The System Performance of Wireless CSMA/CA Protocol with Capture Effect

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Abstract: **This work presents a deterministic channel that rules according to inverse α power propagation law. The proposed channel model allows us to derive the lower bound and upper bound of packet's capture probability in Rayleigh fading and shadowing cellular mobile system. According to these capture probabilities, we analyze the system performance in the case of finite stations and finite communicated coverage of a base station. We also adopted a dynamic backoff window size to discuss the robustness of IEEE 802.11 draft standard. Some suggestions and conclusions from numerical results are given to establish the more strong CSMA/CA protocol.**

Index Terms: **Capture, modified CSMA, noiseless, Rayleigh fading, shadowing effect.**

I. INTRODUCTION

A significant feature in the system performance of CSMA protocol [1]–[3] is the ability to sense the carrier status of the channel. In the CSMA protocol, each station must listen the channel status before it attempts to transmit its packets. The process of listening to the channel does not require receiving the information, which is transmitted in the channel. Therefore, same receiver must be equipped for each station. If no packet is transmitted during some transmission period, then the channel is denoted to be idle during the period. Otherwise, the channel is in the busy state if any transmit packets are sensed. Only when each user senses the channel to be idle, it is permitted to transmit its packet if some packets are generated and stored in its buffer. When two or more stations transmit their packets during a transmission period, then collision occurs. When a collision occurs, every transmitting station reschedules a retransmission of the collided packet to some time in the future. The packet collision may be incurred due to the signal propagation time. In other words, station A starts transmitting its packet and the station B is also transmitted its rescheduled packet before the transmitted packet from station A arrived.

In order to enhance the system performance due to uncontrolled packet collision, the family of CSMA protocol is devised to combat this problem. Restated, reducing the collision probability is the resolution to enhance the system performance. Owing to the geographical distribution of a mobile station, an active station can not detect the sensing carrier before it attempts to transmit its packet. This phenomenon increases the probability of colliding packets. Therefore, the issue of a hidden terminal is a major problem to be resolved in CSMA protocol when applying the CSMA protocol in wireless networks.

According to the operation algorithm of CSMA system, an unsuccessful transmission period must last some seconds to detect collided packets. One question is that reducing the detection time of packet's collision whether can enhance the system performance or not. To shorten the idle period means that the offered traffics are heavy. From the analysis results of CSMA system, the throughput of system with heavy traffic is worse than that with lower traffics. Therefore, it is not an allowed method to enhance the throughput of CSMA system by shortening idle period. Institutively, to inhibit transmission among these collided packets when the collision is sensed can reduce the unsuccessful transmission period. Therefore, the ability of system performance in CSMA system with collision detection scheme has been studied [4]. In these works, they assume that each station can detect interference among several transmissions while transmission is in progress and sufficiently fast abort the unsuccessful transmission as soon as their collided packets are detected. Then, we call the system as carrier sense multiple access with collision detection and denoted as CSMA/CD in abbreviation.

However, the real transmission channel is not perfect. When a radio signal travels from a transmitting antenna to a receiving one, path loss occurs due to the propagation medium. With respect to the fading of a transmitted signal, the intensity or relative phase, or both of a received signal varies with time due to the changes in the propagation path with time. Due to the atoms, molecules, or large particles in the atmosphere or other media between the transmitting antenna and receiving antenna, radiation is emitted from many directions instead of only from the direction of the source. This phenomenon forms the diversion of radiation. Multipath is a propagation phenomenon that allows radio signals to reach the receiving antenna by two or more paths. Rayleigh fading is a phase interference fading due to multipath. An obstruction, such as ridges, cliffs, buildings, and trees, generally may lie between the transmitting antenna and receiving antenna. The signal strength of a radio signal is attenuated by obstructions in the propagation path.

It is obvious that the performance of CSMA protocol will be very disgusting if the ability to sense the carrier is not reliable, such as some interference is incurred or the signal fading is very severe in the wireless network. In advance, all interference problems make the carrier sense unreliable to degrade the CSMA performance. We see that the performance will rapidly decay with heavy traffic in CSMA protocol. This phenomenon is incurred by the increment of colliding packets. Therefore, how to support an efficient scheme to decrease the collision probability is the first issue to resolve the packets' collision. In IEEE 802.11 draft standard [5], CSMA/CA scheme is proposed by

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adopting the concept of backoff time to perform collision avoidance through the modification of the traditional CSMA protocol. In the operation algorithm of CSMA/CA, each station must wait a period of time, called backoff time, even though it detects the channel being idle. The random backoff time (in unit slots) is randomly generated by a random number generator. If some slots are chosen as its random backoff time, then the random backoff time decreased by one if it still senses the channel being idle for future coming time. It is permitted to transmit its packet immediately if its backoff time reached to zero. Otherwise, the scheme of backoff time is frozen when the channel changed into busy state. For this situation, all active stations with nonzero backoff time will hold their scheduled packet in the buffer and restart the same mechanism when the channel is idle again. Of course, collision is incurred when two or more active stations want to transmit their packet simultaneously and have the same generated backoff time.

From the above descriptions, the drawback in the IEEE 802.11 draft standard is that an active station will freeze its backoff time counting once the station detects the channel being busy. But, this standard does not tell me how to process the frozen backoff time counting in the future if the status of channel is in idle again. To resolve this condition of dead lock for any station, we assume all active stations, which has frozen their backoff time counting, will regenerate a new random backoff time counting with initial backoff time window $CW = CW_{\min}$ and rescheduled for the transmission of packets.

In this paper, we introduce the concept of capture to reduce the collision probability and to enhance the system performance. The rest of this paper is organized follows. In Section II, we develop the channel model to derive the capture probability among some contending packets at the same time and same channel. In Section III, we derive the system performance of CSMA/CA protocol with and without capture effect. Section IV presents the numerical results and, finally, concluding remarks are made in Section V.

II. THE CHANNEL MODEL AND CAPTURE PROBABILITY

When a radio signal travels from a transmitting antenna to a receiving one, path loss occurs due to the propagation medium. With respect to the fading of a transmitted signal, the intensity or relative phase, or both of a received signal varies with time due to the changes in the propagation path. Due to the atoms, molecules, or large particles in the atmosphere or other media between the transmitting antenna and receiving antenna, radiation is emitted from many directions instead of only from the direction of the source. This phenomenon forms the diversion of radiation. Multipath is a propagation phenomenon that allows radio signals to reach the receiving antenna by two or more paths. Rayleigh fading is a phase interference fading due to multipath.

An obstruction, such as ridges, cliffs, buildings, and trees, generally may lie between the transmitting antenna and receiving antenna. The signal strength of a radio signal is attenuated by obstructions in the propagation path. Therefore, the mobile station with a stronger received signal can successfully transmit its packet to the base station in a practical wireless network even though two or more mobile stations simultaneously transmit their packets by using the same frequency. This phenomenon is called the capture effect for these transmitted packets.

Capture effect is associated with the reception of signals in which, if two signals are received on the same channel, only the stronger of the two appears in the output. The weaker signal is completely suppressed at the receiver limiter, where it is treated as noise or interference and rejected. The threshold set by the receiver limiter to allow the stronger signal to capture the channel is called the capture ratio. Obviously, the capture effect refers to a situation in which a collision occurs, i.e., two or more stations attempt to simultaneously transmit their packets using the same channel, and the base station (controller) can successfully receive the packet that has the stronger signal's power. The transmitted packets of the stations, which simultaneously use the same channel are called the collided packets. In this work, we present a channel model and approximately derive the capture probability, which is defined as the probability that a collided packet can capture the channel to successfully transmit its packet, at near-far fading, Rayleigh fading, and shadowing cellular mobile systems.

Severe signal fading (scattering and multi-path phenomena) and propagation path loss can degrade the transmitted signal. In general, the measured signal strength of a transmitted packet decreases with greater distance, the distance measured away from the base station. In this section, we establish a channel model to obtain the probability in which a collided packet can capture the channel given a reasonable capture ratio.

D. J. Goodman and Adel A. M. Saleh proposed a deterministic channel model in which it governs according to inverse α power propagation law [6]. For this model, some singular points occur while calculating the probability in which a packet can capture the channel. In a related work, Chiu [7] measured the path loss, observing that the path loss is the same among some indoor stations with respect to a clear space. Bertoni [8] indicated that when the transmitting and the receiving antennas are separated in a clear space, the scatterer do not influence the received signal strength within this range. Therefore, the path loss can be neglected within a small free space (i.e., Fresnel zone in [8]).

In complex environments or under atypical atmospheric conditions, the transmitted signal propagation is divided into more distinct paths. The various signal paths have their propagation delay and take unequal phase shifts. Rayleigh fading [9] occurs due to the waves reflected from the surrounding buildings and other structures. The received power of the base station varies according to the terrain contour between the base station and mobile station. Furthermore, the mobile station traveling along tree-lined roads may encounter shadowing of the direct line-of-sight signal; these encountered environments produce more severe signal fading. Therefore, these propagation problems must be examined when a system is designed to compensate for the degradation due to these factors. To characterize the fading, the probability distribution function of the received RF envelope must be known.

In light of above analysis, the inverse α power propagation law is modified according to the propagation fields (near field

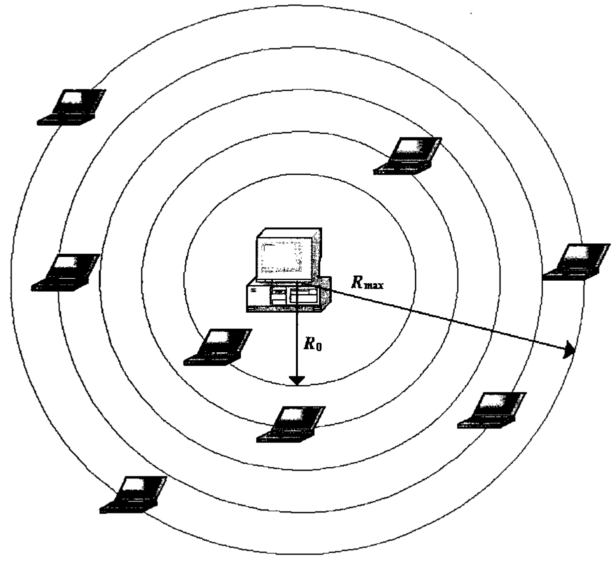

Fig. 1. Mobile station distribution.

and far field). The law claims that the received power $W(R)$ by the base station at distance R from one station [10], [11] is

$$W(R)=\begin{cases} A^2GW(0)\kappa e^{\xi}, & \text{if } R \le \gamma R_{\max} \\ A^2GW(0)\kappa e^{\xi}R^{-\alpha}, & \text{if } R > \gamma R_{\max}, \end{cases} \tag{1}$$

where the shadowing effect is included, A is Rayleigh distributed with unit power, G denotes a factor which is the same for all stations, ξ is Gaussian distributed with zero mean and standard deviation σ_s, and κ is a scaling constant such that $E[\kappa e^{\xi}] = 1$ [12]. In addition, $W(0)$ represents the transmitted power for each station. The definition of γ is the ratio between Fresnel zone and maximum coverage range of a base station. The value of γ also denotes the maximum distance where the received power can be maintained at a fixed level. Obviously, the value can be adjusted according to the used frequency or practical environments. The value of α is 2 in free space and roughly within the range of 3 and 4 in mobile radio communications [6]. To apply in a building's interior, α may exceed 4. A serious fading to make the propagation loss of a transmitted signal occurs when the value of α becomes large. Herein, the near propagation field is advantageous so as to avert the singularities of an irregularly bounded region in an integrating function.

The background noise is negligible when the sum of the transmitted signal power from each station significantly exceeds that of background noise. Restated, the channel is assumed herein to be noiseless. In the channel model, the base station is centrally located within a circular communication area (with radius $R_{\max}$) that the base station can serve. In addition, the distance distribution of each station is uniform within the coverage of the base station and is independent of an identical distribution with other stations. However, the distance distribution of each station within the coverage of the base station is stochastic. Fig. 1 illustrates the concept of such a model. Where R_0 denotes the random variable that represents the distance (in which the station captures the channel) away from the base station. Moreover, the coverage range of communication of the base station is bounded to the distance $R_{\max}$.

To show how impact on the performance of CSMA/CA protocol in capture effect, we first recall the capture probabilities in the presence of Rayleigh and shadowing [10]. Let $\mathbf{a_r} = \{a_{r,0}, a_{r,1}, \cdots, a_{r,|\mathbf{a_r}|-1}\}$ represent the set of these stations with the collision slot r and allow the number of stations with collision slot r to be denoted as $a_{r,0}$. These a_r stations simultaneously transmit their packets at the beginning of each time duration. For any slot r, allow $W_{a_{r,s}}$ to be the received power of the station s and $W_{a_{r,0}}$ to be the received power of the captured packet by the base station. If we denote β as the capture ratio, station $a_{r,0}$ can capture the channel when $\frac{W_{a_{r,0}}}{\sum_{m=1}^{|\mathbf{a_r}|-1} W_{a_{r,m}}} \ge \beta$, where $\beta \ge 1$. Herein, the capture is defined as a perfect capture if $\beta = 1$. In addition, the capture is considered to be a no capture system if $\beta = \infty$.

Allow the random variable $\tilde{R}_{a_{r,m}}$ to be the distance between the mth station with collision slot r and the base station. Denote the conditional probability $P_{C|R_{a_{r,m}}}$, $0 \le m \le |\mathbf{a_r}| - 1$ as the probability that a captured packet occurs among these $|\mathbf{a_r}|$ stations with the collision slot r given all $\tilde{R}_{a_{r,m}} = R_{a_{r,m}}$ away from the base station. Considering the maximum distance of $R_{a_{r,0}}$ to appropriately estimate the capture probability, we consider the mean received power of each mobile station to the receiver terminal of the base station. If the random variable $\tilde{R}_{a_{r,0}}$ represents the distance of the captured packet away from the base station, then its upper bound can be expressed as [10]

$$\max R_{a_{r,0}} = \frac{R_{\max}}{[\beta(|\mathbf{a_r}| - 1)]^{\frac{1}{\alpha}}}. \tag{2}$$

From the channel model with Rayleigh fading and shadowing effect, the capture probability conditioned on the ξ and $R_{a_{r,\{i:i\ge1\}}}$ is obtained as [12]

$$P_{c||\mathbf{a_r}|}(R_{a_{r,0}}|\{\xi_{\{m:m\ge2\}}\}, \{R_{a_{r,\{m:m\ge2\}}}\}) = \prod_{m=1}^{|\mathbf{a_r}|-1} \frac{1}{1+\beta e^{\xi_m-\xi_0}(\frac{R_{a_{r,0}}}{R_{a_{r,m}}})^{\alpha}}, \tag{3}$$

and the capture probability can be expressed as

$$\begin{aligned} P_{c||\mathbf{a_r}|} =& \frac{1}{(2\pi)^{1/2}\sigma_s R_{\max}^{2|\mathbf{a_r}|}} \\ &\times \left\{ \int_{-\infty}^{\infty} \int_{0}^{\gamma R_{\max}} [g(\xi_0, R_{a_{r,0}})]^{|\mathbf{a_r}|-1} 2R_{a_{r,0}} dR_{a_{r,0}} \right. \\ &\times e^{\frac{-\xi_0^2}{2\sigma_s^2}} d\xi_0 + \int_{-\infty}^{\infty} \int_{\gamma R_{\max}}^{\frac{R_{\max}}{[\beta(|\mathbf{a_r}|-1)]^{\frac{1}{\alpha}}}} [g(\xi_0, R_{a_{r,0}})]^{|\mathbf{a_r}|-1} \\ &\left. \times\ 2R_{a_{r,0}} dR_{a_{r,0}} e^{\frac{-\xi_0^2}{2\sigma_s^2}} d\xi_0 \right\}. \end{aligned} \tag{4}$$

The function $g(\xi_0, R_{a_{r,0}})$ in (4) will be given as following cases to derive the capture probability. Herein, we assume that each bit interval in the transmitted packet is larger than the coherent time of the channel. Restated, assume that the channel is a fast fading channel. Also assumed herein is that the attenuation and phase shift of the channel associated with path delay are uncorrelated. If $R_{a_{r,0}} \le \gamma R_{\max}$, the lower bound value of capture probability can be obtained as

$$g(\xi_0, R_{a_{r,0}}) = \frac{1}{(2\pi)^{1/2}\sigma_s} \times \int_{-\infty}^{\infty} \left[\int_{[\beta(|\mathbf{a_r}|-1)]^{1/\alpha}}^{R_{\max}} \frac{2R_{a_{r,1}} dR_{a_{r,1}}}{1+\beta e^{\xi-\xi_0}(\frac{R_{a_{r,0}}}{R_{a_{r,1}}})\alpha} \right] e^{\frac{-\xi^2}{2\sigma_s^2}} d\xi,$$

and if $R_{a_{r,0}} > \gamma R_{\max}$, then the lower bound value of capture probability can be obtained as

$$g(\xi_0, R_{a_{r,0}}) = \frac{1}{(2\pi)^{1/2}\sigma_s} \times \int_{-\infty}^{\infty} \left[\int_{[\beta(|\mathbf{a_r}|-1)^{\frac{1}{\alpha}}]R_{a_{r,0}}}^{R_{\max}} \frac{2R_{a_{r,1}} dR_{a_{r,1}}}{1+\beta e^{\xi-\xi_0}(\frac{R_{a_{r,0}}}{R_{a_{r,1}}})\alpha} \right] e^{\frac{-\xi^2}{2\sigma_s^2}} d\xi.$$

For upper bound value of capture probability, when $R_{a_{r,0}} \leq \gamma R_{\max}$, we have

$$g(\xi_0, R_{a_{r,0}}) = \frac{1}{(2\pi)^{1/2}\sigma_s} \times \int_{-\infty}^{\infty} \left[\int_{[\frac{\beta R_{\max}^{\alpha}}{R_{\max}^{\alpha}-\beta(|\mathbf{a_r}|-2)}]^{\frac{1}{\alpha}}}^{R_{\max}} \frac{2R_{a_{r,1}} dR_{a_{r,1}}}{1+\beta e^{\xi-\xi_0}(\frac{R_{a_{r,0}}}{R_{a_{r,1}}})\alpha} \right] e^{\frac{-\xi^2}{2\sigma_s^2}} d\xi,$$

and

$$g(\xi_0,R_{a_{r,0}}) = \frac{1}{(2\pi)^{1/2}\sigma_s} \times \int_{-\infty}^{\infty} \left[\int_{[\frac{\beta R_{\max}^{\alpha} R_{a_{r,0}}^{\alpha}}{R_{\max}^{\alpha}-\beta(|\mathbf{a_r}|-2)R_{a_{r,0}}^{\alpha}}]^{\frac{1}{\alpha}}}^{R_{\max}} \frac{2R_{a_{r,1}} dR_{a_{r,1}}}{1+\beta e^{\xi-\xi_0}(\frac{R_{a_{r,0}}}{R_{a_{r,1}}})\alpha} \right] \times e^{\frac{-\xi^2}{2\sigma_s^2}} d\xi,$$

if $R_{a_{r,0}} > \gamma R_{\max}$.

A. Rayleigh Fading Effect

Consider a situation in which a signal envelope at any time is always Rayleigh distribution and its impulse response can be modeled as a zero mean complex valued Gaussian process. Under this circumstance, the channel is called as a Rayleigh fading channel. Rayleigh scattering results from inhomogeneities of a random characteristic which has a small scale compared with the wavelength of the light. The dominant instrinistic loss makes refractive index fluctuations. In particular, the effect is more obvious in infrared regions. Therefore, Rayleigh fading is called multipath fading in mobile radio system owing to these standing wave pairs. Therefore, Rayleigh fading is more realistic to determine the spectrum efficiency of a cellular mobile radio.

In general, Rayleigh scattering is resulted from the fluctuations of refractive index. The fluctuations are only slight with respect to signal's wavelength. In general, the scattered field is inversely proportional to the fourth power of the wavelength. Therefore, in this section, we consider a situation in which shadowing can be omitted and let $\alpha = 4$. From [10], we obtain the lower bound of capture probability as

$$P_{c,|\mathbf{a_r}|} = \frac{2}{R_{\max}^{2|\mathbf{a_r}|}}(P_1 + P_2). \tag{5}$$

From [10] and [13], we have

$$P_1 \geq \sum_{m=0}^{|\mathbf{a_r}|-1} \binom{|\mathbf{a_r}|-1}{m} \{R_{\max}^2 - [\beta(|\mathbf{a_r}|-1)]^{\frac{1}{2}}\}^{|\mathbf{a_r}|-m-1}\beta^{\frac{m}{2}} \times \frac{(\gamma R_{\max})^{2m+2}}{2m+2}\left\{ - \tan^{-1}(\frac{\gamma^2(R_{\max}^2 - [\beta(|\mathbf{a_r}|-1)])^{\frac{1}{2}}}{(|\mathbf{a_r}|-1)^{1/2}})\right\}^m; \tag{6}$$

$$P_2 \geq \sum_{m=0}^{|\mathbf{a_r}|-1} \binom{|\mathbf{a_r}|-1}{m} R_{\max}^{2|\mathbf{a_r}|}(-1)^m \times \frac{[\beta(|\mathbf{a_r}|-1)]^{\frac{m}{2}}}{2m+2}\left\{ \left[\frac{1}{[\beta(|\mathbf{a_r}|-1)]^{\frac{1}{4}}}\right]^{2m+2} - \gamma^{2m+2}\right\}. \tag{7}$$

Similar to obtaining the upper bound of capture probability, from [10], the upper bound of capture probability can be obtained as,

$$P_{c,|\mathbf{a_r}|} = \frac{2}{R_{\max}^{2|\mathbf{a_r}|}}(P_3 + P_4), \tag{8}$$

and

$$P_3 \leq \sum_{m=0}^{|\mathbf{a_r}|-1} \binom{|\mathbf{a_r}|-1}{m} \left\{ R_{\max}^2 - \left[\frac{\beta R_{\max}^4}{R_{\max}^4 - \beta(|\mathbf{a_r}|-2)}\right]^{\frac{1}{2}} \right\} \times \frac{1}{2m+2}(\gamma R_{\max})^{2m+2}, \tag{9}$$

$$P_4 \leq \sum_{m=0}^{|\mathbf{a_r}|-1} \binom{|\mathbf{a_r}|-1}{m} R_{\max}^{2|\mathbf{a_r}|}(-1)^m \left[\frac{\beta}{1-\beta(|\mathbf{a_r}|-2)\gamma^4}\right]^{\frac{m}{2}} \times \frac{1}{2m+2}\left\{ \left[\frac{1}{[\beta(|\mathbf{a_r}|-1)]^{\frac{1}{4}}}\right]^{2m+2} - \gamma^{2m+2}\right\}. \tag{10}$$

B. Long-Term Shadowing Effect

The shadow losses are attributed to buildings and trees. This observation implies that the variation in signaling level changes with the surroundings of communication site. These phenomena occur at the situation of which the antenna height is below tree-top level or surrounded by thick trees. In addition, hills also influence the signal level and make the shadow losses increase with the frequency and roughness of the terrain [12]. The received signal strength density due to the standing wave by reflections from buildings or trees varies rapidly. When a shadowing is attributed to surrounding objects, we always treat the object as a diffracting knife edge to estimate the amount of signal attenuation [6].

To ensure good voice quality, the received signal level should exceed a pre-defined level. In this section, we examine how significant variation of capture probability is on the considered shadowing environments. While considering shadowing effect, from [10], we obtain the lower bound of capture probability as

$$
\begin{aligned}
P_{C,|\mathbf{a_r}|} &= 2\sum_{z=0}^{|\mathbf{a_r}|-1}\binom{|\mathbf{a_r}|-1}{z}\left[\beta^{\frac{1}{2}}\exp(\frac{\sigma_s^2}{8})\right]^z \\
&\times\left[1-\frac{\beta^{\frac{1}{2}}(|\mathbf{a_r}|-\frac{1}{2})}{R_{\max}^2}\right]^{|\mathbf{a_r}|-1-z}\qquad(-\frac{\pi}{2})^z\gamma^{2z+2},
\end{aligned}
\tag{11}
$$

and the upper bound of capture probability is obtained as

$$
\begin{aligned}
P_{C,|\mathbf{a_r}|} = \frac{2}{R_{\max}^2}&\left[\sum_{z=0}^{|\mathbf{a_r}|-1}\binom{|\mathbf{a_r}|-1}{z}\left[\beta^{1/2}\exp(\frac{\sigma_s^2}{8})\right]^z\right. \\
&\times\left\{\left[1-\left(\frac{\beta}{R_{\max}^4-\beta(|\mathbf{a_r}|-2)}\right)^{\frac{1}{2}}\right]^{|\mathbf{a_r}|-z-1}\right. \\
&\times\left[-\tan^{-1}\left(\frac{1-\left(\frac{\beta}{R_{\max}^4-\beta(|\mathbf{a_r}|-2)}\right)^{\frac{1}{2}}}{\beta^{1/2}\gamma^2}\right)\right]^z\left.(\gamma R_{\max}^{2z+2})\right\} \\
&\left.\times\frac{1}{2z+2}\right]+\left[1-\left(\frac{\beta\gamma^4}{1-\beta(|\mathbf{a_r}|-2)\gamma^4}\right)^{\frac{1}{2}}\right]^{|\mathbf{a_r}|-1} \\
&\times\left[\left(\frac{1}{[\beta(|\mathbf{a_r}|-1)]^{\frac{1}{4}}}\right)^2-\gamma^2\right].
\end{aligned}
\tag{12}
$$

III. THE PERFORMANCE OF MODIFIED CSMA/CA PROTOCOL WITH CAPTURE EFFECT

Restated that CSMA/CA scheme is proposed by adopting the concept of backoff time to perform collision avoidance through the modification of the traditional CSMA protocol in IEEE 802.11 draft standard. In the operation algorithm of CSMA/CA, each station must wait a period of time, called backoff time, even through it detects the channel being idle. In IEEE 802.11 draft standard, random backoff time is given as $INT(CW * Random()) * slot\ time$. Where $INT(x)$ represents the integer part of x is taken and CW denotes the size of a contention window, which is also an integer. To avoid the colliding packets to be incurred again after previous collision has occurred, the value of the available random backoff time must be extended. In IEEE 802.11 draft standard, it constrains the value of CW to be increased by two times, i.e., $CW_\ell = 2CW_{\ell-1}$, from the initial $CW_{\min}$ for all active stations. When CW reaches the upper constrained value $CW_{\max} = 2^m CW_{\min}$, then CW keeps the value of $CW_{\max}$ even when a collision takes place again. That is,

$$
CW_\ell = \begin{cases} 2^\ell CW_{\min}, & \text{if } \ell \le m \\ 2^m CW_{\min}, & \text{if } \ell \ge m, \end{cases}
\tag{13}
$$

where ℓ represents the number of collision of each scheduled for transmission among transmitted packets at a frame and m is the allowed maximum number of collision of each scheduled for transmission among transmitted packets at a frame. This reason for this processing is to reduce the probability of colliding packets at the same slot by extending the random waiting time. The value of $CW_{\min}$ and $CW_{\max}$ is given as 31 and 255 in IEEE 802.11 draft standard, respectively.

Restate that the backoff window size of contending stations is double until it reaches the maximum size once the collision is occurred for IEEE 802.11 draft standard. In fact, the number of contending stations that have collided may each be two or fewer. Therefore, to extend the backoff window size of contending stations with collided packets is not an optimal scheme to enhance the system performance. That is, the backoff window size should be properly selected according to the number of collided packets. Moreover, the initial $CW_{\min}$ is a key parameter and must be carefully selected according to the offered traffic load. To improve the throughput performance of IEEE 802.11 draft standard, Bianchi [14] proposed an adaptive backoff window control technique based on a dynamic estimation of the number of contending stations. In this method, they showed that the throughput performance is independent of the number of contending stations.

A. The Transient Probability [15]

In our system, we divided three types according to the number of arrivals in a slot. First, type 0 is defined as the condition that only one station has a packet to be transmitted for the given slot. Second, we define type 1 to be the state that stations will start transmission at the beginning of the transmission period. Third, type 2 is denoted that stations have already given up transmission in the frame after they detect the channel being busy. Final, we also define an idle state or idle mode as no station has packet to be generated at the current slot. Let us divide a frame into some slots. Slot is the minimum unit for any measured time. In other words, all time factors consists of different integer number of slots.

To derive the transient probabilities, let us start the derivation of state transient in the first slot of a frame. In the initial slot of the system operation, the number of the active stations is zero. Define N as the total number of stations within the coverage of a base station. In other words, there are total N mobile stations that share a common channel to communicate with each other. We also assume that a nonpersistent CSMA/CA scheme is adopted. If there exists i stations with type 0 in the first slot of a frame, then we have $N-i$ stations being idle in the first slot of the frame where $0 \le i \le N$. After contending algorithm, the number of stations in the type 0 is assumed to be n_0, $0 \le n_0 \le N$, and the number of stations in the type 1 is n_1, $0 \le n_1 \le N$. In other words, the corresponding number of stations in the idle mode is $N - n_0 - n_1$. Let the packet generation rate be λ. We can obtain the probability that there are $N-i$ number of stations in the idle mode at the ends of the current slot and exists $N - n_0 - n_1$ stations at the next slot as

$$
\binom{N-i}{n_0+n_1-i}\lambda^{n_0+n_1-i}(1-\lambda)^{N-n_0-n_1}.
$$

Let ν be the probability that an active station in the backlogged state join the active mode. Corresponding to the above description, the probability that there are i stations in the type 0 at the end of the current slot but only there are n_0 stations still stay at the same mode at the next slot is given as

$$\binom{i}{i-n_0}\nu^{i-n_0}(1-\nu)^{n_0}.$$

Therefore, a Markov model with two states can be established here. Assume a finite state Markov model with Markov state $\mathbf{S}$ as $\mathbf{S} \overset{def}{=} (n_0, n_1)$ is given. Therefore, the transient probability of the system state that changes from state i to $\mathbf{n} = [n_0, n_1]$ is derived as

$$\begin{aligned}P\{S_{n+1} = \mathbf{n}|S_n = (i,0)\} = \Bigg[\binom{N-i}{n_0+n_1-i}\\ \times \lambda^{N-n_0-n_1}(1-\lambda)^{N-n_0-n_1}\Bigg]\Bigg[\binom{i}{i-n_0}\nu^{i-n_0}(1-\nu)^{n_0}\Bigg].\end{aligned} \tag{14}$$

Now, let k_0 and k_1 be the number of stations in the type 0 and type 1 at the current slot and the next slot, respectively. We also denote $\mathbf{k} = [k_0, k_1]$. Therefore, the transient probability from the first slot of a frame to the end of a collision avoidance period of a frame is obtained as

$$\begin{aligned}\tilde{\mathbf{A}}_{i,k} &= P\{S_{n+1} = \mathbf{k} = (k_0, k_1)|S_n = (i,0)\}\\ &= \sum_{n_1=0}^{N-i}\sum_{n_0=0}^{i} P\{S_{n+1} = \mathbf{n} = (n_0, n_1)|S_n = (i,0)\}\mathbf{A}_{\mathbf{n},\mathbf{k}},\end{aligned} \tag{15}$$

where $0 \leq k_0 + k_1 \leq N$ and $0 \leq m_0 + m_1 \leq N$. The state transient probability, $\mathbf{A}_{\mathbf{n},\mathbf{k}}$, is from the second slot to the end of the collision avoidance period. If p represents the probability that a station in type 1 decides to schedule for transmission by generating a backoff time, then k_1 stations still listen the channel at the beginning of a slot is $1-p$. Therefore, based on the condition of $0 \leq m_0 + m_1 = k_0 + k_1 \leq N$, we can derive the transition probability to change the system state from state $\mathbf{k}$ to state $\mathbf{m} = (m_0, m_1)$ as

$$\begin{aligned}\mathbf{A}_{\mathbf{k},\mathbf{m}} &\overset{def}{=} P\{S_{n+1} = \mathbf{m} = (m_0, m_1)|S_n = \mathbf{k} = (k_0, K-1)\}\\ &= (1-p)^{k_1}\delta(k_0 = m_0),\end{aligned} \tag{16}$$

if $k_0 + m_1 = 0$, and

$$\begin{aligned}\mathbf{A}_{\mathbf{k},\mathbf{m}} &\overset{def}{=} P\{S_{n+1} = \mathbf{m} = (m_0, m_1)|S_n = \mathbf{k} = (k_0, K-1)\}\\ &= (1-p)^{k_1}\delta(k_0 = m_0) + \binom{k_1}{m_1}p^{m_1}(1-p)^{k_1-m_1},\end{aligned} \tag{17}$$

if $k_1 \geq 1$ where $0 \leq k_0, k_1, m_1 \leq N$ and $k_0 \leq m_0 \leq N$.

To resolve the system performance, the successful probability to transmit one packet among these packets that are rescheduled for transmission at the same slot must be derived. After the collision avoidance period, a packet with length T (in unit slot) belongs to one of the following three cases: Successful transmission, no transmission, and packet collision. For successful transmission case, if without capture is considered, then the probability of successful transmission is

$$U_{\mathbf{m},\mathbf{j}} = \delta(m_1 - 1)\delta(j - m_0), \tag{18}$$

and the probability of successful transmission is given as

$$\begin{aligned}U_{\mathbf{m},\mathbf{j}} \;=\;& \delta(m_1-1)\delta(j-m_0) + [1-\delta(m_1)]\\ &\times[1-\delta(m_1-1)]\delta(j-m_0-m_1)P_{C,m_1},\end{aligned} \tag{19}$$

if capture effect is considered. The probability of no transmission is given as $I_{\mathbf{m},\mathbf{j}} = \delta(m_1)\delta(j - m_0)$. On the case of packet collision, the probability that the capture effect is not considered is given as

$$B_{\mathbf{m},\mathbf{j}} = (1-\delta(m_1))(1-\delta(m_1-1))\delta(j-m_0-m_1), \tag{20}$$

and the probability that capture effect is considered is given as

$$\begin{aligned}B_{\mathbf{m},\mathbf{j}} \;=\;& (1-\delta(m_1))(1-\delta(m_1-1))\\ &\times\delta(j-m_0-m_1)(1-P_{C,m_1}),\end{aligned} \tag{21}$$

where j is the number of backlogged stations at the end of a frame. Denote x be the length of the collision avoidance period, which consists of some slots. Therefore, the transient probabilities for a frame are given as follows in the matrix form if the second problem can be neglected in Section II-A.

$$\mathbf{P} = \tilde{\mathbf{A}}\mathbf{A}^{x-1}(\mathbf{I} + \mathbf{U} + \mathbf{B}). \tag{22}$$

B. The System Performance

To resolve the system performance, the average holding time of state $\mathbf{S}$ must be known. Let $\pi = [\pi_0, \pi_1, \cdots, \pi_N]$ be the stationary distribution. From [16], we have

$$\pi = \pi\mathbf{P}. \tag{23}$$

Let H be the packet header and the propagation delay time be τ; L be the average length of the longest packet payload; SIFS and DIFS be the short inter-frame space (IFS) time, denoted as SIFS, and the DCF (Distributed coordination function)-IFS, denoted as DIFS; and ACK time. A positive acknowledgement (ACK) is transmitted by the destination station to the corresponding successful packet. Therefore, the average time that the channel is sensed busy because of a successful transmission is given as

$$x = H + L + \text{SIFS} + \text{DIFS} + \text{ACK} + 2\tau. \tag{24}$$

If $\mathbf{e}$ represents a column vector with all elements are each equal to one and the spanning dimension is $(N+1)$, then the throughput performance is obtained from [15] as

$$\text{Throughput} = E_x[\pi\tilde{\mathbf{A}}\mathbf{A}^{\mathbf{x}-\mathbf{1}}\mathbf{U}\mathbf{e}]. \tag{25}$$

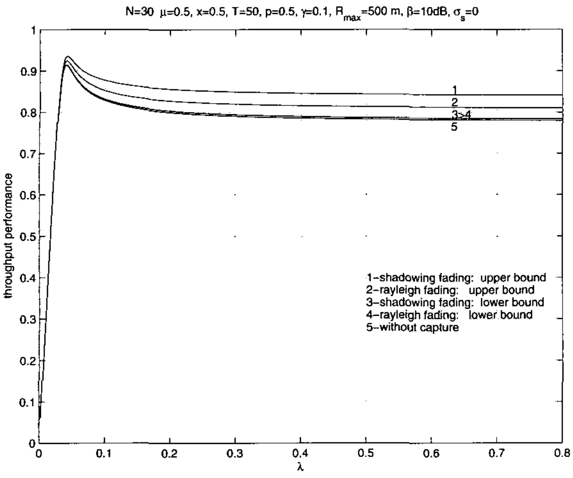

Fig. 2. The throughput performance for various value of λ.

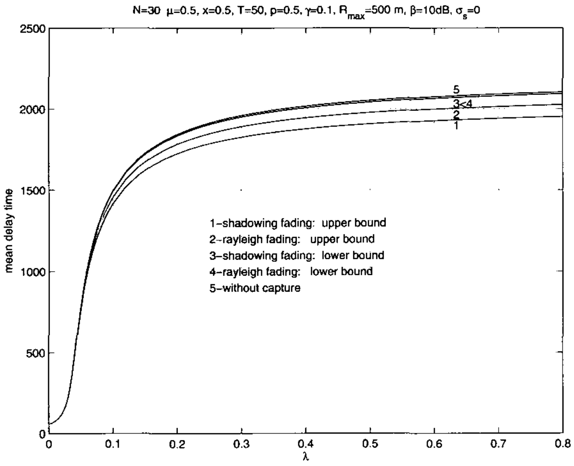

Fig. 3. The mean delay time of each mobile station for various value of λ.

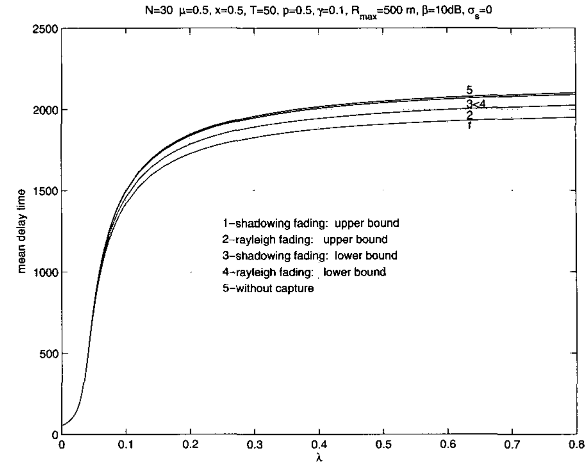

Fig. 4. The throughput performance for various value of p.

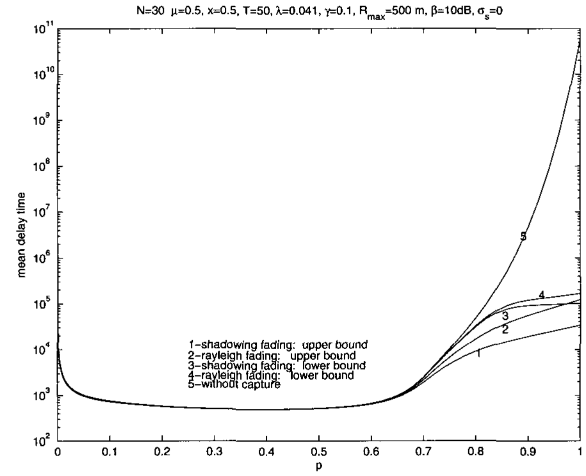

Fig. 5. The mean delay time of each mobile station for various value of p.

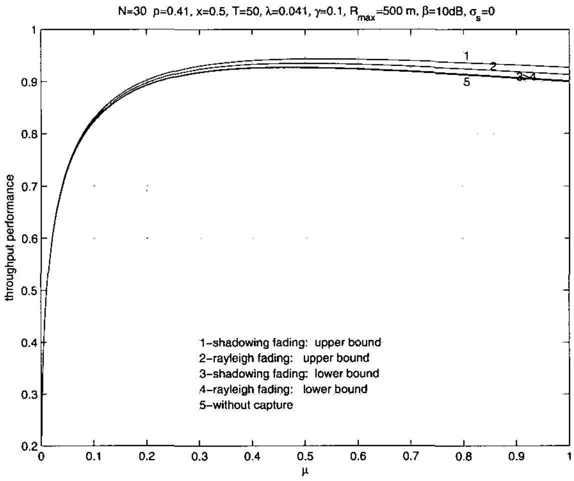

Fig. 6. The throughput performance for various value of ν.

Similar to the result in [15], the average delay time of a packet is also given as

$$E[D] = E_x\left[(x+T)\Big(1+\frac{\sum_{i=0}^{N} i\pi_i}{\pi\tilde{\mathbf{A}}\mathbf{A}_{\mathbf{x}-1}\mathbf{Ue}}\Big)\right]. \qquad (26)$$

IV. NUMERICAL RESULTS

Owing to our assumption that the channel is noiseless, we set $\sigma_s = 0$ for the following analyses. This study presents a more approximate channel model for radio propagation environments of mobile stations than previous ones. The first comparison is made by varying the value of λ in the environments with shadowing effect and the effect of Rayleigh fading to compare with the CSMA/CA protocol without capture. From Fig. 2, we can infer no obvious change in the throughput performance from the lower bound of the effect with shadowing effect and the effect of Rayleigh fading. In other words, the lower bound of performance approximates to a bounded value of without capture. While considering the impact of the upper bound with shadowing effect and the effect of Rayleigh fading, all figures reveal that the system performance experiences a significant change. Only for the upper bound value of system performance, the perfor-

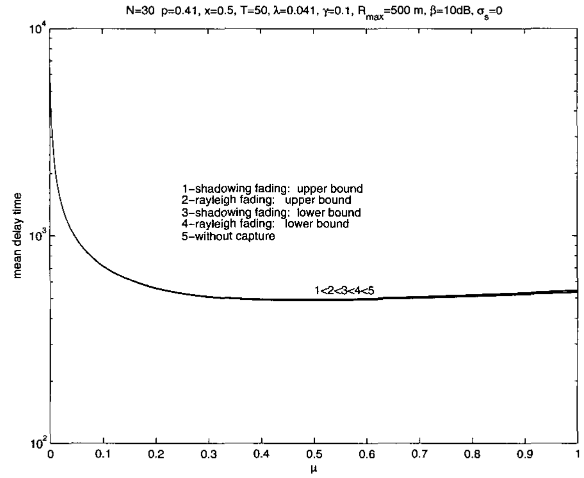

Fig. 7. The mean delay time of each mobile station for various value of ν.

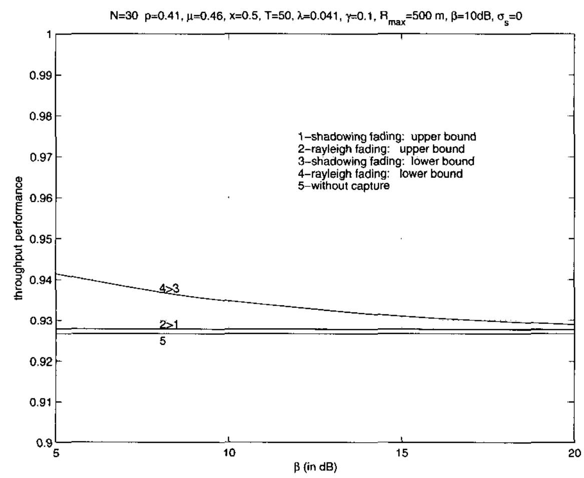

Fig. 8. The throughput performance for various value of β.

mance on the environments with shadowing is better than that with Rayleigh fading due to the serious fading of interference signal. Based on these given parameters in Figs. 2 and 3, the maximum throughput performance occurs at $\lambda = 0.041$.

As shown in Figs. 2 and 3, the second comparison is to discuss p value that can optimize system performance when $\lambda = 0.041$. Figs. 4 and 5 show that the capture effect will not improve significantly in terms of the performance when $p \leq 0.7$ and the highest point of the performance appears when $p = 0.41$ in comparison with the CSMA/CA protocol without capture effect. The system with capture effect has higher performance. However, since the system performance decreases to a significant extent, we will not discuss the decision point after $p \geq 0.7$. When $p = 0.41$ and $\lambda = 0.041$ (retrieved from Figs. 2–5), the third comparison is to change the value of ν. The changing the ν can gain the system performance as shown in Figs. 6 and 7. The ν in Fig. 6 does not improve the system performance significantly for the CSMA/CA protocol with capture effect and, especially, the delay performance in Fig. 7 is almost the same as the CSMA/CA protocols without capture effect.

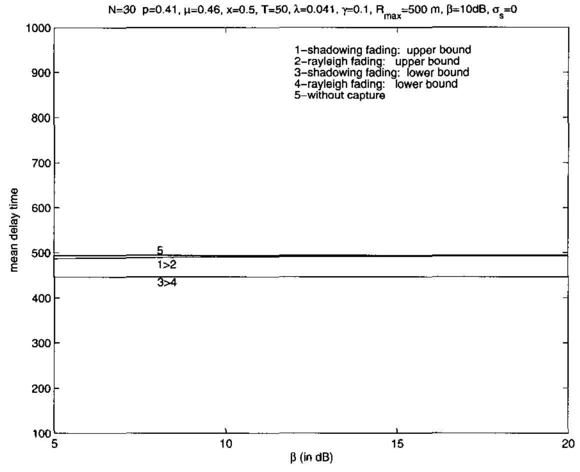

Fig. 9. The mean delay time of each mobile station for various value of β.

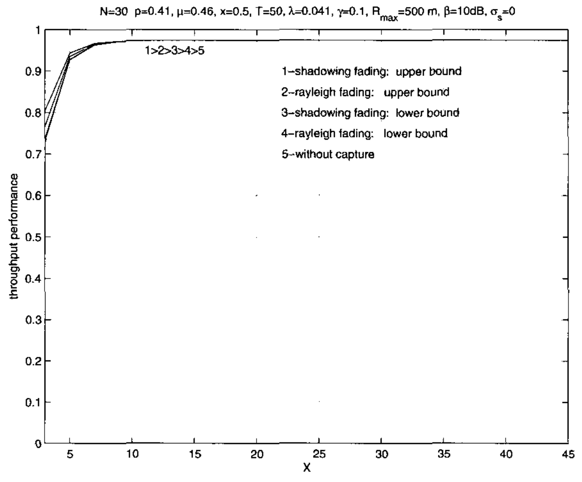

Fig. 10. The throughput performance for various value of x.

The study also discusses the effect of the capture ratio on the system performance. With the given optimal p, λ, and ν values (i.e. $p = 0.41$, $\lambda = 0.041$, and $\nu = 0.46$) as shown in Figs. 8 and 9, only the lower bound value, rather than the upper bound value, of the fading effect has a significant effect on the system performance.

We will also make sure whether the x value affects the system performance significantly when ideal parameters are selected for the system. In other words, we will find out whether it is required to re-select the ideal parameters when the x value changes. It is evident in Figs. 10 and 11 that the system performance is not affected when $x = 8$ and the effect is very low when $x \leq 8$.

V. CONCLUSIONS

From the perspective of the capture model in wide area networks, the environments are more complex. Our analysis results indicate that when the fading is more obvious, the base station can easily capture one of colliding packets in these en-

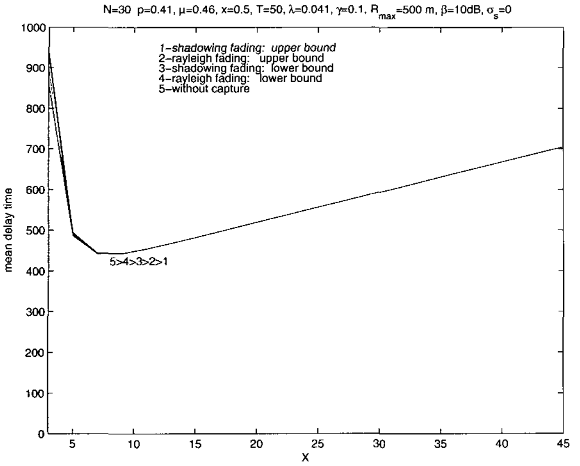

Fig. 11. The mean delay time of each mobile station for various value of x.

vironments. From simulation result, the clear space dominates the capture probability. For the value of γ, our results further indicate that the fading significantly varies at the environments with shadowing fading. Therefore, the system performance can be obviously enhanced in the wireless network with shadowing fading. However, the complexity of designed hardware must be considered to achieve the desired system performance by using a specific multiple access protocol in a wireless network system.

According to [17], the dynamic tuning mechanism is the most useful approach for optimal system performance. The active station estimates that the average number of empty slots in each channel competition is based on the use of channels and the p value (retrieved from the contention window) for the transmission of packets to obtain the number of conflict active stations. But from our analysis in Figs. 10 and 11, the optimal system performance can be obtained only by selecting the ideal parameters for the system without the need to use complicated mechanisms, such as the dynamic tuning mechanism described in [17]. In fact, the optimum value of system parameters will be changed when the given value of these parameters are changed. Therefore, how to select the optimal values among these parameters at the same time with respect to the system performance should be studied in the future work.

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