate of 11Mbps in a stationary channel with an average BER of 5E-7, whereas the others transmit at 1Mbps with an equal BER of 5E-7 initially, and later with a deteriorated BER of 2E-5 and 4E-5 sequentially due to mobility. Fig. 4 presents the saturated throughput of an 11Mbps host and a 1Mbps host. It is shown that when all the hosts are initially with an equal BER 5E-7, they present identical performances, which is so called "performance anomaly" [3] meaning that if at least one host transmits at a lower data rate, the throughput of the others at higher rates will be degraded below the level of the lower rate. The analytical results demonstrate that 802.11 CSMA/CA can present fairness regardless of the same or different data rates under the condition of homogeneous link qualities.

However, it is shown that when *BER(1Mbps)* degrades to 2E-5 and 4E-5 successively, the throughput of a 1Mbps host in adverse channel conditions suffers from more and more starvation whereas that of an 11Mbps host in a better condition is progressively increased. It is also shown that the fairness gradually fades away. For example, in case that *K* is 2 and *BER(1Mbps)* is equal to 4E-5, the achievable throughput of an 11Mbps host is 1.295Mbps which exceeds the boundary of 1Mbps. The corresponding fairness index shown in Fig. 5 also indicates that fairness degrades as the difference of link qualities increases. From these results, we show that the unbalanced channel sharing is caused by heterogeneous link qualities rather than unequal data rates. The heterogeneous link qualities can cause the severe

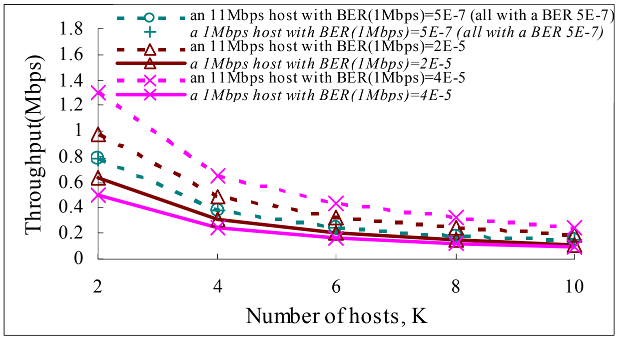

Fig. 4 Saturated throughput of an 11Mbps host and a 1Mbps host vs. the number of hosts varying with the BER level of 1Mbps hosts

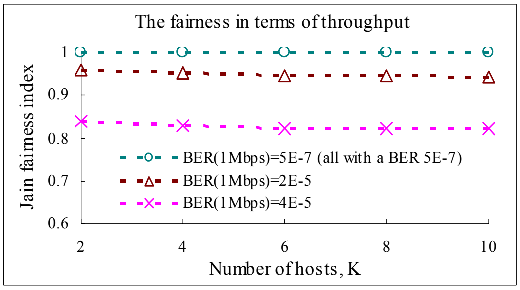

Fig. 5 The Jain fairness index corresponding to throughput vs. the number of hosts varying with the BER level of 1Mbps hosts

unfairness to hosts either at an equal rate or at different rates with a link adaptation mechanism.

IV. CONCLUSION

In this paper, we study the fairness of 802.11 DCF in the heterogeneous channel conditions. On condition of homogeneous link qualities, the analyses in past efforts [3] [4] show that 802.11 CSMA/CA presents both long-term and short-term fairness. In this paper we exploit an analytical approach which extends a well-used two dimensional Markov chain model of DCF. With our analytical results, it is shown that 802.11 CSMA/CA can only present fairness provided that the link qualities of all the hosts are equal in a statistical average sense. It is also shown that the presence of heterogeneous channel conditions can cause severe unfairness of channel sharing even with a link adaptation mechanism.

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出席國際學術會議心得報告

計畫編號	NSC 95-2219-E-002-018
計畫名稱	數位家庭:網路、平台與應用--子計畫五：數位內容 P2P 串流平台之相關技術(2/3)
出國人員姓名 服務機關及職稱	林宗男　國立臺灣大學電信工程學研究所副教授
會議時間地點	2006/11/27-2006/12/01 美國加州舊金山
會議名稱	IEEE GLOBECOM 2006
發表論文題目	(1) Dynamic Search Algorithm in Unstructured Peer-to-Peer Networks (2) On Fairness in Heterogeneous WLAN Environments

一、參加會議經過

2006/11/26：搭乘中華航空直飛美國加州舊金山。
2006/11/27：前往會議現場註冊暨報到。
2006/11/27：參與 Tutorial “WiMAX: An Advanced Broadband Wireless System” 以及 “Unraveling QoS in 802.16 Wireless Broadband Access Networks: The Role of MAC, Cross-Layer Design, and Scheduling”。
2006/11/28：參與 Session MMC-04: Peer-to-Peer Overlay Networks
2006/11/29：參與 Session WLC-29: WLAN Networks -III 並發表之論文。
2006/11/30：參與 Session ISE-02: Peer-to-Peer Services and Technologies 並發表論文。
2006/12/01：參加 Tutorial “Roadmap to Cross-Layer and Cross-System Optimization for B3G” 以及 “Technologies for All-IP Wireless Networks from 3G to 4G”。

二、與會心得

GLOBECOM 是全世界有關通訊網路領域的頂尖研討會之一，這次有幸能夠參加 IEEE GLOBECOM 2006 並發表論文，實屬難得的機會。在會議中我發表研究成果 (1) “Dynamic Search Algorithm in Unstructured Peer-to-Peer Networks” ，這是在非結構化的對等式網路中相當重要的研究議題，我們提出了動態搜尋演算法，這個演算法擷取了先前各種演算法適用於各種不同情境的優點，可以在搜尋效能以及花費之間取得平衡。研究成果(2) “On Fairness in Heterogeneous WLAN Environments” 。除了發表論文之外，並參加各種不同研究主題的研究成果報告，以吸收新知，了解現今世界各國有關通訊網路領域的研究方向及成果。能到世界級的技術會議去發表研究成果，並同時吸收世界上其他人的研究精華，對於日後做研究將會有極大的啟發及幫助。