

PAPER

Performance Analysis of Wireless MAC Protocols with Rayleigh Fading, Log-Normal Shadowing and Capture Effects*

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SUMMARY The channel throughput and packet delay of wireless medium access control (MAC) protocols with Rayleigh fading, shadowing and capture effect are analyzed. We consider CSMA/CA protocols as the wireless MAC protocols, since CSMA/CA protocols are based on the standard for wireless Local Area Networks (LANs) IEEE 802.11. We analyze the channel throughput and packet delay for three types of CSMA/CA protocols; Basic CSMA/CA, Stop-and-Wait CSMA/CA and 4-Way Handshake CSMA/CA. We calculate the capture probability of an Access Point (AP) in a channel with Rayleigh fading, shadowing, and near-far effects, and we derive the throughput and packet delay for the various protocols. We have found that the performance of CSMA/CA in a radio channel model is 50 percent less than in an error free channel model in low traffic load, while the throughput and packet delay of CSMA/CA in a radio channel model show better performance than in an error free channel model in high traffic load. We also found that the 4-Way Handshake CSMA/CA protocol is superior to the other CSMA/CA protocols in high traffic load.

key words: wireless LAN, MAC protocol, CSMA/CA, rayleigh fading, capture effect

1. Introduction

Many interesting developments have taken place in wireless communications and portable communications in recent years. Wireless LAN manufacturers currently offer a number of nonstandardized products based on conventional radio modem technology, spread-spectrum technology in ISM (Industrial, Scientific and Medical) bands, and infrared technology [1].

Since 1990, the IEEE Project 802.11 committee has worked to establish a universal standard for wireless LAN protocol for interoperability between competing products [2], and ETSI (European Telecommunications Standards Institute) set up an ad hoc group to investigate radio LANs in 1991 [3]. One of the important research issues in wireless LANs is the design and analysis of Medium Access Control (MAC) protocols. In this paper, we consider a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol, which is a basic mechanism of the IEEE 802.11 MAC

protocol, and analyze the performance of CSMA/CA protocols by using a mathematical method based on renewal theory.

MAC protocols for wireless communications have been widely studied. There are some analytical studies for CSMA/CA protocols [4], [5], and some simulation studies [6], [7]. However, Chen assumes that CSMA/CA is a non-persistent CSMA, and Chhaya calculates the throughput of CSMA/CA with a simple model. Other studies do not present analytical approaches. There are also many studies for ALOHA family protocols in a fading channel and with shadowing [8]–[10]. However, the characteristics of the CSMA/CA cannot be described by ALOHA protocols and has not yet been analyzed in a fading channel model. In this paper, we present exact analytical approach for the channel throughput and the normalized packet delay of CSMA/CA protocols in Rayleigh fading, shadowing, and with the near-far effect. We consider a centralized wireless LAN configuration, and focus on the performance of an Access Point (AP) in a wireless LAN.

This paper is organized as follows: In Sect. 2, the propagation model and system model for CSMA/CA protocols is described. The throughput of three types of CSMA/CA is analyzed in Sect. 3, and in Sect. 4, packet delay is calculated. In Sect. 5, some numerical results are reported. Finally, we give concluding remarks in Sect. 6.

2. System Descriptions

2.1 Propagation and Power Capture Model

We focus on the performance of an AP in the infrastructure networks. We consider that the AP is located in the center of the infra-structure configuration and the other terminals are distributed in the Basic Service Area (BSA) with a given spatial distribution density function. The groundwave propagation gives rise to the near-far effect and determines the area-mean power w_a . Therefore, the normalized area-mean power received from a wireless terminal at a distance r_i is taken to have the form of $w_a = r_i^{-\xi}$, with the exponent, ξ , typically taking values in the range of two to four [11]. We assumed

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that shadowing is superimposed on the near-far effect. This fluctuation is described by a lognormal distribution of the local-mean power w_L about the area-mean power w_a with logarithmic standard deviation σ_s . We also assume that power control is not used, and that Rayleigh fading is an accurate characterization of the link fading process. Thus, the instantaneous received power w_s of a signal from a wireless terminal is exponentially distributed about the local-mean power w_L . Taking into account Rayleigh fading, log-normal shadowing and near-far effects, the unconditional probability density function (pdf) of the instantaneous power w_0 of a received packet is

$$f_{w_s}(w_s) = \int_0^\infty \int_0^\infty \frac{1}{w_L} \exp\left(-\frac{w_0}{w_L}\right) \frac{f(r_i)}{\sqrt{2}\sigma_s w_L} \cdot \exp\left\{-\frac{\ln^2(r_i^\xi w_L)}{2\sigma_s}\right\} dr_i dw_L \quad (1)$$

where $f(r_i)$ is the pdf of the propagation distance describing the spatial distribution. We consider the uniform spatial distribution in which we assume that the wireless terminals are uniformly distributed over a circle of unit radius about the access point. In this case, the pdf of the propagation distance is given by $f(r_i) = 2r_i$, $r_i \in (0, 1)$ [12].

We consider that a wireless network consists of M terminals $(s_1, s_2, \dots, s_i, \dots, s_M)$. We define \mathcal{R}_n as the set of terminals, which means n terminals transmit a packet at the same time. s_1 denotes a receiver which wants to receive the packet from a certain transmitter s_i ($s_i \in \mathcal{R}_n$). If s_1 receives the packet successfully from s_i , the instantaneous signal power w_s should exceed the joint interference signal power w_L from $n-1$ terminals ($\mathcal{R}_n - \{s_i\}$) by the capture ratio z . However, the s_1 does not receive the packet successfully from s_i if only w_s is captured from w_L , since the w_s also includes the joint interference signal with multipath fading, shadowing and near-far effect by itself. Let w_f be the joint interference signal for only s_i and w_0 denote the desired signal power of a packet, then w_0 and w_f are included in w_s . In order to find the capture probability, denoted by $q(n|z)$, for n colliding packets, we first consider that $q(0|z)$ denotes the probability of capture for a packet from s_i with a distance of r_i . Given the instantaneous interference power (w_f), the capture probability can be expressed as

$$q(0|z) = \int_0^\infty \int_0^\infty \frac{f(r_i)}{\sqrt{2}\sigma_s w_f} \exp\left\{-\frac{\ln^2(r_i^\xi w_f)}{\sqrt{2}\sigma_s}\right\} \left\{\phi_{w_f}\left(\frac{z}{w_f}\right)\right\} dr_i dw_f. \quad (2)$$

Here, $\phi_{w_f}(\cdot)$ is the one side Laplace image of the pdf of the instantaneous joint interference power w_f , defined

as

$$\begin{aligned} \phi_{w_f}(s) &\triangleq \int_0^\infty \exp(-sx) f_{w_f}(x) dx \\ &= \int_0^\infty \int_0^\infty \frac{1}{1+sw_f} \frac{f(r)}{\sqrt{2}\sigma_s w_f} \cdot \exp\left\{-\frac{\ln^2(r^\xi w_f)}{\sqrt{2}\sigma_s}\right\} dr dw_f. \end{aligned} \quad (3)$$

Further, if the interference received power w_L is due to incoherent accumulation of n independent fading signals for $n-1$ wireless terminals, the joint pdf of the received power is the $(n-1)$ -fold convolution of the pdf of the individual signal power [12]. Finally, the capture probability, conditioned on n interferers, is a three-fold integral of the form

$$\begin{aligned} q(n|z) &= \frac{2}{\sqrt{\pi}} \int_{-\infty}^\infty r_1 e^{-x_1^2} \left[\frac{1}{\sqrt{\pi}} \int_{-\infty}^\infty e^{-y_1^2} \right] dx_1 dr_1 \\ &\cdot \frac{2}{\sqrt{\pi}} \int_{-\infty}^\infty r_2 e^{-x_2^2} \left[\frac{1}{\sqrt{\pi}} \int_{-\infty}^\infty e^{-y_2^2} \right] dx_2 dr_2 \end{aligned} \quad (4)$$

where

$$\begin{aligned} f(x_1, y_1) &\triangleq \left[\sqrt{z} r_1^2 \exp\left\{\frac{\sqrt{2}}{2}\sigma_s(y_1 - x_1)\right\} \right] \\ &\cdot \arctan\left[\frac{1}{z r_1^4} \exp\left\{\frac{\sqrt{2}}{2}\sigma_s(x_1 - y_1)\right\} \right] \\ f(x_2, y_2) &\triangleq \left[\sqrt{z} r_2^2 \exp\left\{\frac{\sqrt{2}}{2}\sigma_s(y_2 - x_2)\right\} \right] \\ &\cdot \arctan\left[\frac{1}{z r_2^4} \exp\left\{\frac{\sqrt{2}}{2}\sigma_s(x_2 - y_2)\right\} \right] \end{aligned} \quad (5)$$

The $q(n|z)$ is obtained using the Hermite polynomial methods [13]. The probability q_n that one out of n packets captures the access point is found from $q_n = nq(n|z)$.

2.2 CSMA/CA Protocols and System Model

The IEEE 802.11 MAC protocol supports coexisting asynchronous and time-bounded services using different priority levels with different IFS (Inter Frame Space) delay controls. Three kinds of IFS are used to support three backoff priorities such as a SIFS (Short IFS), a PIFS (Priority Inter Frame Space) and DIFS (Distributed Coordination function IFS) [2]. Wireless packet transmission suffers from "the hidden terminal effect," so IEEE 802.11 MAC protocol provides alternative ways of packet transmission flow control. We consider three types of CSMA/CA according to the packet transmission flow control in this paper. First, an actual

data packet is used only for a packet transmission. This is called Basic CSMA/CA. Second, immediate positive acknowledgements are employed to confirm the successful reception of each packet. We call this scheme SW (Stop-and-Wait) CSMA/CA. The last is 4-WH (4-Way Handshake) CSMA/CA which uses RTS (Request To Send) and CTS (Clear To Send) packets prior to the transmission of the actual data packet.

With the CSMA/CA, we assume that the time is slotted with slot size a (propagation delay/packet transmission time). To analyze better the exact throughput of the CSMA/CA, we use a finite population (M terminals). A terminal generates a new packet with probability g , which includes new arrival and rescheduled packets during a slot. We assume that each ready station starts a packet transmission with probability p and this p is related to the backoff delay in the IEEE 802.11 standard. The duration of the packet transmission period is assumed to be fixed to unit of time 1. We consider the CSMA/CA as a hybrid protocol of slotted 1-persistent CSMA and p -persistent CSMA. We assume that a channel state consists of a sequence of regeneration cycles composed of idle (I) and busy periods (B). Let U be the time spent in useful transmission during a regeneration cycle and S be the channel throughput. The throughput S can be obtained by the above three terms, and the normalized packet delay is also calculated using the throughput.

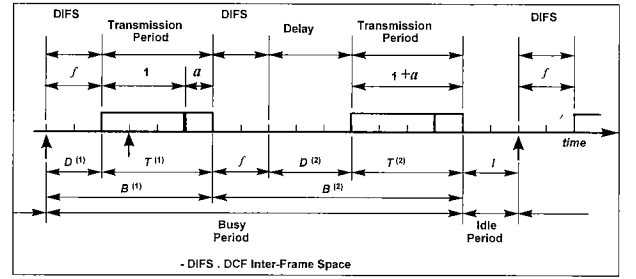
3. Throughput Analysis

3.1 Basic CSMA/CA

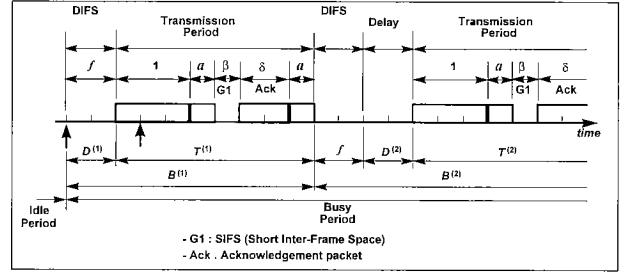
We consider the Basic CSMA/CA protocol, and calculate the expected value of the idle period, the busy period, and the useful transmission period. The throughput of CSMA/CA is then derived. In CSMA/CA, channel states are illustrated as in Fig.1(a). In Fig.1(a), the busy period is divided into several sub-busy periods such that the j th sub-busy period, which is denoted by $B^{(j)}$, is composed of a transmission delay (denoted by $D^{(j)}$) and transmission time (denoted by $T^{(j)}$).

In the sub-busy period $B^{(1)}$, $D^{(1)}$ is DIFS delay. However, $D^{(j)}$ is the stochastic random variable, if $j \geq 2$. $B^{(j)}$ is composed of a DIFS delay, $D^{(j)}$ and $T^{(j)}$. The DIFS delay is assumed to have l slots, and the size of DIFS is $f (= l \times a)$. In the case of the Basic CSMA/CA model, transmission period $T^{(j)}$ is fixed at $1 + a$, whether the transmission is successful or not. Let J be the number of sub-busy periods in a busy period. The busy period B and the useful transmission period U are simply given by

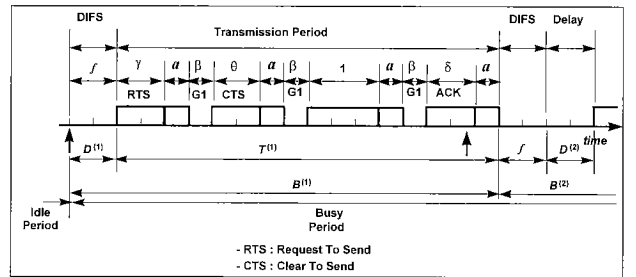
$$B = \sum_{j=1}^J B^{(j)}, \quad U = \sum_{j=1}^J U^{(j)}. \quad (6)$$



(a)



(b)



(c)

Fig. 1 Channel model in the three types of CSMA/CA (a) Basic CSMA/CA (b) SW ARQ CSMA/CA (c) 4-WH CSMA/CA.

In CSMA/CA, the busy period continues in the case that a packet is generated during the last transmission period as well as the last DIFS delay. Let TP be the sum of the last transmission period and the last DIFS delay, then TP is $1 + a + f$ in the Basic CSMA/CA model. Since J is geometrically distributed, the distribution and the expectation of J are

$$\Pr[J = j] = \left[1 - (1-g) \left(\frac{TP}{a} \right)^M \right]^{j-1} \cdot (1-g) \left(\frac{TP}{a} \right)^M$$

$$\bar{J} = \frac{1}{(1-g) \left(\frac{TP}{a} \right)^M}; \quad j = 1, 2, \dots \quad (7)$$

$B^{(1)}$ occurs when one or more packets arrive in the last slot of the idle period, and $B^{(2)}$ occurs when one or more packets arrive in $T^{(1)}$. Since the length of $B^{(j)}$ ($j \geq 3$) is independent of $B^{(2)}$ and identically distributed, the expectation of $B^{(j)}$ ($j \geq 2$) is $(\bar{J} - 1) \times E[B^{(2)}]$. In the same manner, we get $U^{(j)}$. Thus, the expectation of busy period and useful transmission time is given by

$$\bar{B} = E[B^{(1)}] + (\bar{J} - 1)E[B^{(2)}]$$

$$\bar{U} = E[U^{(1)}] + (\bar{J} - 1)E[U^{(2)}]. \quad (8)$$

Since the idle period is geometrically distributed, distribution and expectation of the duration for an idle period is given by

$$\Pr[I = ka] = (1-g)^{M(k-1)} \cdot [1 - (1-g)^M],$$

$$\bar{I} = \frac{a}{[1 - (1-g)^M]}; \quad k = 1, 2, \dots \quad (9)$$

To find $E[D^{(j)}]$ and $E[U^{(j)}]$, let $P_n(X)$ be the probability that n packets arrive at M users during X slots. $P_n(X)$ is expressed as

$$P_n(X) = \frac{\binom{M}{n} [1 - (1-g)^{X/a}]^n (1-g)^{X(M-n)/a}}{1 - (1-g)^{XM/a}}$$

$$n = 1, 2, \dots, M. \quad (10)$$

Furthermore, let $N_0^{(j)}$ be the number of packets accumulated at the end of a transmission period, then the distribution of $N_0^{(j)}$ is expressed as

$$\Pr[N_0^{(j)} = n] = P_n(TP) \quad ; \quad j = 2, 3, \dots \quad (11)$$

In order to find the distribution of $D^{(j)}$ when $N_0^{(j)} = n$ and $j \geq 2$, we consider k , $k = 0, 1, 2, \dots$, to be the number of slot boundaries as $D^{(j)}$ is greater than or equal to k slots in the following cases: n terminals, which are already scheduled to transmit a packet, do not transmit a packet and $(M-n)$ empty terminals generate no packets during k slots. Thus, we have

$$\Pr[D^{(j)} \geq ka | N_0^{(j)} = n] = (1-p)^{kn} (1-g)^{k(M-n)}. \quad (12)$$

We can derive the expectation of $D^{(j)}$, given that $N_0^{(j)} = n$, by unconditioning on $N_0^{(j)}$ in (12). The expectation of $D^{(j)}$ ($j \geq 2$) can then be calculated.

$$E[D^{(j)}] = \begin{cases} \frac{f[1 - (1-g)^M]}{1 - (1-g)^{\left(\frac{TP}{a}\right)^M}} \left(\sum_{k=1}^{\infty} \{(1-p)^k \right. \\ \left. - (1-g)^{\left(\frac{TP}{a}\right)^M} [(1-p)^k - (1-g)^k] \}^M \right. \\ \left. (1-g)^{\left(\frac{TP}{a}\right)^M} \sum_{k=1}^{\infty} (1-g)^{kM} \right) \\ ; \quad j = 2, 3, \dots \end{cases} \quad (13)$$

Using (8), (9) and (13), we obtain the sum of the expectation of the busy and the idle period as

$$\bar{B} + \bar{I} = f[1 - (1-g)^M] + 1 + a + \frac{1}{(1-g)^{(TP/a)M}}$$

$$\cdot \left((f+1+a)[1 - (1-g)^{(TP/a)M}] + a \sum_{k=1}^{\infty} \left\{ (1-p)^k - (1-g)^{(TP/a)} [(1-p)^k - (1-g)^k] \right\}^M \right. \\ \left. - a(1-g)^{(TP/a)M} \sum_{k=1}^{\infty} (1-g)^{kM} \right) + \frac{a}{1 - (1-g)^M} \quad (14)$$

We calculate the expected value of useful transmission time $E[U^{(j)}]$. In order to calculate $E[U^{(j)}]$, we consider the condition when $N_0^{(j)} = n$ and $D^{(j)} \geq ka$. Then, we have

$$E[U^{(j)} | D^{(j)} \geq ka, N_0^{(j)} = n] = \begin{cases} \sum_{i=1}^n \binom{M}{n} p^i (1-p)^{n-i} i q(i-1|z) & ; k = 0 \\ \sum_{i=1}^n \binom{M}{n} p^i (1-p)^{n-i} \sum_{l=1}^n \binom{M-n}{l} \\ \cdot g^l (1-g)^{M-n-l} (i+l) q(i+l-1|z) & ; k > 0 \end{cases} \quad (15)$$

where $i, i \in \{1, 2, \dots, n\}$, is the number of backlogged terminals which will transmit a packet with probability p , and l is the number of terminals which generate the a packet with probability g . Using the conditional expectation in (15), we can obtain the mean successful transmission period. Since $U^{(1)}$ is the useful transmission time when one or more packets arrive during the last slot of the previous idle period, it is equal to $P_1(1)$ in (10). Thus, we have

$$\bar{U} = E[U^{(1)}] + (\bar{J} - 1)E[U^{(2)}]$$

$$= \frac{1}{1 - (1-g)^M} \sum_{i=1}^M \frac{M-n}{l} [1 - (1-g)^i] \\ \cdot (1-g)^{M-i} i q(i|z) + \left(\frac{1}{(1-g)^{(TP/a)M}} \right) \\ \cdot \sum_{n=1}^M \left[\left\{ \sum_{i=1}^n \binom{n}{i} p^i (1-p)^{n-i} \cdot \sum_{l=1}^n \binom{M-n}{l} \right. \right. \\ \left. \left. g^l (1-g)^{M-n-l} (i+l) q(i+l|z) \right\} \cdot \left(\frac{(1-p)^n}{1 - (1-p)^n} \right) \right. \\ \left. \cdot \left(\frac{(1-g)^{M-n}}{(1-g)^{M-n}} \right) + \sum_{i=1}^n \binom{n}{i} p^i (1-p)^{n-i} i q(i|z) \right] \\ \left\{ \frac{\binom{M}{n} [1 - (1-g)^{(TP/a)]^n (1-g)^{(TP/a)(M-i)}}{1 - (1-g)^{(TP/a)M}} \right\} \quad (16)$$

Dividing (14) by (16), we obtain the throughput of a slotted Basic CSMA/CA system composed of M identical users, each user having geometric arrival rate g , slot time a and DIFS delay f .

3.2 Stop-and-Wait CSMA/CA

For SW CSMA/CA, channel states are illustrated in Fig.1 (b), in which β means the normalized time of SIFS and δ does that of ACK packet. Here the parameters and assumptions are the same as in the Basic CSMA/CA protocol except that the successful transmission period (TP_S) is given by $1 + \beta + \delta + 2a + f$. When a packet transmission is unsuccessful, the ACK packet transmission period is omitted and the unsuccessful transmission period (TP_F) is $1 + a + f$. Let TP denote the duration of the j th transmission period in the busy period, then the $(j + 1)$ th transmission period depends only on TP . Hence, given a transmission period (TP), the length of the remainder of the busy period is a function of TP , and its average period is denoted by $B(TP)$. Similarly the average useful transmission period in the remainder of the busy period is denoted by $U(TP)$.

$$\begin{aligned} B(TP) &= d(TP) + \left\{ (TP_S + [1 - (1-g)^{(TP_S/a)}] \right. \\ &\quad \cdot B(TP_S) \left. \right\} \cdot u(TP) \\ &\quad + \left\{ TP_F + [1 - (1-g)^{(TP_F/a)}] \right. \\ &\quad \cdot B(TP_F) \left. \right\} [1 - u(TP)] \end{aligned}$$

$$\begin{aligned} U(TP) &= \left\{ 1 + [1 - (1-g)^{(TP_S/a)}] U(TP_S) \right\} u(TP) \\ &\quad + \left\{ [1 - (1-g)^{(TP_F/a)}] U(TP_F) \right\} [1 - u(TP)] \end{aligned} \quad (17)$$

where,

$$\begin{aligned} d(1) &= f[1 - (1-g)^M] \\ d(TP) &= \frac{a}{1 - (1-g)^{(TP/a)M}} \left(\sum_{k=1}^{\infty} \{ (1-p)^k \right. \\ &\quad \left. - (1-g)^{(TP/a)} [(1-p)^k - (1-g)^k] \right\}^M \\ &\quad \cdot (1-g)^{(TP/a)M} \sum_{k=1}^{\infty} (1-g)^{kM} \Big) \\ u(1) &= \left(1 - \frac{1}{1 - (1-g)^M} \right) q(i-1|z) \\ u(TP) &= \sum_{n=1}^M \left[\left\{ \sum_{i=1}^n \binom{n}{i} p^i (1-p)^{n-i} \right. \right. \\ &\quad \cdot \sum_{l=1}^n \binom{M-n}{l} g^l (1-g)^{M-n-l} (i+l) q(i+l|z) \left. \right\} \\ &\quad \cdot \left(\frac{(1-p)^n (1-g)^{M-n}}{1 - (1-p)^n (1-g)^{M-n}} \right) \end{aligned}$$

$$\left. + \sum_{i=1}^n \binom{n}{i} p^i (1-p)^{n-i} q(i-1|z) \right] \left\{ \frac{\binom{M}{n} [1 - (1-g)^{(TP/a)]^n (1-g)^{(TP/a)(M-i)}]}{1 - (1-g)^{(TP/a)M}} \right\} \quad (18)$$

where $d(TP)$ and $u(TP)$ are derived from (13) and (15), respectively. If $j \geq 2$, we have to consider that TP is the case of both TP_S and TP_F . Since a busy period is induced by the first slot before it starts, we get

$$\bar{B} = B(1) \quad ; \quad \bar{U} = U(1) \quad (19)$$

Since the duration of a successful transmission is different from that of an unsuccessful transmission, $B(TP_S)$, $B(TP_F)$, $U(TP_S)$ and $U(TP_F)$ should be calculated respectively. Substituting TP by TP_S and TP_F in (12), we obtain two easily solved equations with the two unknowns $B(TP_S)$ and $B(TP_F)$. The average length of an idle period is the same as in (9). Thus we find the throughput of SW ARQ CSMA/CA.

$$S = \frac{U(1)}{B(1) + \frac{a}{[1 - (1-g)^M]}} \quad (20)$$

3.3 4-Way Handshake CSMA/CA

We now proceed to calculate the throughput of the 4-Way Handshake CSMA/CA. The channel model for slotted 4-WH CSMA/CA is shown in Fig. 1 (c). If the RTS packet transmission is successful, the transmission period ($T^{(j)}$) is composed of an RTS packet transmission period (γ), CTS packet transmission period (θ), data packet transmission period (1), ACK packet transmission period (δ), 3 SIFS (3β) and 4 propagation delay ($4a$). We denote TP_{4S} as the sum of the successful transmission period and DIFS delay. Therefore, TP_{4S} is $1 + \gamma + \theta + \delta + 3\beta + 4a + f$. In an unsuccessful case, $T^{(j)}$ is the sum of the RTS packet transmission period and an SIFS. Let TP_{4F} be the sum of the last unsuccessful transmission period and DIFS, then TP_{4F} is $\gamma + a + f$. In order to calculate the throughput of 4-WH CSMA/CA, we modify the analysis in the previous Section. Substituting TP_S and TP_F with TP_{4S} and TP_{4F} respectively, we can easily obtain $B(TP)$ and $U(TP)$. Using (17), (19) and (20) and calculating recursive forms of $B(TP_{4S})(U(TP_{4S}))$ and $B(TP_{4F})(U(TP_{4F}))$, we can obtain $B(1)$ and $U(1)$. Then we can derive the throughput of 4-WH CSMA/CA.

4. Delay Analysis

4.1 Basic CSMA/CA

In a packet transmission network, the performance is

usually represented by channel throughput and packet delay. We denote the expected packet delay L to be the average time between the generation and successful reception of a packet. In order to calculate the packet delay, we use offered traffic (G) and throughput (S). We use the average number of retransmissions for a packet ($G/S-1$). We now introduce the average delay R which is the time elapsed from the moment that a terminal starts sensing the channel to the moment that terminal accesses the channel. This is one of the following three cases: 1) A packet arrives and senses the channel to be in an idle period. 2) A packet arrives and senses the channel to be in a delay period (D). 3) A packet arrives and senses the channel to be in the transmission period. Let T be the packet transmission period and T is $(1+a)$ in the Basic CSMA/CA model. So we can get the average delay R as The average delay can be calculated by residual life period in renewal theory [14]. Let T be the packet transmission period and T is $(1+a)$ in the Basic CSMA/CA model. So we can get the average delay R as

$$\bar{R} = \frac{\bar{I}}{\bar{B} + \bar{I}} f + \frac{\bar{D}}{\bar{B} + \bar{I}} f + \frac{\bar{B} - \bar{D}}{\bar{B} + \bar{I}} \left[\frac{(T + f + E[D^{(2)}])^2}{2(T + f + E[D^{(2)}])} \right]. \quad (21)$$

In (21), we can obtain $E[D^{(2)}]$ using (13) and calculate

$$\bar{D} = E[D^{(1)}] + (\bar{J} - 1)E[D^{(2)}]. \quad (22)$$

We can obtain the normalized average packet delay by

$$L = \left(\frac{G}{S} - 1 \right) [T + \bar{Y} + \bar{R}] + T + \bar{R} \quad (23)$$

where, Y denotes random delay for a collided packet that waits for Y before sensing the channel.

4.2 Stop-and-Wait ARQ CSMA/CA

As in the case of Basic CSMA/CA, we calculate the average delay for the interval of successive transmission by

$$\bar{R} = \frac{\bar{I}}{\bar{B} + \bar{I}} f + \frac{\bar{D}}{\bar{B} + \bar{I}} f + \frac{\bar{B} - \bar{D}}{\bar{B} + \bar{I}} \left\{ P_{Succ} \left[\frac{(T_S + f + d(TP_S))^2}{2(T_S + f + d(TP_S))} \right] + P_{Fail} \left[\frac{(T_F + f + d(TP_F))^2}{2(T_F + f + d(TP_F))} \right] \right\} \quad (24)$$

where, TP_S is the sum of the last successful transmission period with DIFS equal to $1 + \beta + \delta + 2a + f$ and TP_F is the sum of the last unsuccessful transmission period with DIFS equal to $1 + a + f$. T_S is the successful transmission period ($1 + \beta + \delta + 2a$) and T_F is the unsuccessful transmission period ($1 + a$). P_{Succ} denotes the

probability of a successful packet transmission which is (G/S) and P_{Fail} is $1 - P_{Succ}$. \bar{D} can be obtain by $D(1)$ as follows

$$D(1) = f + \left\{ d(TP_S) + \left[1 - (1-g)^{(TP_S/a)} \right] D(TP_S) \right\} u(1) + \left\{ d(TP_F) + \left[1 - (1-g)^{(TP_F/a)} \right] D(TP_F) \right\} [1 - u(1)] \quad (25)$$

where $d(TP_S)$ and $d(TP_F)$ can be obtained, substituting TP with TP_S and TP_F in (17). $D(TP_S)$ and $D(TP_F)$ can be calculated by substituting 1 with TP_S and TP_F respectively. Since the backoff delay is determined by the previous transmission period, we have to calculate the backoff delay in both the cases of a successful and an unsuccessful transmission period. Then, normalized delay L in SW CSMA/CA is obtained easily by substituting former T by T_F and later T by T_S in (23). In the case of the infinite population model, we can obtain the normalized delay by using a method similar to that used in calculating throughput.

4.3 4-Way Handshake CSMA/CA

The packet transmission period is different from that of SW CSMA/CA. Since we have assumed that TP_{4S} is $1 + \gamma + \theta + \delta + 3\beta + 4a + f$, TP_{4F} is $\gamma + a + f$, T_{4S} is $1 + \gamma + \theta + \delta + 3\beta + 4a$ and T_{4F} is $\gamma + a$, we calculate the average delay for the interval of a successive transmission (\bar{R}) by

$$\bar{R} = \frac{\bar{I}}{\bar{B} + \bar{I}} f + \frac{\bar{D}}{\bar{B} + \bar{I}} f + \frac{\bar{B} - \bar{D}}{\bar{B} + \bar{I}} \left\{ P_{Succ} \left[\frac{(T_{4S} + f + d(TP_{4S}))^2}{2(T_{4S} + f + d(TP_{4S}))} \right] + P_{Fail} \left[\frac{(T_{4F} + f + d(TP_{4F}))^2}{2(T_{4F} + f + d(TP_{4F}))} \right] \right\} \quad (26)$$

where P_{Succ} denotes the probability that a packet transmission is successful (G/S), and P_{Fail} is $1 - P_{Succ}$ as in Sect. 4.2. \bar{D} has to be calculated in a manner similar to that of SW ARQ CSMA/CA. In the case of 4-WH CSMA/CA model, $D(1)$ is a recursive form as in (25), by substituting TP_S with TP_{4S} and TP_F with TP_{4F} . Then the normalized delay L in 4-WH CSMA/CA can be easily obtained by substituting the former T by T_{4F} and the latter T by T_{4S} in (23).

5. Numerical Results

Several numerical results are shown and the performances of three types of CSMA/CA are compared in this section. Figure 2 plots the capture probability for the number of terminals, when the capture ratio z is varied. The capture probabilities are decreased exponentially when the number of colliding terminals are in

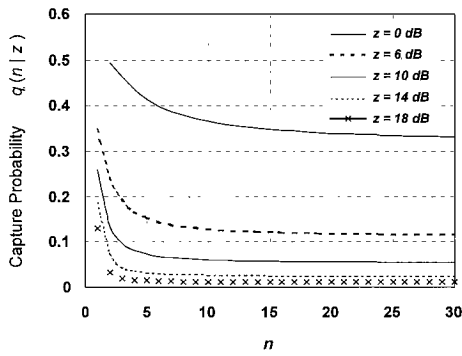
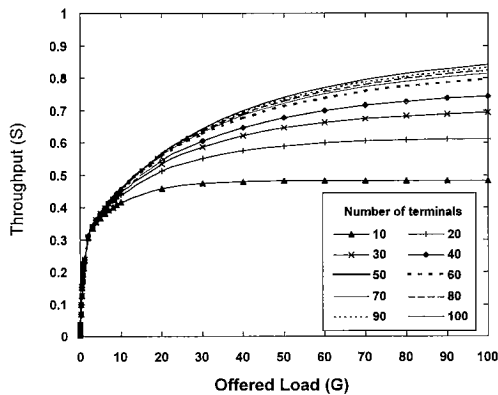
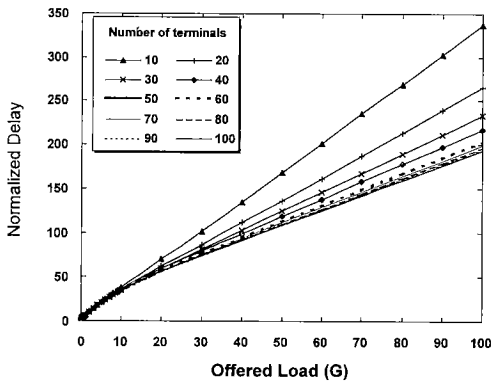


Fig. 2 Capture probability for the number of colliding terminals ($\sigma_s = 6$ dB, $\xi = 4$).



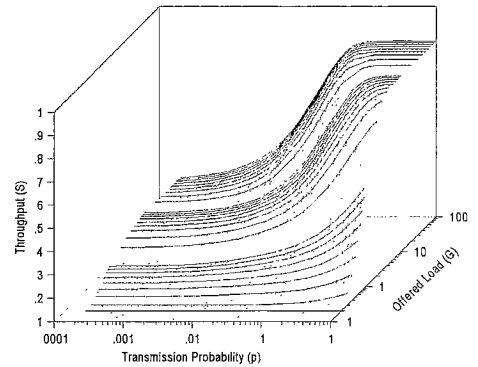
(a)



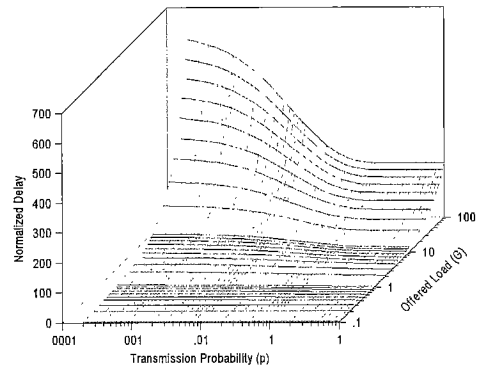
(b)

Fig. 3 Throughput and packet delay vs. offered load of Basic CSMA/CA for varying of the number of terminals ($a = 0.01$, $p = 0.03$, $f = 0.06$, $Y = 0.06$, $\sigma_s = 6$ dB, $\xi = 4$, $z = 4$) (a) Throughput vs. offered load (b) Normalized packet delay vs. offered load.

the range of 1 to 10. However, if the number of colliding terminals is increased above 10, the capture probabilities converge to a finite limit. In Fig. 3, note that as the number of terminals increases, the throughput does not decrease but becomes saturates asymptotically in Fig. 3(a). In Fig. 3(b), the packet delay is decreased as the number of terminals is increased, while it is linearly



(a)



(b)

Fig. 4 Throughput and packet delay vs. transmission probability p of SW ARQ CSMA/CA for varying of the offered load ($a = 0.01$, $p = 0.03$, $f = 0.06$, $\delta = 0.06$, $\beta = 0.03$, $Y = 0.06$, $\sigma_s = 6$ dB, $\xi = 4$, $z = 4$, $M = 50$) (a) Throughput vs. p (b) Normalized packet delay vs. p .

increased as the offered load is increased. To investigate the performance of SW ARQ CSMA/CA under varying transmission probability p , the throughput and normalized packet delay are represented in Fig. 4. We note that the performance of SW ARQ CSMA/CA is not degraded as the transmission probability increases. In usual cases of p -persistent CSMA, the performance is degraded when the transmission probability is increased above a specific value. The performance of CSMA/CA in the error free channel model also shows similar drift as the transmission probability p is varied [16]. Increasing p enhances the performance, due to the beneficial effect of power capture. When p is increased, the probability of packet collision is increased, while the chance to capture a packet is increased. This is why the capture probability converges to a finite limit.

Figure 5 reports throughput and packet delay versus capture ratio z and offered load G . In Fig. 5 (a), we note that throughput decreases more rapidly in low offered traffic while the throughput decreases less rapidly in high offered load. In the case of Fig. 5 (b), the packet delay increases linearly with respect to the capture ratio z . The performance comparison of three types of

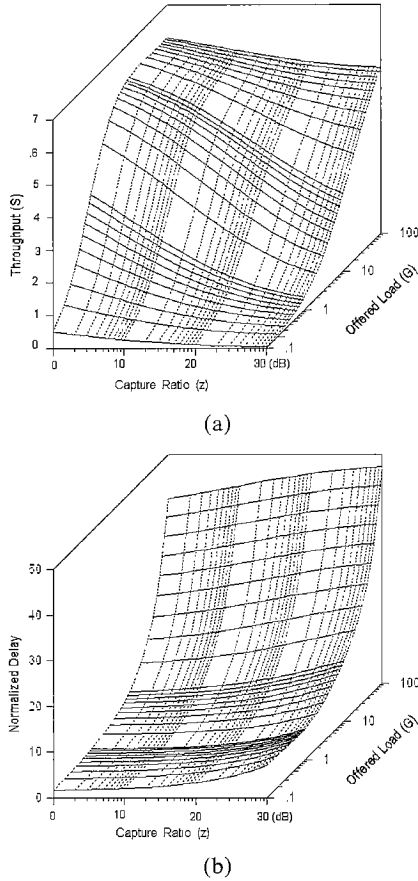


Fig. 5 Throughput and packet delay vs. capture ratio z of 4-WH CSMA/CA for varying of the offered load ($a = 0.01$, $p = 0.03$, $f = 0.06$, $\delta = 0.06$, $\beta = 0.03$, $\theta = 0.06$, $\gamma = 0.1$, $Y = 0.06$, $\sigma_s = 6$ dB, $\xi = 4$, $M = 20$) (a) Throughput vs. z (b) Normalized packet delay vs. z .

CSMA/CA is represented in Fig. 6. Note that curves with polygons indicate the analytical results in the error free channel model [16]. They can be obtained by substituting the capture ratio with 0 in the presented equations, when the number of colliding terminals is above 2. In the case of the error free channel model, the Basic CSMA/CA shows better performance than that of other two CSMA/CA protocols in low traffic load, while the 4-WH CSMA/CA is superior to others in high traffic load. In the case of fading, shadowing and power capture model, the performance of the 4-WH CSMA/CA is always better than that of the other two protocols. Moreover, we note that the performance of CSMA/CA in the fading channel model is worse than that in the error free channel model when the traffic is low. However, the throughput of CSMA/CA in the fading channel model increases continuously with the increase of the offered load, while the throughput in the error free channel model decreases when the traffic increased above a specific point. This is due to the capture effect. Finally, we note that the 4-WH CSMA/CA protocol is more appropriate than the Basic CSMA/CA

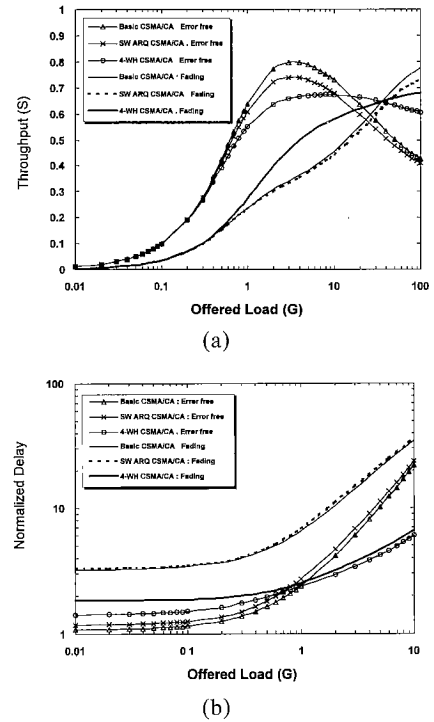


Fig. 6 Performance comparison of three types of CSMA/CA protocols for error channel model and fading channel model. ($a = 0.01$, $p = 0.03$, $f = 0.06$, $\delta = 0.06$, $\beta = 0.03$, $\theta = 0.06$, $\gamma = 0.1$, $Y = 0.06$, $\sigma_s = 6$ dB, $\xi = 4$, $M = 50$) (a) Throughput comparison (b) Normalized packet delay comparison.

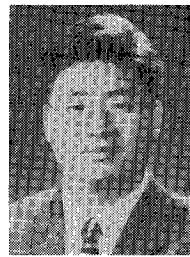
or the SW ARQ CSMA/CA in practical wireless communication environments.

6. Conclusions

In this paper, we have analyzed the performance of CSMA/CA protocols with power capture, operating on a channel impaired by Rayleigh fading, lognormal shadowing and the near-far effect. We have considered three types of CSMA/CA protocols, including Basic, SW ARQ and 4-WH CSMA/CA, and have analyzed their throughput and packet delay. We have found that capture probability converges to a finite limit as the number of colliding terminals is increased. Then, we have developed a new analytical approximation for the performance of CSMA/CA protocols with Rayleigh fading, lognormal shadowing and power capture effect. From the analytical results, we have found that the throughput of CSMA/CA protocols does not decrease as the number of terminals and the offered load increases. We have also found that the performance of CSMA/CA is enhanced as transmission probability p increases, and is sensitive to the capture ratio z . Extensive numerical results have been presented showing that 4-WH CSMA/CA protocol is a more attractive protocol than the other two types of CSMA/CA in practical wireless communication environments.

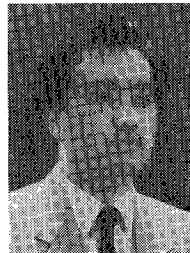
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