# Performance Analysis of MAC Protocols for Wireless LAN in Rayleigh and Shadow Fading Channel.

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**Abstract** The channel throughput and packet delay of wireless MAC (medium access control) protocols with Rayleigh fading, shadowing, and capture effect are analyzed. We consider CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) protocols as the wireless MAC protocols, since CSMA/CA protocols are based on the standard for wireless LANs (Local Area Networks) 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 a AP (Access Point) 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 4-Way Handshake CSMA/CA protocol is superior to the other CSMA/CA protocols in high traffic load.

## I. Introduction

Wireless LANs offer many advantages in installation, maintenance and relocation from the viewpoint of cost and efficiency. Wireless LAN manufacturers currently offer a number of non-standardized products based on conventional radio modem technology, spread-spectrum technology in ISM(Industrial, Scientific and Medical) bands, and infrared technology.

Since 1990, the IEEE Project 802.11 committee has worked to establish a universal standard for wireless LAN protocol for interoperability between competing products [1], and ETSI(European Telecommunications Standards Institute) set up an ad hoc group to investigate radio LANs in 1991 [2]. One of the important research issues in wireless LANs is the design and analysis of MAC protocols. MAC protocols for wireless communications have been widely studied. There are some analytical studies for CSMA/CA protocols,[3], and some simulation studies[4]. However, 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 [5],[6]. 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 AP in a wireless LAN. We analyze the performances of three types of CSMA/CA protocols and compare the throughput and normalized packet delay with each other.

## II. System Desciptions

We focus on the performance of an AP in the infra-structure 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, $\xi$, typically taking values in the rage of three to four[7]. We assumed 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 $\sigma_s$. 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 $w_0$ 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

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

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 $f(r_i) = 2r_i$ , $r_i \in (0,1)$ [7]. We consider that a wireless network consists of $M$ terminals $(s_1, s_2, \cdots, s_i, \cdots, s_M)$. 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 $q(s_1|z)$ denotes the probability of capture for a packet from $s_i$ with a distance of $r_i$. Given the local mean power $(w_f)$, the capture probability can be expressed as

$$q(s_1|z) = \int_0^\infty \int_0^\infty \frac{f(r_i)}{\sqrt{2}\sigma_s w_f} \exp\left\{-\frac{ln^2(r_i^\xi w_f)}{\sqrt{2}\sigma_s}\right\} \left\{\phi_{w_f}\left(\frac{z}{w_0}\right)\right\} dr_i\, dw_L. \quad (2)$$

Here, $\phi(*)$ is the one side Laplace image of the pdf of the instantaneous joint interference power $w_f$, defined as

$$\phi_{w_f}(s) \triangleq \int_0^\infty \exp(-sx) f_{w_f}(x)\, dx. \quad (3)$$

Further, if the interference received power $w_L$ is due to incoherent accumulation of $n$ independent fading signals for $n$ wireless terminals, the joint pdf of the received power is the $n$-fold convolution of the pdf of the individual signal power [7]. Finally, the capture probability, conditioned on $n$ interferers, is a three-fold integral of the form

$$q(n|z) = \frac{2}{\sqrt{\pi}} \int_0^1 \int_{-\infty}^\infty r_1 \exp(-x_1^2) \left[\frac{1}{\sqrt{\pi}} \int_{-\infty}^\infty \exp(-y_1^2) dy_1\right] dx_1 dr_1 \cdot \frac{2}{\sqrt{\pi}} \int_0^1 \int_{-\infty}^\infty r_2 \exp(-x_2^2) \left[\frac{1}{\sqrt{\pi}} \int_{-\infty}^\infty \exp(-y_2^2) dy_2\right]^{n-1} dx_2 dr_2 \quad (4)$$

where

$$f(x_1, y_1) \triangleq \left[\sqrt{z} r_1^2 \exp\left\{\frac{\sqrt{2}}{2}\sigma_s(y_1 - x_1)\right\}\right] \cdot \arctan\left[\frac{1}{z r_1^4} \exp\left\{\frac{\sqrt{2}}{2}\sigma_s(x_1 - y_1)\right\}\right]$$

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

The probability $q_n$ that one out of $n$ packets is captured by the access point is found from $q_n = nq(n|z)$.

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 (Point coordination function IFS) and DIFS (Distributed Coordination function IFS) [1]. 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.

## III. Throughput Analysis

### A. Basic CSMA/CA

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 a 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 $f(= l \times a)$. 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

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

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

$$\Pr[J = j] = \left[1 - (1-g)^{(TP/a)M}\right]^{j-1} \cdot (1-g)^{(TP/a)M}$$
$$\bar{J} = \frac{1}{(1-g)^{(TP/a)M}} \; ; \; j = 1, 2, \cdots. \quad (7)$$

Since the length of $B^{(j)} (j \geq 3)$ is independent of f $B^{(2)}$ 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

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

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

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

To find $E[D^{(j)}]$ and $E[U^{(j)}]$, 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

$$\Pr[N_0^{(j)} = n] = \frac{\binom{M}{n} \left[1 - (1-g)^{TP/a}\right]^n (1-g)^{TP(M-n)/a}}{1 - (1-g)^{TPM/a}} \; ; \quad n = 1, 2, \cdots, M. \;\; j = 2, 3, \cdots. \quad (10)$$

In order to find the distribution of $D^{(j)}$ when $N_0^{(j)} = n$ and $j \geq 2$ , we consider $k (k = 0, 1, 2, \cdots)$ to be the number of slot boundaries.

$$\Pr[D^{(j)} \geq ka | N_0^{(j)} = n] = (1-p)^{kn}(1-g)^{k(M-n)}. \tag{11}$$

We can derive the expectation of $D^{(j)}$, given $N_0^{(j)} = n$, by unconditioning on $N_0^{(j)}$ in (11), the expectation of $D^{(j)} (j \geq 2)$ can then be calculated.

$$E[D^{(j)}] = \begin{cases} f[1-(1-g)^M]; & j=1 \\ \frac{a}{1-(1-g)^{(TP/a)M}} \left( \sum_{k=1}^{\infty} \left\{ (1-p)^k \right.\right. & \\ \left. -(1-g)^{(TP/a)} \left[(1-p)^k - (1-g)^k\right] \right\}^M & \\ \left. (1-g)^{(TP/a)M} \sum_{k=1}^{\infty} (1-g)^{kM} \right); & j = 2, 3, \cdots \end{cases} \tag{12}$$

Using (8), (9) and (12), we obtain the sum of the expectation of the busy and the idle period as

$$\begin{aligned} \bar{B} + \bar{I} &= f[1-(1-g)^M] + 1 + a + \frac{1}{(1-g)^{(TP/a)M}} \\ &\cdot \Big( (f+1+a)[1-(1-g)^{(TP/a)M}] + a \sum_{k=1}^{\infty} \\ &\left\{ (1-p)^k - (1-g)^{(TP/a)}[(1-p)^k - (1-g)^k] \right\}^M \\ &-a(1-g)^{(TP/a)M} \sum_{k=1}^{\infty} (1-g)^{kM} \Big) + \frac{a}{1-(1-g)^M} \end{aligned} \tag{13}$$

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

$$\begin{aligned} \bar{U} &= E[U^{(1)}] + (\bar{J} - 1)E[U^{(2)}] \\ &= \frac{1}{1-(1-g)^M} \sum_{i=1}^{M} \begin{matrix} M-n \\ l \end{matrix} [1-(1-g)]^i (1-g)^{M-i} iq(i|z) \\ &+ \left( \frac{1}{(1-g)^{(TP/a)M}} \right) \sum_{n=1}^{M} \left[ \left\{ \sum_{i=1}^{n} \binom{n}{i} p^i (1-p)^{n-i} \right.\right. \\ &\cdot \sum_{l=1}^{n} \binom{M-n}{l} g^l (1-g)^{M-n-l} (i+l)\ q(i+l|z) \Big\} \\ &\cdot \left. \left( \frac{(1-p)^n (1-g)^{M-n}}{1-(1-p)^n(1-g)^{M-n}} \right) + \sum_{i=1}^{n} \binom{n}{i} p^i (1-p)^{n-i} iq(i|z) \right] \\ &\cdot \left\{ \frac{\binom{M}{n} [1-(1-g)^{(TP/a)}]^n (1-g)^{(TP/a)(M-i)}}{1-(1-g)^{(TP/a)M}} \right\} \end{aligned} \tag{14}$$

Dividing (13) by (14), we obtain the throughput of a slotted Basic CSMA/CA system composed of $M$ terminals, each user having the geometric arrival rate $g$ , slot time $a$ and DIFS delay $f$.

### B. Stop-and-Wait CSMA/CA

In the following, we consider the SW CSMA/CA protocol and calculate its throughput. For SW CSMA/CA, whose channel states are illustrated in Fig. 1(b), $\beta$ is the normalized time of SIFS and $\delta$ is the normalized time of an 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 $U(TP)$.

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

$$\begin{aligned} U(TP) &= \left\{ 1 + [1-(1-g)^{(TP_S/a)}] U(TP_S) \right\} u(TP) \\ &+ \left\{ [1-(1-g)^{(TP_F/a)}] U(TP_F) \right\} [1-u(TP)] \end{aligned} \tag{15}$$

where

$$\begin{aligned} &d(1) = f[1-(1-g)^M] \\ &d(TP) = \frac{a}{1-(1-g)^{(TP/a)M}} \left( \sum_{k=1}^{\infty} \left\{ (1-p)^k - (1-g)^{(TP/a)} \right.\right. \\ &\cdot \left. \left[ (1-p)^k - (1-g)^k \right] \right\}^M (1-g)^{(TP/a)M} \sum_{k=1}^{\infty} (1-g)^{kM} \Big) \\ &u(1) = \left( 1 - \frac{1}{1-(1-g)^M} \right) q(i-1|z) \\ &u(TP) = \sum_{n=1}^{M} \left[ \left\{ \sum_{i=1}^{n} \binom{n}{i} p^i (1-p)^{n-i} \cdot \sum_{l=1}^{n} \binom{M-n}{l} \right.\right. \\ &\cdot g^l (1-g)^{M-n-l}\ (i+l) q(i+l|z) \Big\} \left( \frac{(1-p)^n (1-g)^{M-n}}{1-(1-p)^n(1-g)^{M-n}} \right) \\ &+ \left. \sum_{i=1}^{n} \binom{n}{i} p^i (1-p)^{n-i} iq(i-1|z) \right] \\ &\cdot \left\{ \frac{\binom{M}{n} [1-(1-g)^{(TP/a)}]^n (1-g)^{(TP/a)(M-i)}}{1-(1-g)^{(TP/a)M}} \right\} \end{aligned} \tag{16}$$

where $d(TP)$ and $u(TP)$ are derived from (12) and (14), 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 $\bar{B} = B(1) (\bar{U} = U(1))$. 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 (11), 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.

$$S = \frac{U(1)}{B(1) + \frac{a}{[1-(1-g)^M]}}. \tag{17}$$

### C. 4-Way Handshake CSMA/CA

Since a packet transmission is not absolutely reliable in wireless communication environments, IEEE 802.11 provides 4-Way handshaking with a CSMA/CA mechanism. We assume that packet transmission of RTS and CTS are normalized respectively. 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 ($\gamma$), CTS packet transmission period ($\theta$), data packet transmission period (1), ACK packet transmission period ($\delta$), 3 SIFS ($3\beta$ ) 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 (15)and (17) 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.

## IV. Delay Analysis

### A. Basic CSMA/CA

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 a 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

$$\bar{R}=\frac{\bar{I}}{\bar{B}+\bar{I}}f+\frac{\bar{D}}{\bar{B}+\bar{I}}f+\frac{\bar{B}-\bar{D}}{\bar{B}+\bar{I}}\left[\frac{\overline{(T+f+E[D^{(2)}])^2}}{2(T+f+\overline{E[D^{(2)}]})}\right]. \quad (18)$$

In (18), we can obtain $E[D^{(2)}]$ using (12) and calculate

$$\bar{D}=E[D^{(1)}]+(\bar{J}-1)E[D^{(2)}]. \quad (19)$$

We can obtain the normalized average packet delay by

$$L=\left(\frac{G}{S}-1\right)[T+\bar{Y}+\bar{R}]+T+\bar{R} \quad (20)$$

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

### B. 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

$$\begin{aligned}\bar{R} \quad = \quad & \frac{\bar{I}}{\bar{B}+\bar{I}}f+\frac{\bar{D}}{\bar{B}+\bar{I}}f+\frac{\bar{B}-\bar{D}}{\bar{B}+\bar{I}}\cdot\left\{P_{Succ}\left[\frac{\overline{(T_S+f+d(TP_S))^2}}{2(T_S+f+\overline{d(TP_S)})}\right]\right.\\ & \left.+P_{Fail}\left[\frac{\overline{(T_F+f+d(TP_F))^2}}{2(T_F+f+\overline{d(TP_F)})}\right]\right\} \quad (21)\end{aligned}$$

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 $(G/S)$ and $P_{Fail}$ is $1-P_{Succ}$. Other notations are the same as those in Section A., but $\bar{D}$ has to be calculated differently. $\bar{D}$ can be obtain by $D(1)$ as follows

$$\begin{aligned}& D(1)=f+\left\{d(TP_S)+\left[1-(1-g)^{(TP_S/a)}\right]D(TP_S)\right\}u(1)\\ & +\left\{d(TP_F)+\left[1-(1-g)^{(TP_F/a)}\right]D\left(TP_F\right)\right\}[1-u(1)] \quad (22)\end{aligned}$$

where $d(TP_S)$ and $d(TP_F)$ can be obtained, substituting $TP$ with $TP_S$ and $TP_F$ in (16). $D(TP_S)$ 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 (20). 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.

### C. 4-Way Handshake CSMA/CA

In the 4-WH CSMA/CA protocol, 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

$$\begin{aligned}\bar{R} \quad = \quad & \frac{\bar{I}}{\bar{B}+\bar{I}}f+\frac{\bar{D}}{\bar{B}+\bar{I}}f+\frac{\bar{B}-\bar{D}}{\bar{B}+\bar{I}}\cdot\left\{P_{Succ}\left[\frac{\overline{(T_{4S}+f+d(TP_{4S}))^2}}{2(T_{4S}+f+\overline{d(TP_{4S})})}\right]\right.\\ & \left.+P_{Fail}\left[\frac{\overline{(T_{4F}+f+d(TP_{4F}))^2}}{2(T_{4F}+f+\overline{d(TP_{4F})})}\right]\right\} \quad (23)\end{aligned}$$

where $P_{Succ}$ denotes the probability that a packet transmission is successful $(G/S)$, and $P_{Fail}$ is $1-P_{Succ}$ as in Section B.. $\overline{D}$ has to be calculated in a manner similar to that of SW CSMA/CA. In the case of 4-WH CSMA/CA model, $D(1)$ is a recursive form as in (22), 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 (20).

## V. Numerical Results

Several numerical results are shown and the performances of three types of CSMA/CA are compared in this section. Fig.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 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 increased as the offered load is increased. Fig.4 reports throughput and packet delay versus capture ratio $z$ and offered load $G$. In Fig.4(a), we note that throughput decreases more rapidly in low offered traffic while the throughput decreases less rapidly in high offered load. This means that the power capture is more effective in high traffic loads. In the case of Fig.4(b), the packet delay increases linearly with respect to the capture ratio $z$. The performance comparison of three types of CSMA/CA is represented in Fig.5. Note that curves with polygons indicate the analytical results in the error free channel model [9]. In the case of the error free channel model, the Basic CSMA/CA shows better performance than that of other two 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. Finally, we note that the 4-WH CSMA/CA protocol is more appropriate than the Basic CSMA/CA or the SW ARQ CSMA/CA in practical wireless communication environments.

## VI. Conclusions

We have analyzed the performance of CSMA/CA protocols with power capture, operating on a channel impaired by Rayleigh fading, 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. To analyze the performance of CSMA/CA, we have considered capture probability in fading and shadowing channels. We have found that capture probability converges to a finite limit as the number of colliding terminals is increased. Furthermore, we have developed a new analytical approximation for the performance of CSMA/CA protocols with Rayleigh fading, lognormal shadowing and power capture effect. As a result of our analysis, we have found that the throughput of CSMA/CA protocols does not decreased 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.

## References


[1] “Wireless LAN Medium Access Control (MAC) And Physical Layer(PHY) Specification,” *IEEE 802.11 Standard Draft*, Dec. 1994.

[2] T. Wilkinson, T. G. C. Phipps and S. K. Barton, “A Report on HIPERLAN Standardization,” *International Journal of Wireless Information Networks*, vol. 2, no. 2, pp. 99 120, Apr. 1995.

[3] H. S. Chhaya and S. Gupta, “Throughput and Fairness Properties of Asynchronous Data Transfer Methods in the IEEE 802.11 MAC Protocol,” *Proc. IEEE PIMRC ’95*, pp. 613-617, Toronto, Canada Sep. 27-29, 1995.

[4] A. Visser and M. E. Zarki, “Voice and data transmission over an 802.11 Wireless network,” Proc. *IEEE PIMRC ’95*, pp. 648-652, Toronto, Canada Sep. 27-29, 1995.

[5] C. V. D. Plas and J. P. M. G. Linnartz, “Stability of Mobile Slotted ALOHA Network with Rayleigh Fading, Shadowing, and Near-Far Effect,” *IEEE Trans. Veh. Technol.*, vol.39, no.4, pp.359-366, Nov. 1990.

[6] F. Borgonovo and M. Zorzi, “Slotted ALOHA and CDPA : A comparison of Channel Access Performance in Cellular Systems,” *Proc. IEEE INFOCOM ’96*, pp. 696-703, San Francisco, USA, Mar. 26-28, 1996.

[7] J. P. Linnartz, Narrowband Land-Mobile Radio Networks, Artech House 1993.

[8] L. Kleinrock and F. A. Tobagi, “Packet Switching in Radio Channels: Part I Carrier Sense Multiple Access Modes and Their Throughput Delay Characteristics“ *IEEE Trans. on Commun.*, vol. com-23, no. 12, pp. 1400-1416, Dec. 1975.

[9] J .H. Kim and J. K. Lee, “Throughput and Packet Delay Analysis of IEEE 802.11 MAC Protocols for Wireless LANs,” *Proceeding of MDMC ’96*, Seoul, Korea. pp. 530-535, 1996.

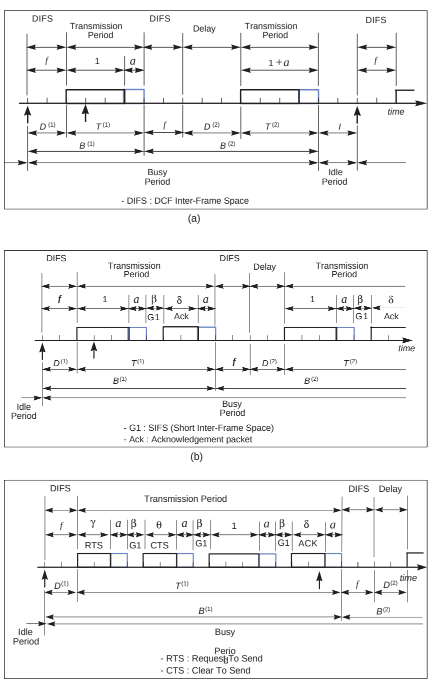




Figure 1: Channel model in the three types of CSMA/CA (a) Basic CSMA/CA (b) SW ARQ CSMA/CA (c) 4-WH CSMA/CA

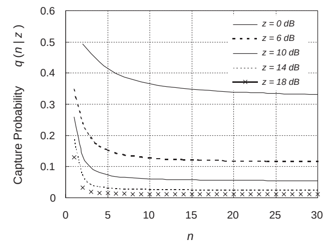
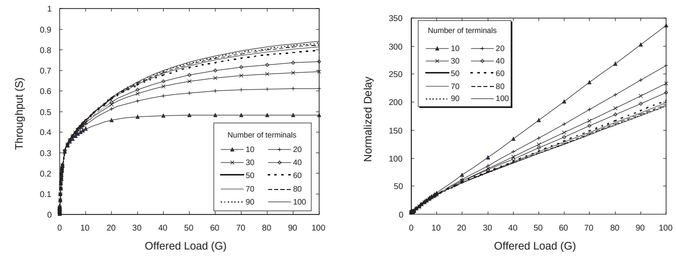
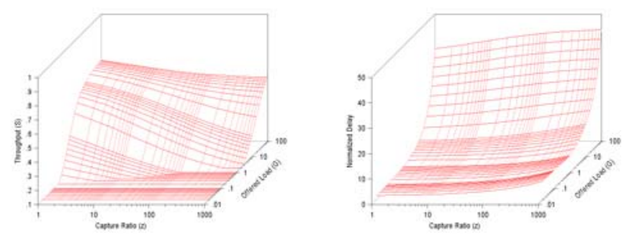



Figure 2: Capture probability for the number of colliding terminals ($\sigma_s = 6dB, \xi = 4$)



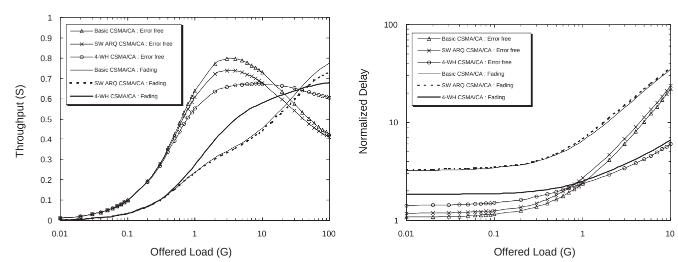

(a) (b)

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




(a) (b)

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




(a) (b)

Figure 5: Performance comparison of three types of CSMA/CA protocols for error channel model and fading channel model. ( $a = 0.01, p = 0.03, f = 0.06, \delta = 0.06, \beta = 0.03, \theta = 0.06, \gamma = 0.1, Y = 0.06, \sigma_s = 6dB, \xi = 4, M = 50$) (a) Throughput comparison (b) Normalized packet delay comparison.